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SYMPOSIUM

11th International Vacuum Insulation Symposium

Proceedings

Dübendorf, Switzerland
September 19 – 20, 2013

11th International Vacuum Insulation Symposium

Dübendorf, Switzerland

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11th International Vacuum Insulation Symposium
Dübendorf, Switzerland

Program

Wednesday, September 18, 2013

18:00 IVIS Registration and Reception at Empa Akademie

Thursday, September 19, 2013

Extended abstract on page

8:00 IVIS Registration

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Welcome of Head of "Building Science and Technology Lab" Prof. Jan Carmeliet

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  Ulrich Heinemann, *ZAE Bayern, Germany* 1
- **Keynote lecture:** VIP used in Buildings
  Beat Kämpfen, *kämpfen für architektur ag, Switzerland* 3

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- New exploratory testing conditions to understand the gas transfer mechanisms through VIPs' barriers
  Mathias Bouquerel and Thierry Duforestel, *EdF, France* 5
- Numerical Examination of Thermal Bridging Effects at the Edges of Vacuum-Insulation-Panels (VIP) in various Constructions
  Christoph Sprengard and Andreas Holm, *FIW, Germany* 7
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  Mikkel Kragh and Valerie Hayez, *Dow Corning, Belgium* 9

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- Measurement of airborne sound transmission loss of a small-scale assembly containing vacuum insulated panels
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- Thermal Conductivity measured at center of panel - that is only half of the truth!
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  Vacuum insulation panels in thermal packaging solutions - functioning, application, solutions
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18.45 Option 2 of guided tour with public transport from Hotel Sonnental to ETH Main building

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Speaker underlined

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Vacuum Insulation Panels — Potentials, Challenges and Applications

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Abstract:
Vacuum insulation panels (VIP) have a thermal resistance about a factor of 10 higher than that of equally thick conventional polystyrene boards. Similar to thermos flasks these systems make use of ‘vacuum’ to suppress the heat transfer via gaseous conduction. While thermos flasks are to be pumped down to a high vacuum, filling material integrated in the flat VIP elements, which bears the atmospheric pressure load, reduces the requirements on the vacuum and thus on the tightness of the vacuum casing. Optimal in this respect is a kernel of fumed silica. This kernel is evacuated down to about 1 mbar and sealed in a high-barrier laminate, which consists of several layers of Al-coated polyethylene (PE) and polyethylene terephthalate (PET). The laminate is optimized for low air and moisture leakage rates and thus for a long service life. The evacuated silica kernel has a thermal conductivity of about 0.004 W $m^{-1}K^{-1}$ at room temperature. The combination of kernels made of fumed silica and envelopes of metallized high barrier laminates yields products which also fulfill the extreme requirements on durability for building applications. Other filler materials that may be evacuated are optimized for the use in VIP: precipitated silica, organic foams made of Polystyrene or Polyurethane and glass fiber fillings. These may be advantageous with respect to weight, handling or even lower thermal conductivity down to below 0.002 W $m^{-1}K^{-1}$. The consequence of larger pores however is a higher sensitivity of the thermal conductivity on internal gas pressure, causing higher requirements on the tightness of the envelope or resulting in a higher degradation rate. Preferred applications for VIP with these filler materials are appliances, transport containers and cold chain packaging. A successful ‘‘self-trial’’ using VIP within a façade of the ZAE-building in Wuerzburg in 1999 was the starting point for new applications of evacuated insulations in the building sector [4].

Keywords:
Vacuum insulation panels (VIP), Heat transfer, Thermal conductivity, Thermal insulation, Vacuum super insulation.

1. Introduction

Driven by a temperature gradient different physical mechanisms contribute to the total heat transfer: convection, related to the transport of gases or liquids, thermal conductivity, the energy transfer between neighboring molecules in the solid, liquid or gaseous phase, and infra-red radiative heat transfer even in vacuum. First task of any thermal insulation material at room temperature is to suppress convection, the most efficient heat transfer mechanism. Second task is to attenuate radiative heat transfer. As the thermal conductivity of gases is much smaller than that of liquids and solids thermal insulation materials usually are highly porous. Optimization of air-filled thermal insulation materials balances between radiative heat transfer and thermal conductivity via the solid skeleton. Nevertheless the conductivity of the gas in the hollow spaces is the dominant heat transfer path. Thus further improvements are achieved 1.) by modification of the gas - heavy gases have a smaller conductivity than air - (PU-foam with closed cells), 2.) by reducing the size of the hollow spaces down to the mean free path of the gas molecules in the order of about 100 nm, so that the heat transfer of the gas molecules additionally effectively is hindered by numerous collisions with the solid structure (nano-structured aerogels or fumed silica), or 3.) at the best by removing the gas by evacuation. Different to cylindrical vessels like thermos flasks in flat evacuated elements a filler material is necessary able to bear the external atmospheric pressure. The so called vacuum insulation panels VIP thus in principle are composed by an envelope and a filler material.

2. Potentials

Different filler materials are optimized for the use in VIP: fibers, powders or foams. Fig 1 depicts the thermal conductivity as a function of N_2 gas pressure [3]. Despite relatively high thermal conductivity in the non-evacuated state the lowest thermal conductivity when evacuated is achieved for glass fibers, 0.002 W $m^{-1}K^{-1}$. For fibers oriented perpendicular to the overall temperature gradient dot like contacts between single fibers yield a high thermal resistance. In the non-evacuated state these contacts are short-cut by the gas. Foams are preferable if low weight is essential. The typical thermal conductivity is about 0.006 to 0.007 W $m^{-1}K^{-1}$. Nano-structured silica with a thermal conductivity of about 0.004 W $m^{-1}K^{-1}$ are least sensitive against pressure increase. Thus these fillers are preferred when high durability is required.

Evacuated, load bearing materials in VIP may yield a thermal insulation performance up to a factor of 20 better than that of conventional non-evacuated insulation materials.

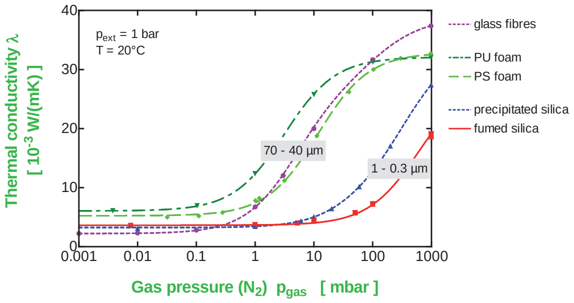

Fig 1: Thermal conductivity of fibers, powders and foams as a function of gas (N_2) pressure [3].

3. Challenges

Realizing the concept of VIP most challenging is to maintain the vacuum gas pressure on the required level. For fumed silica panels used in buildings an annual pressure increase of about 1 mbar/yr may be tolerable. For a typical panel sized 0.5·1 m², 2 cm thick, with a volume of 10 l, this rate corresponds to a tolerable leak rate of $3{\cdot}10^{-7}$ mbar l s^{-1}, the leak rate of one single sealing ring used in high and ultra-high vacuum technique. Only metallic layers or an envelope made of glass fulfill the high requirements on low permeation rates. Getters and dryers integrated to the VIP may bind gases desorbing from the filler and/or penetrating through the envelope. Assuming the same permeation rate for all components of air, beside water vapor, the noble gas Argon (1% in air) limits the potential of a getter to reduce requirements on the tightness of an envelope to a factor of 100. Argon cannot be bound. Due to a high solubility water vapor permeation in plastic laminates is about a factor of 1000 higher compared to that of Nitrogen or Oxygen. However water vapor may be bound by chemical dryers (CaO, BaO) or by physical sorption of the filler itself. As may be seen from Fig 1 for foams and glass fibers the transition from evacuated to non-evacuated state occurs at gas pressures two orders of magnitude lower than that for silica. Correspondingly higher the requirements on the tightness of the envelope are, if not a higher degradation rate is acceptable for the specific application.

The second challenge is to avoid thermal bridging at the rim of a VIP, i.e. thermal bridging by the envelope, thermal bridging by the way panels are abutted and thermal bridging by the way VIP are integrated to the application. The overall extent of thermal bridging depends on the size of the panels and the thermal conductivity of adjacent layers. Even air in the gaps may be a significant thermal bridge. Critical in this aspect are laminates made of metallic foils. E.g. for panels sized 1 by 1 meter in the best case, when additional conventional thermal insulating layers are used, the overall heat transfer at least is increased by about 50% when a 8 micron layer of Aluminum is used in the envelope, by about 100% when a 200 micron stainless steel envelope is used. For smaller panels thermal bridging is even more pronounced.

Very specific to VIP and uncommon for a thermal insulation is the need for planning the size of the elements and a layout-drawing. Special care is essential when handling and assembling VIP. Puncture of the envelope will cause the loss of all the benefits gained by the vacuum. Thus for VIP the technical risk of degeneration in thermal performance is much larger compared to that of conventional insulation materials.

4. Applications

Considering the same thermal resistance an insulation using VIP is more expensive and somewhat more challenging compared to a conventional solution. Thus VIP are applied when space is limited, valuable or when a significant higher performance is aspired: Especially for refrigerators and freezers the external dimensions are limited to modular dimensions. An improvement of energetic efficiency by better insulation would reduce the internal useable space significantly. Even more pronounced is the benefit for small transport boxes with unpropitious ratio of external surface to internal volume, boxes e.g. for the transport of medicals, organs or other temperature sensitive goods. In new buildings but especially for refurbishment VIP may help to reduce the heating or cooling demand significantly by slim architecturally attractive solutions.

Acknowledgements

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VIP used in buildings

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Abstract:
Energy efficient buildings rely very strongly on high insulation. To reach the passivhouse or Minergie-P standard the average u-value of the building envelope has to be around 0.1 – 0.15 W/m2K. Most architects feel that their design possibilities are limited by thick insulations. So, they ask, that the industry is providing improved insulation materials with better lambda values. VIP can be an answer if the problems of durability and construction will be solved.

Keywords:
Vacuum insulation panels, Minergie-P, roof terraces

1. Introduction

In Switzerland the Minergie-P label has been established over the last ten years. After a period were only small houses have been built according to this label, now large firms and the public start to ask for energy efficient and ecological buildings. The EU demands for NZEB (nearly zero energy buildings) by the year 2020.

2. Reducing the energy demand

Buildings with a high energy performance can be achieved by different strategies.

Minimizing the heat losses
Most promising is to reduce the heating demand. Important elements are the ratio of volume to surface and the orientation of the windows. So a good and continuous insulation of the envelope is essential. An average u-value of approximately 0.1 W/m2K or 30 – 35cm of standard mineral wool is needed. Thermal bridges have to be minimized. While this strategy is simple to adopt for new buildings, it often is difficult for remodels. Reasons are lack of space, changes of the appearance or generally esthetical problems.

Maximizing the solar gains
The solar strategy is an opposite approach. Instead of reducing the heat losses, maximizing the solar gains (in the winter) becomes the priority. Large, south facing windows and surfaces which can be used for technical solar gains are needed. The insulation of the envelope becomes secondary.

Technical solutions
Instead of using rather “passive” architectural principles, this strategy relies on improving the technical equipment. The efficiency of the components is important, but also the coordination and management of the technical system as a whole.

Obviously, in any energy efficient building the three strategies are never used alone, but in combination. The art of design is to find the right mixture.


Picture 1: Slender south façade with VIP around the windows. The balconies are shading the windows and solar collectors are integrated in the railings.

3. VIP applications

Since the 1930’s architects intended often to create elegant cubes and imagined the wall as a skin or curtain. The wall should to be dematerialized and the window should not be set back, but lie on the outer surface. So long, horizontal windows on the surface became almost a brand of modernity.
The thick insulations which are required today for the building envelope are often causing problems in construction and design. So, in many situations VIP

can be an interesting solution to unite modern design and ecology.

Roof terrace
In modern architecture continuous floors are preferred for esthetical and practical reasons. Terraces on the same level as the indoor space look wider, seem to be more ample and are an advantage for handicapped persons as well.

Picture 2: Roof terrace with double layer VIP. The complete insulation amounts to 24cm rock wool, 4cm VIP and 3 – 6cm foam glass.

Slender walls
Slender walls in combination with large windows look more elegant. The idea of a skin can be made visible.

Picture 3: Window frames are covered with custom sized VIP. The VIP is protected by a wooden box.

Blinds
Exterior blinds are a necessity for energy efficient buildings to avoid overheating. For esthetic reasons, blinds are integrated in the façade and so producing a large energy leakage above the windows.

Doors
The door is a large opening in the building envelope of about 2 m2. It always is constructed as a sandwich panel. For practical reasons it should be light weight and slim.

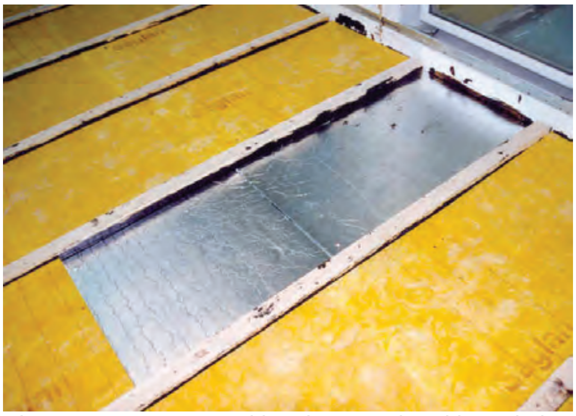
Technical equipment in the façade
Especially in timber construction new technical equipment like ventilation or additional electrical wiring are integrated in the facade. Such leaks can be compensated by VIP. The retrofit system of the EMPA is based on VIP. a)

4. Technical aspects

In the world of construction and building some aspects of VIP are discussed arbitrarily. The prize, the durability and the problems of the construction period are questioned. Even so VIP has very promising qualities, it still is used very seldomly.

Prize
Compared to traditional mineral wool, VIP is nowadays roughly five times more expensive. But on the other hand, as a material it is also five times as efficient, so the high prize is not

Durability
As there is not a long experience, the life span of VIP is unsure. My personal experience has a length of twelve years now. It seems, that in the building built twelve years ago all the panels are still working.



Picture 4: VIP protected by glass wool and by a timber panel. It can be replaced easily.

Construction
The process of construction is still a rough job with little supervision and coordination. The construction period is the main problem for using VIP. So, VIP has to be brought in the building as late as possible, as controlled as possible and has to be protected immediately.

References

Pictures 1, 3, 4: Project Sunny Woods, 2001, Zürich kämpfen für architektur, Zürich
Pictures 2: Project SunnyWatt, 2010, Watt-Zurich, kämpfen für architektur, Zürich
a) IEA ECBCS, Annex 50, March 2011, Retrofit Module design Guide

New exploratory testing conditions to understand the gas transfer mechanisms through VIPs' barriers

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Abstract: This paper summarizes a PhD thesis (defended is December 2012) aiming at getting a better understanding of mass transfer phenomena across tight barriers of VIPs. One objective was to find physical models able to simulate the long term (more than 30 years) gas permeation through VIPs' barriers in order to determine the resulting thermal behaviour of VIPs in service life conditions. This work lays on various experimental results, obtained by the IEA annex 39 partners or by EDF R&D. It includes aging tests in climatic chambers on full size panels and permeation tests carried out on barrier multilayer films only. For these last tests, the Technolox Deltaperm apparatus has been employed. In both cases, various climatic conditions (temperature, humidity and overall pressure) have been applied.

Keywords:
Vacuum insulation panels, gas transfer, barrier envelope, mass transfer modeling

1. Introduction

Most of the research carried out in the field of VIPs aims at reconciling thermal performance and durability [1]. Both are generally evaluated by accelerated aging tests in climatic rooms [2,3]. Various VIP configurations are compared at fixed temperature and relative humidity. But these results are generally not sufficient to get a clear understanding of the mechanisms of gas transfer through VIP barriers [4]. In order to get a more complete understanding of these phenomena, we have carried out gas transfer tests under new climatic conditions: fixed climatic conditions (temperature and relative humidity) but various total gas pressures. This paper describes the measurements, shows their results and gives some conclusions about the impact of gas pressure on apparent gas transfers through VIP barriers.

2. Gas permeation in climatic rooms

Aging tests in climatic rooms on full size panels seem to lead to the largest amount of information, providing some care is taken concerning samples and measurements. The contribution of the perimeter *P* (which can be assimilated to the welded joint) and of the surfaces *A* (which can be assimilated to the barrier multilayer film) to the overall gas permeation can be separated provided various sizes of VIPs have been tested for a same configuration of panels and for the same climatic conditions.

In addition, the separated contributions of dry air and water vapour in the overall gas transmission rate (GTR) can be identified, provided both internal pressure and mass gains are measured. The measured total mass gain is the sum of three contributions: by dry air, water vapour and adsorbed humidity.

Combining the approach of separating perimeter and surfaces contributions, and the approach of separating dry air and water vapour, it is possible to get the surface and perimeter GTR for dry air and water vapour separately. Nevertheless, it requires i) an accurate measurement of the hygroscopic properties of the core material, ii) a relatively large number of samples (at least three) having sufficiently different P/A ratios, iii) a combined and accurate measurement of mass and pressure increase, and iv) a long aging duration. This kind of complete approach of aging tests does not really exists in the literature, but should lead to very interesting conclusions. At this time, these conclusions remain unknown.

3. Manometric method (Deltaperm)

Aging tests could be completed by permeance measurements carried out on barrier multilayer films only. This is currently possible with a sufficient accuracy thanks to new pressure gauges which are able to measure a pressure between 0 and 1.3 mbar with an accuracy of 0.5 %. The Technolox company has developed an equipment using this kind of sensors called DeltaPerm, which is able to measure the permeance by a manometric method. When applied to VIP barrier multilayer films, DeltaPerm measurements can give the opportunity to compare the value obtained for the overall gas permeance to the value obtained in climatic rooms on full size VIPs. The Deltaperm originally developed for pure gas permeation test has been adapted to humid air permeation tests (see Figure 1), in order to measure the water vapour permeance in a humid air environment.

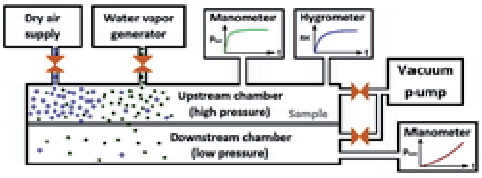

Figure 1: Deltaperm in humid air configuration

Even if not fully understood at the moment, up till now the permeances measured by DeltaPerm are at least three times lower than those identified in climatic rooms for identical barriers and climatic conditions.

4. Reference model for gas permeation

Short term experimental evaluations are carried out to determine physical characteristics which are used for the numerical simulation of the long term behaviour of VIPs integrated in insulation systems. The link between experimental and simulation results is crucial in this approach. The present reference model adapted to the simulation of gas transfers through the tight barriers of VIP is the so called dissolution and diffusion model. This model postulates that for gas i, the gas transmission rate GTR_i is the product of a permeance Π_i times the partial pressure difference Δp_i across the barrier: $GTR_i = \Pi_i \Delta p_i$. This model has been initially developed to study gas transfers through polymeric films. It thus can be assumed that its validity can be extended to the case of the VIPs' welded joint which is a polymeric medium, but its extension to multi-layer aluminized polymer films is not straightforward. The dissolution properties, mainly influenced by the polymeric layer, may probably be extended, but transfer properties, which are mainly influenced by the aluminum coating, may not. Indeed, the comparison between the results of this model and some aging experiments has shown contradictions [4]. It can be especially observed that the impact of moisture on the mass transfer rates is not correctly represented. Given these observations, it has been concluded that the efficiency of the dissolution diffusion model is questionable for the simulation of the long term behavior of VIP-based insulation systems.

5. New experimental conditions

The aim being to develop a new model, taking into account the impact of the atmospheric gas composition on the transfer properties, the PhD thesis has studied the relevance of a mass flow equation which includes two potentials (partial and total pressures). This approach makes it necessary to study the impact of overall gas pressure on the mass transfer. New experimental conditions have been used for permeance measurements, at constant temperature and water vapour partial pressure but with different total gas pressure for both methods listed above: full size VIP aging in climatic rooms and Deltaperm measurements on barrier samples (see Figure 1). These conditions are listed in Table 1.

Cond.	T [°C]	p_{sat} [mbar]	RH φ [%]	p_{vap} [mbar]	p_{tot} [mbar]	Water vapour mol. concentr. X_{vap} [%]
1	48	111.8	65 %	72.7	72.7	100 %
2	48	111.8	65 %	72.7	240	30 %
3	48	111.8	65 %	72.7	1 000	7 %

Table 1: Experimental conditions for measuring the influence of total pressure

Two aspects are truly innovative in this experimental plan: the comparison of results from two independent methods, and the depressurized conditions with a gas mixture having varying dry air partial pressure.

The barrier studied is a multilayer component containing two Al-coated PET films. It is represented on Figure 2.

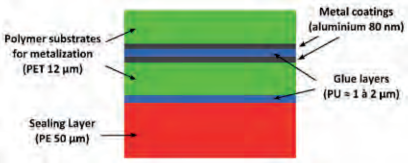

Figure 2: VIP barrier with two Al-coated PET films

6. Results and discussions

In figure 3, the surface water vapour permeance of the barrier measured by the full size VIP aging (red points) measurements and the one using the manometric method (blue points) are represented.

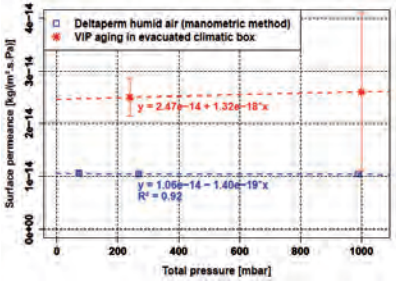

Figure 3: Measured values of surface permeance to water vapour

No significant impact of overall gas pressure could be observed for each method. However, tests in climatic rooms lead to measured permeances 2.5 higher than the Deltaperm ones, and this gap remains unexplained at the moment.

Nevertheless, for practical reasons (mainly the shortening of the tests' duration) all tests have been carried out in rather high temperature and humidity conditions, with a water vapour molar concentration X_{vap} higher than 7%. It can be calculated that the potential impact of gas pressure can't be significant at this relatively high X_{vap}. Other measurements at lower X_{vap} are planned, in order to see if the influence can be detected at lower temperature and humidity.

7. Conclusions and outlook

New experimental methods for the measurement of gas permeation through VIP barrier have been implemented, with a varying total pressure. The idea was to test alternative hypotheses for gas transfer modeling. No influence of the total pressure could be measured, but it has been shown a posteriori that climatic conditions and tests duration were not set to produce a significant effect. Indeed, in very wet conditions, moisture transfer dominates so much that the impact of gas pressure on air transfer can't be determined. Same tests should be carried out in dryer conditions and for longer periods to make a clear conclusion about this influence. This makes necessary to admit long test periods in future evaluations for VIP durability evaluation.

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Numerical Examination of Thermal Bridging Effects at the Edges of Vacuum-Insulation-Panels (VIP) in various Constructions

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Abstract:
The thermal losses on the edges of vacuum insulation panels (VIP) are influenced by the type of edge design (single- or multi-layered foils), the inorganic barrier material, the thickness of the barrier layers, the material in the joint between two panels (e.g. elastomeric foam), and the covering layers on the panels. Via numerical simulations for VIP of varying thickness the thermal bridge effects are determined for different influencing factors. Further investigation is carried out on alternative barrier materials such as SiO_2 and stainless steel in multilayer films. The impact of the linear thermal transmittance on thermal resistance of panels of various sizes is calculated and equivalent thermal conductivity of the panels determined.

Keywords:
Vacuum insulation panels, thermal bridges, barrier layer, alternative barrier material, edge heat loss, linear thermal transmittance.

1. Introduction

Aluminium laminated films (ultra-barrier films) and metallized plastic films (high-barrier films) are currently used as envelopes for VIP. Aluminium laminated films show very large thermal bridging effects on VIP edges, but low permeation rates, allowing the use of cheaper core materials, such as special mineral fibers even for long term applications (e.g. for VIP in buildings). Fig. 1 shows the remarkable differences for single- and multi-layered edge designs for VIP with varying thickness from 20 mm to 40 mm when using aluminium as barrier material for both, metallized and laminated films.

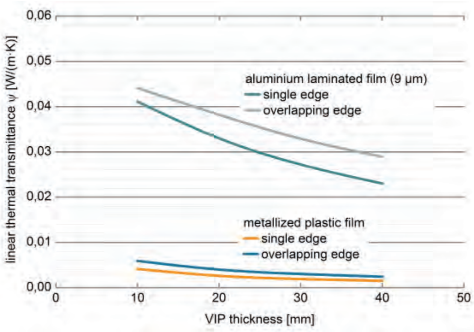

Fig 1: Comparison of the linear thermal transmittance for the single-layered and multi-layered edge designs for a metallized film and for an aluminium laminated film with 9 µm aluminium for VIP of 20 mm to 40 mm thickness.

The use of aluminum as a barrier layer in multilayer films is common, because of the foolproofness of the material in sputtering and vacuum lamination. Almost all films used as envelopes for VIP rely on aluminum for barrier layer. Unfortunately the thermal conductivity of aluminum is 160 times higher than that of SiO_2 and still about 11 times higher than that of stainless steel. By using stainless steel or inorganic substances with crystal structure (e.g. SiO_2) instead of aluminum, a considerable reduction of the edge thermal bridges could be achieved even for thick inorganic barriers.

2. Influence factors on linear thermal transmittance

A lot of research work has been carried out during the last years to determine the influencing factors on linear thermal transmittance on VIP edges using numerical calculations and measurement, e.g. [1-4]. Focusing on constructions made of VIP in combination with other building materials, the linear thermal transmittance is not only depending on the thickness and the material of the barrier layer, the edge design and panel thickness. Influence factors from constructions are:

- Material used in the joints between two panels (e.g. pre-compressed gasket strips)
- Cover layers on the panels, widely used to produce sandwich elements for easy use at construction sites (e.g. wood, plastics, metal)
- Components for mounting and fixing (e.g. glue, screws, mechanical fasteners etc.)
- Single- or double layer constructions (stacked VIP [4])

A large influence on overall panel heat loss is given by the size of the panels. Small panels have a remarkably lower thermal resistance and therefor a higher equivalent thermal conductivity. As an example how sensitively the system VIP is in combination with other materials, the influence of an insulating material strip in between two panels is shown in Fig. 2. Even an inserted strip of insulating material leads to significantly higher values for linear thermal transmittance at the joint of two panels [2].

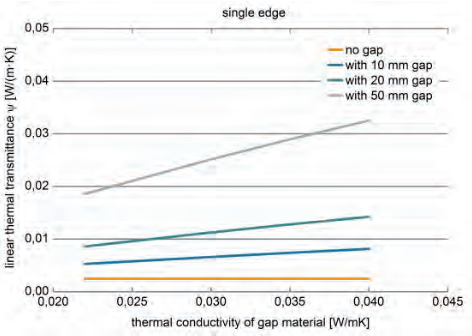

Fig 2: Influence of the gap width and the thermal conductivity of the gap filler material on linear thermal transmittance of a joint between two panels (20 mm panel thickness; single edge design)

3. Investigations on alternative barrier layers

Thermal bridges of the construction have a large impact on the overall thermal performance of an insulating layer made from VIP, but they have no impact on reducing the equivalent thermal conductivity of the panels themselves as placed on the market. Biggest influence on linear thermal transmittance of the panel edge has the material used as inorganic barrier layer and it's thickness in the multilayer foil. There have been some new developments on multilayer foils during the last few years. A huge effort has been taken to reduce the thickness of the aluminium layers by improving the sputtering and by preparing the plastic surfaces before metallization. The method of using organic-modified-ceramics (ORMOCER) to prepare the plastic carrier materials is described in [5]. The result is an improvement in the permeation resistance without an increase in thickness of the barrier layers – or alternatively - thinner barrier layers without change of permeation rates.

Some research has been done on replacing aluminium as inorganic barrier material [2]. Especially for organic light emitting diodes (OLEDs) transparent foils with very low permeation rates are needed. SiO_2 is used widely as inorganic barrier material. Unfortunately SiO_2 is more sensitive to brittle failure when folded tightly at VIP edges. An alternative for VIP envelopes could be the replacement of aluminium by stainless steel. Calculations for determining linear thermal transmittance values have been carried out (e.g. for research work in [2]) for 20 mm and 40 mm thick panels of both edge designs and for thermal conductivities reaching from 1,0 W/(m·K) (SiO_2) to 160 W/(m·K) (Aluminium).

4. Results and discussions

Fig. 3 shows that for metallized films, the linear thermal transmittance of the panel edge is not rising noteworthy for inorganic materials up to the thermal conductivity of approx. 20 W/(m·K). The predominant part of the edge heat loss is due to the plastic layers. Above 20 W/(m·K), the barrier layer's influence rises.

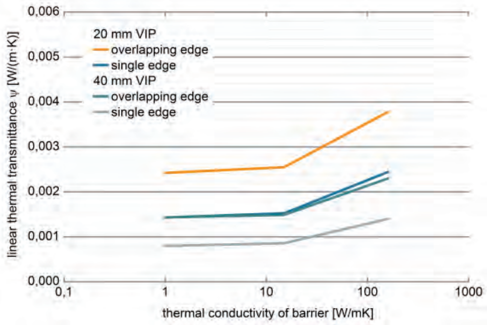

Fig 3: linear thermal transmittance for 20 mm and 40 mm thick panels with metallized films, depending on thermal conductivity of the barrier material.

5. Conclusions and outlook

VIP producers desperately wait for improvements and further developments in multilayer foils with low thermal bridging effects and high barrier properties. SiO_2 and stainless steel based products have very low edge heat losses - if used properly - and could be an alternative, if the brittle failure resistance can be improved. Thermal bridging effects from constructive parts need to be considered when calculating thermal resistance values for building purposes. The impact on various panel sizes will be demonstrated at IVIS.

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Next-generation curtain walling with vacuum insulation panels – Energy performance and design freedom

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Abstract:
Future energy regulations will pose a real challenge in terms of building envelope energy performance and restriction of design freedom. This paper presents thermal modelling of a high performance curtain wall system. The objective is to discuss a solution integrating vacuum insulation panel (VIP) solutions in façades, the potential value of performance enhancements for slim envelopes and the influence of VIP thermal conductivity on the overall façade performance. The focus on high performance solutions and architectural expression is an integral part of the effort to ultimately offer freedom to develop geometrically expressive curtain walling for high performance buildings.

Keywords:
Vacuum insulation panels, Design, Curtain wall Façade, Thermal Performance.

1. Introduction

As building performance requirements call for higher levels of thermal insulation and the architecture trends evolve towards broken up elevation layouts whereby high performance is delivered through a combination of alternating vision area and insulated parts in a more or less randomised pattern across the elevation (Figure 1), traditional insulation methods reach their limits and alternative thin, high performance solutions become both necessary and desirable.

Fig 1: left: traditional façade, right: new trends in façade design, whereby more 'non-vision area' is introduced 'randomly' to meet the higher energy performance requirements

Integration of vacuum insulation panels (VIP) in curtain walling (CW) is an attractive solution to meet the architectural needs. A robust product, which can be handled during assembly and installation is obtained by sealing the VIP within the cavity of an insulating glazing unit (IGU). Offering customized finish and performance completes the attractiveness to architects. A cross-section of the Architectural Insulation Module (AIM) is illustrated in Figure 2.

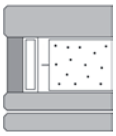

Fig 2: Cross-section of the edge of an Architectural Insulation Module (AIM), showing a Vacuum Insulation Panel (VIP) inserted in the cavity of an insulating glazing unit (IGU).

Several extensive studies evaluate the best way to model VIPs and the evolution of their thermal conductivity with ageing [2]. However, integrating the VIP in a façade includes a protection (e.g. through encapsulation in IGUs) and installation systems (e.g. frames). Due to their higher conductivity, it is probable that these elements will influence or even dominate the heat transfer for the overall façade. The goal of this paper is therefore to investigate the sensitivity of the overall U-value for a façade when the thermal conductivity of the VIP inside the AIM changes.

2. Design

A state-of-the-art framing system for unitized CW was modelled. The CW units are 1,500mm x 4,000mm (WxH). The vision area consisted of 36mm double insulating glazing unit with a centre-of-glass thermal performance (U_g) of 1.4W/m²K. The spandrel area of the CW unit was insulated with AIMs, built up with 8mm heat strengthened glass for the external face and 44.2 laminated glass for the internal face in order to cope with potential safety requirements and typical high rise building wind load (taken as 2.4kPa). The VIP thickness was chosen so that the overall thickness of the AIMs would correspond to a double IGU, in order to create a flush façade design without the need for adapter profiles. Therefore, an AIM containing a 20mm VIP for an overall thickness of 36mm was combined with the IGU. The secondary seal is performed with silicone joints. Figure 3 illustrates this AIM in the split transom of a representative framing system. Different vision/spandrel units were combined to form representations of façade layouts with different ratios of vision/opaque as illustrated in Figure 4.

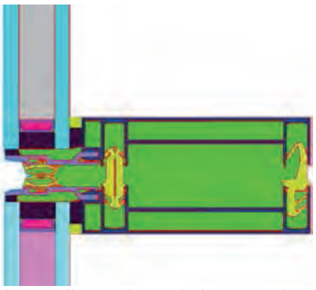

Fig 3: Illustration of the AIM in a split transom. Note the absence of adaptor piece in the frame thanks to the alignment of AIM and DGU thickness

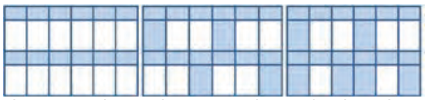

Fig 4: Schematic examples of elevations designed by combination of the vision/spandrel units. From left to right: classic elevation with 88% vision, 60% vision, 44% vision.

The classic elevation consisting of a spandrel strip layout has been modelled with 88% vision area. The next designs see the vision percentage decrease to 60 and even 44%. The facade U-values were then compared to explore sensitivities to changes in glazing percentages and thermal conductivity.

3. Modelling

Curtain wall systems consist of component parts (framing, glazing, and infill panels) with different functions. The overall thermal transmittance (U-value) of the façade depends on these components and on the detailing of the interfaces between them. Due to the interdependency of the heat transfer through the connected parts, it is not meaningful to define the required performance for separate parts. Instead, it is necessary to consider the CW system as a whole and assess the overall thermal performance, including frames, infill panels, and glazing, specifically for a given project.

The area weighting method was used to calculate the overall facade U-value. This method of calculation takes into account the individual U-value of a component and the corresponding transmission area. The following equation is used for the area weighting:

$$U_{façade} = \frac{\sum U_i A_i}{\sum A_i} \quad (Eq.1)$$

Where:

U_i	is the component U-value
A_i	is the transmission area of the component
ΣA_i	is the total transmission area

Simplifying assumptions are introduced in the VIP modelling as the focus of this study is not the VIP itself, but the VIP integrated in a façade. The VIP was modelled as a homogeneous core material with a thermal conductivity (λ) of 0.005W/mK (surrounded by a foil of 100µm thickness). This thermal conductivity was changed to 0.007W/mK (design value including ageing and edge effects) and 0.020W/mK (VIP after losing vacuum). The models were run for idealized VIP, without seams or differences in laminate thickness at the edges. No air gap is modelled between the facings of the AIM and the VIP. All U-values were determined using LBNL software (THERM).

4. Results and discussions

Table 1: U-façade obtained for state-of-the-art unitized frame system, double IGU, varying the thermal conductivity of the vacuum insulation panels in the AIM: initial, after ageing, and after loss of vacuum.

$U_{façade}$ (W/m²K) for different façade designs			
Vision area (%)	λ 0.005W/mK	λ 0.007W/mK	λ 0.020W/mK
88	1.6	1.6	1.7
60	1.3	1.3	1.5
44	1.1	1.2	1.4

The obtained facade U-values show that the degradation of the thermal conductivity of the VIP from 0.005 to 0.007W/mK does not significantly impact on the overall facade thermal performance. Increases in U-façade are fairly limited. This can be explained by the fact that facade performance is dominated by the frame heat transfer. Due to the high conductivity of the frame in comparison with the insulation module, a slight change in its performance will not significantly influence the overall result. Once vacuum is lost, however, we observe a more substantial loss in performance of the façade.

5. Conclusions and outlook

The results presented in this paper are based on a number of assumptions and serve to illustrate aspects pertaining to curtain wall detailing. The performance of the façade is mainly dominated by the vision area percentage and frame detail whilst the change in thermal conductivity of the VIP has comparatively less impact. Further work includes the study of the influence of non-idealized AIMs (presence of air gaps and seams) on the overall façade thermal transmittance.

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VIP as Thermal Breaker for Interior Insulation System

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Abstract:
Building renovation is a major challenge in Europe with more than 200 million of existing buildings to renovate. Generally, ETICS (External Thermal Insulation Complex System) is claimed as being the most efficient system especially for tackling thermal bridges and keeping thermal inertia. Nevertheless, this system cannot be applied to some existing buildings, especially those having a façade with a high architectural character. In this communication, a slim thermal breaker (STB) integrating a VIP is presented. This thermal breaker is made of a VIP protected with PU foam and with plasterboard as a finishing. A mock-up has been built up in order to investigate the efficiency of the thermal breaker for partition wall. The experimental results and the simulation have shown that the use of this slim thermal breaker(STB) yield a reduction of around 30% of the whole U-value whereas a reduction of 50% is obtained using ETICS.

Keywords:
Vacuum Insulation Panels, Thermal Breaker, Retrofitting, Energy

1. Introduction

In existing building, thermal bridges represent a significant share of heat losses in buildings. They account for about 40% of the whole U-value and they are the source of a lot of pathologies. To meet the requirement of the French Thermal Regulation, many thermal breakers have been developed for new buildings but technical solutions for existing buildings are missing whereas renovation is the great challenge to reduce energy consumption in the building sector. In order to meet this requirement, a slim thermal breaker (STB) has been developed using a VIP panel.

2. Description of the Slim Thermal Breaker (STB)

The thermal breaker is made of a VIP protected on the hindered side by PU foam and on the visible side by plasterboard, in order to offer a traditional surface finishing. At the tip of the STB there a small gap between the VIP and the plaster board for fastening the STB to the ceiling. This gap can be also used to install lighting or for wiring.

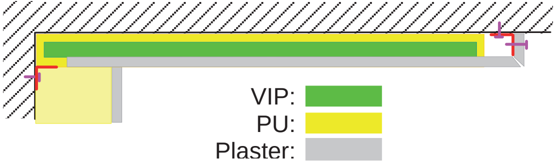

Fig 1: Scheme of the slim thermal breaker (STB)

The length and the thickness of the STB have been defined by thermal modelling, carried out with the software HEAT 2D [1] according to the following geometry:

- Concrete Wall: 20 cm $\lambda = 2$ W/m.K
- EPS insulation: 80 mm $\lambda = 32$ mW/m.K
- VIP : 20 mm $\lambda = 8$ mW/m.K),
- Two STB are installed on both sides of the wall. The parametric analysis considered two cases:
-STB made of EPS with a thickness from 10 to 80 mm (thin lines in Figure 2)
-STB made of VIP with thicknesses of 10, 20 and 30 mm (thick lines in Figure 2)

In the figure 2, the reduction of the heat loss is presented versus the type, the length and the thickness of the insulating materials. The computation shows that a VIP of 20 mm thick and 700 mm length gives a reduction of about 60 %.

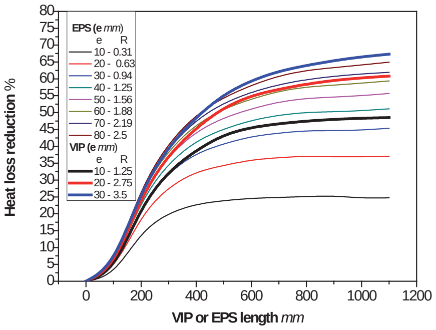

Figure 2: Optimisation of the length & thickness

An STB installed in a corner between a vertical wall and a concrete ceiling is presented in Figure3.

Figure 3: STB installed on-site – Thickness = 43 mm

3. Experimental Set-up.

The mock-up is made of one main wall and two partition walls made of concrete blocks. An insulating wooden structure closes the volume. The indoor temperature is kept close to 30°C with and electrical heater whereas the external temperature was below zero, about -2°C during the test (Figure 4)

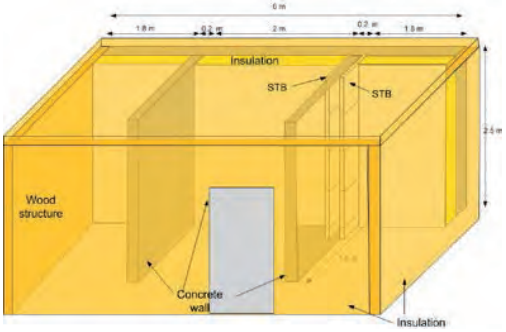

Figure 4: Mock-up for STB testing

In Figure 5, the IR image exhibits the role of the STB and gives a good approximation of the outside temperature given by the "blue" steel pillar of the testing hall. The small black spots indicate the thermocouple positions and the black square (on the right of the "blue" pillar) is the reference surface for the IR camera.

4. Results and discussions

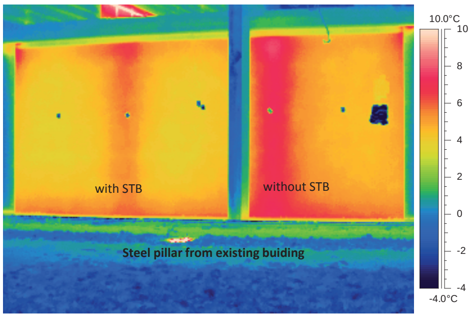

Figure 5: IR camera

The red vertical strip on the right, on the right of the "blue" steel pillar, corresponds to the wall without STB.

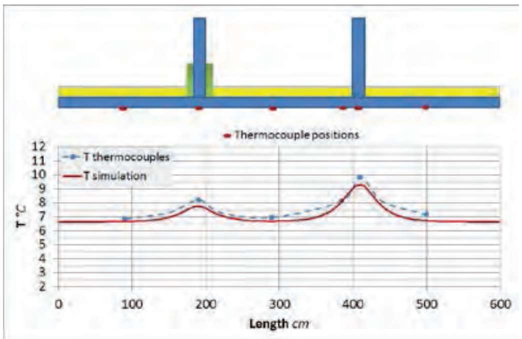

Figure 6: Comparison Thermocouples vs Simulation

In Figure 6, the temperature profile from the thermocouples is compared to the simulation result and the agreement is reasonable. The impact of STB, installed on both sides of the wall, is clearly shown. The temperature profiles at the surface, either on the partition wall without STB or on the STB and the partition wall, are presented In Figure 7. The temperature, at the tip of the STB is lower with STB. This effect results from the penetration of the outside low temperature which "flows" into the insulated wall with STB on both sides; as illustrated in the Figure 8 on the right.

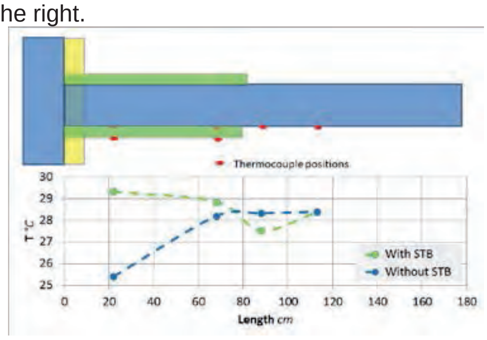

Figure 7: Temperature profiles at the surface of the partition wall, with & without STB.

Figure 8: Simulation with HEAT 2D

Finally, the reduction of the whole Uvalue of the wall thanks to the STB is of about 30 % compared to a reduction of 50% with ETICS.

Table 1: U-value of the wall – STB vs ETICS

Wall	Without STB	STB one side	STB two sides	ETICS
Mean U-value *W/m².K)*	0.6	0.5	0.4	0.3
∆U %	0%	16%	29%	51%

5. Conclusions and outlook

A slim thermal breaker for indoor application has been tested. The heat loss reduction reaches around 60% of that obtained with ETICS.

Acknowledgements

The authors would like to thank ADEME for the financial support and highly appreciate the great interest of Samira Kherrouf (ADEME's supervisor) in this project.

Reference

[1] BLOCON – Software HEAT-2D

Measurement of airborne sound transmission loss of a small-scale assembly containing vacuum insulated panels (VIPs)

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Abstract:
This paper presents the measurement results of airborne sound transmission loss of three types of small-scale wall assemblies containing (1) vacuum insulation panels (VIPs), (2) extruded polystyrene (XPS) insulation board, and (3) glass fibre insulation. The specimens were all 2.44 m wide x 0.61 m high. The testing was conducted in accordance with ASTM Standard E90-09. For each assembly, this paper presents the one-third octave band transmission loss values and the ASTM single-number ratings, sound transmission class (STC) in accordance with ASTM Standard E413-04, and outdoor-indoor transmission class (OITC), determined in accordance with ASTM Standard E1332-10a. The results from these tests show that the VIP assembly had lower Transmission Loss (TL) than the XPS only assembly in the mid-frequency range 315–630 Hz. On the other hand, the glass fibre assembly had lower TL than both others in the low-frequency range 80– 125 Hz, but substantially higher TL than the others between 125–3150 Hz. This behaviour is typical of cavity walls with fibrous absorbers. Future work is required to identify VIP assembly designs that jointly achieve superior thermal and sound insulation performance.

Keywords:
Vacuum insulation panel (VIP), Sound transmission, Small-scale assembly.

1. Introduction

Vacuum insulation panel (VIP) is widely recognized as an attractive technological option to insulate buildings and meet the enhanced energy efficiency requirements prescribed in the national and international building codes or green building regulations [1,2]. Researchers around the world are working on various issues related to the constructability, long-term performance and durability of VIPs in building construction. However, very little is known about acoustic performance of VIP insulated building envelope assemblies [3]. This paper presents experimental results of airborne sound transmission loss of three small-scale wall assemblies: one containing vacuum insulation panels (VIPs), and, for reference, two similar assemblies composed of traditional insulating materials.

2. Construction of small-scale wall assemblies

The specimens were all 2.44 m wide x 0.61 m high and were fabricated as follows:
1.VIP assembly - A layer of 560 mm x 460 mm x 13 mm thick Vacuum Insulated Panels[1] (VIPs) sandwiched between two layers of 13 mm XPS rigid insulation boards, with one layer of 13 mm regular core gypsum board on one side and one layer of 12 mm thick oriented strand board (OSB) on the other (See Figures 1 & 2). There were no framing members: all board products were attached with adhesive.

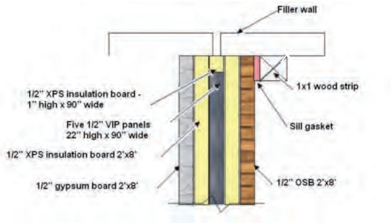

Fig 1: Construction of VIP assembly

Fig 2: Picture of VIP assembly in test frame

2.XPS assembly - Three layers of 13 mm XPS rigid insulation boards, with one layer of 13 mm regular core gypsum board on one side and one layer of 12 mm thick OSB on the other. There were no framing members and all the board products were attached with adhesive.
3.Glass Fibre Assembly – A 38 mm x 90 mm (nominal 2" x 4") wood frame with the cavity filled fully with 90 mm (R-12) glass fibre insulation, having one layer of 13 mm regular core gypsum board on one side, one

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[1] The measured thermal conductivity of this VIP was 0.00339 W/(m.K).

layer of 12 mm OSB on the other side. The framing was only around the perimeter, and the boards were attached to the wood framing with screws every 305 mm.

3. Test Facility

The acoustics test facility comprises two instrumented reverberation rooms with a moveable test frame between the two rooms. In each room, a calibrated microphone with preamplifier is moved under computer control to nine positions, and measurements are made in both rooms using an 8-channel data logging system. Each room has four bi-amped loudspeakers driven by separate amplifiers and noise sources. To increase randomness of the sound field, there are fixed diffusing panels in each room.

4. Test Procedure & Analysis of Results

Airborne sound transmission measurements were conducted in accordance with the requirements of ASTM E90-09 [4]. Airborne sound transmission loss tests were performed in the forward and reverse directions. Results presented in this paper are the average of the tests in these two directions. In each case, sound transmission loss (TL) values were calculated from the average sound pressure levels of both the source and receiving rooms and the average reverberation times of the receiving room. One-third octave band sound pressure levels were measured for 32 seconds at nine microphone positions in each room and then averaged to get the average sound pressure level in each room. Five sound decays were averaged to get the reverberation time at each microphone position in the receiving room; these times were averaged to get the average reverberation times for the room.

For each assembly, this paper also presents the one-third octave band transmission loss values and the ASTM single-number ratings, Sound Transmission Class (STC) in accordance with ASTM E413-04 [5], and Outdoor Indoor Outdoor-Indoor Transmission Class (OITC), determined in accordance with ASTM E1332-10a [6]. It should be noted that due to the small specimen size, the OITC rating which considers TL values as low as 80 Hz may be unreliable.

5. Results and Discussion

The measurement results (Figure 3) show that the VIP assembly (STC 31, OITC 27) had lower TL than the XPS assembly (STC 33, OITC 30) in the mid-frequency range 315–630 Hz. By comparison, the Glass Fibre assembly (STC 42, OITC 31) had lower TL than both others in the low-frequency range (below 125 Hz), but substantially higher TL than the others between 125–3150 Hz. This behaviour is typical of cavity walls with fibrous absorbers. The VIP assembly displays evidence of an undamped spring-like behaviour, with a resonance in the mid-frequencies, which generally leads to unfavourable acoustical behaviour.

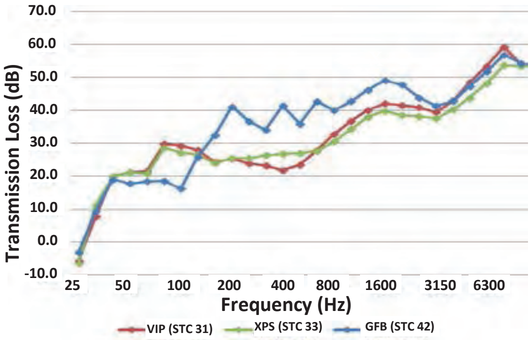

Fig 3: Transmission loss for three assemblies.

6. Conclusions and outlook

Following conclusions can be made from the observations made in this study:

1. The preliminary small-scale study presented in this paper clearly indicates that acoustic response of VIP insulated wall assembly is distinctively different from similar wall assembly insulated with traditional fibrous insulation.
2. Future parametric studies are necessary on full-scale wall assemblies to develop better understanding of the acoustic response of VIP insulated wall assembly.
3. Design details, specific to VIP insulated wall assemblies, should be developed to achieve desirable and superior sound and thermal transmission properties.

Acknowledgements

Authors would like to acknowledge their colleague Mr. Mike Nicholls for the preparation of the test assemblies and Panasonic Canada for the in-kind contributions.

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Accelerated Ageing and Global Warming Potential of VIP Thermal Insulation

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Abstract:
The primary objective of this research was to define the theoretical base supporting measurements of accelerated testing and the connection between ageing and the service life of vacuum insulation panel (VIP). Arrhenius law of accelerated testing was used as a theoretical support to experimental testing.

Differences between various thermal insulations, especially in relation to the environmental impact of densities and thermal conductivities, provided the impetus to perform an additional analytical study, aimed at independently comparing various thermal insulation materials according to their environmental impact in relation to the basic purpose of thermal insulation: effective protection against heat transmittance. The global warming potential (GWP) for different thermal insulations of external building envelope was therefore analyzed, showing that VIPs have surprisingly small environmental influence, primarily because of their extremely low thermal conductivity.

Keywords:
Arrhenius law, accelerated ageing test, vacuum insulation panel (VIP), carbon footprint, global warming potential

1. Introduction

During service life period over years or decades, gases and moisture slowly and constantly penetrate into VIPs, primarily through an envelope of multilayer foils, thus increasing vapour pressure, resulting in higher thermal conductivity. The most important issue is to prevent air and moisture from entering from outside, which can happen due to mechanical damage or to an imperfect weld bonding the two halves of the outer foils. It should be born in mind that even a small amount of air entering a VIP has enormous effect in increasing its thermal conductivity [1], [2].

The experimental methods were oriented to evaluating the rate of degradation of VIPs, i.e., to determine the values of thermal conductivity as a function of thermal loads. By taking into account Arrhenius law of accelerated ageing, the ageing mechanism of VIPs was determined. Other loads, such as humidity and thermal cycling, can be used and their effect on the service life of VIPs can be assessed. However, it is believed that temperature loads have the primary impact on VIP failure and thus deserve detailed investigation.

2. Assesment of accelerating ageing tests

In accordance with Arrhenius law, in order to determine the activation energy (E_a), i.e., the threshold energy required to produce a chemical reaction, at least two accelerated ageing testing procedures at two different temperatures are needed [3].

The main problems encountered in applying the recommended accelerated test procedure for VIPs are, firstly, the selection and application of suitable thermal loads and, secondly, to observe degradation over different periods of time [4]. Laboratory measurements and numerical analyses were carried out on VIPs exposed to stress under high temperature in a laboratory oven.

Due to the non-reversible deformation of VIPs, over-exposure to excessively high thermal loads must be avoided during the procedure of accelerated ageing, since they could cause thermal instability and disintegration of the material (mainly of multilayer protection foils). Since most films are unstable or could be permanently damaged above temperatures around 105°C to 110°C, the following accelerated ageing temperatures were selected: 100°C, 90°C, 80°C, 70°C, and 60°C, with time exposures from half a day up to 3 months or, in some cases, even longer.

Glass fibre and pyrogenic silica, as two types of core material, were compared and evaluated in terms of expected service life based on different specific needs, such as medium service life for domestic appliances and much longer for construction purposes. The assumption for service life span in this study was the time at which double the initial thermal conductivity of the VIP was reached (i.e., increase of thermal conductivity by 100 %).

3. Results and discussion of accelerating tests and determination of service life

As a result of the research, it can be concluded that the thermal load to which the VIPs were exposed caused a degradation process that followed Arrhenius law. With the obtained results, the value of the activation energy for VIP products (E_a = 66 kJ/mol) can be determined. The value of activation energy is used to evaluate the behaviour of the VIP products exposed to different temperatures, by interpolation within the test temperature interval at which accelerated ageing is performed or, more commonly, by extrapolation outside the test temperature interval.

On the basis of assumptions, the service life is the time until the thermal conductivity value is double the initial value of the VIP. The results of the accelerated tests show that the thermal conductivity of a VIP exposed to constant ambient temperature (25 °C for indoor conditions) doubles, i.e., the thermal insulation property of a VIP falls by 50 %, after a period of 26.2 years and a thermal conduction value of 12 mW/(m K) is reached after 48.1 years. Based on these experiments it can be concluded that VIPs are a durable and high quality product, mainly in terms of maintaining an exceptional thermal insulation.

4. Carbon footprint of thermal insulation materials in building envelopes

Differences among thermal insulation materials in their impact on the environment are mosty presented per unit of weight of the material itself, rather than as weight per unit of volume. Such a presentation circumvents the fact that the density and the thermal conductivity value are very different for these materials, which greatly affects the rate of global warming potential (GWP) caused by the installation of such thermal insulation in the building envelope.

Environmental impact does not only have the GWP of a specific thermal insulation material, expressed in kg CO_2-eq. per kilogram of insulation material, or its thickness, but is also strongly dependent on the density of different insulation materials, which varies from 15 kg/m^3 to 400 kg/m^3 and more (thus in a ratio of more than 1 : 26) and on the thermal transmittance of the insulation material (λ value ranges from 4 mW/(m · K) to 45 mW/(m · K)), thus a ratio of more than 1 : 11.

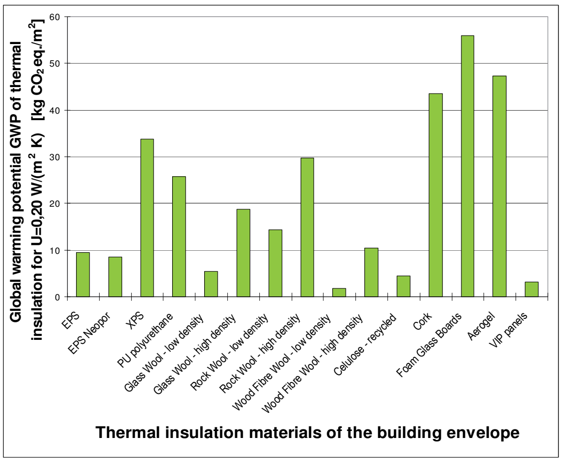

Fig. 1: Global warming potential (GWP) of various thermal insulations for *U*-value of building envelope 0.20 W/(m^2 K) in units kg CO_2 eq./m^2.

A comparison of the environmental impact of various insulation materials using Simapro software (SimaPro Analyst Indefinite, Ecoinvent v2, Product Ecology Consultants, PEC, The Netherlands) was performed. The GWP, also known as carbon footprint, of fifteen thermal insulations (*U*-value 0.2 W/(m^2 K)) was calculated by the IPCC2001 GWP100a V1.02 method [5] (Fig. 1).

The analysis and comparision of the GWP of various thermal insulations of an external building envelope showed that VIPs have a surprisingly small environmental impact, primarily because of their extremely low thermal conductivity (λ).

Additionally, environmental neutrality, i.e., the time in which, because of the replacement of thermal insulation materials in the external building envelope, the carbon footprint equals the carbon footprint of heat losses in the heating season between a current averagely insulated external building envelope and a newly insulated building envelope with U = 0.20 W/(m^2 K) was evaluated. It was determined that environmental neutrality is achieved in extremely short periods. For most environmentally friendy thermal insulation it is achieved after 0.57 years of a heating season and for VIPs after 0.65 years, while the environmental neutrality of thermal insulations with a greater environmental impact is achieved in a maximum of 7.22 heating seasons. However, approximately 2/3 of all fifteen analysed thermal insulations are acieving the environmental neutrality before the end of the fourth heating season.

5. Conclusions and outlook

It can be concluded that the environmental influences of thermal insulation materials, of which VIPs were shown to be very environmentally friendly, in comparison with other materials that are installed in an average building, are small. In addition, energy savings (i.e., a drastic reduction of heat losses), which the thermal insulation materials enable in each heating season after installation, crucially contribute to reducing the impact of buildings on the environment.

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Interactions between barrier envelopes and core material for the prediction of the VIP service life

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Abstract:
As a result of temperature and humidity Vacuum Insulation Panels (VIPs) age: their thermal resistance decreases due to the double effect of internal pressure and solid conduction increase. For given conditions this depends on the duration of the exposure and on the permeance of the envelope, as well as on the hygric and thermal behavior of the core material. This paper begins by assessing the severity of the various building applications with regard to the VIP. Then it explains the life evaluation approach in stationary conditions. It concludes that for a realistic estimation of the service life one needs to take into account both the thermal and hygric behavior of the core material, the permeance of air and water vapor through the envelope, the temperature and humidity service conditions, and the thickness of the panel.

Keywords:
Vacuum insulation panels (VIPs), Permeation, Building applications, Water adsorption, Service life.

1. Introduction

As a result of temperature and humidity VIPs age: their thermal resistance decreases due to the double effect of internal pressure and solid conduction increase leading to a finite service life, which have to be evaluated. This paper shows how the application, the core material and the barrier envelope all strongly influence the possible service life.

2. Definitions

The durability of a VIP is its ability to insulate to the required level until its thermal resistance drops below a required minimum. This duration is called life expectancy. The aging of the VIP product is the set of irreversible modifications affecting the VIP over time. The concept of aging both covers the mechanism(s) and kinetic(s).

VIP experience two ageing mechanisms. A first set of conditions, typically from 50°C and/or 85 %RH, rapidly leads to failing due to the deterioration of the barrier envelope itself, for example by aluminum corrosion or hydrolysis of the polymers [1]. The second, the subject of this paper, is slower and corresponds to a regular aging of the VIP due to the permeation of atmospheric gases without particular aging of the envelope.
The nomenclatures used are shown in Table 1.

3. Operating conditions

The operating conditions in buildings in France have been evaluated by Yrieix et al [2]. They vary strongly because of the variety of climatic conditions and applications. To assess their severity authors have determined for each one the average operating conditions (*T, RH, t*) by distinguishing four periods throughout the year (two hot, one cold and one intermediate) on both sides of the VIP. The severity criteria used are: 1) the maximum temperature or moisture level reached on the hot face of a VIP used alone without additional protection (Table 2); 2) two severity indexes SI_W and SI_a which are derived from the permeation flux and summed over the four periods on both sides:

$$SI_W = \sum_{f=1}^{2}\sum_{i=1}^{4} P_{w\,f,i}.t_i.e^{\frac{-Q_{\delta W}}{RT_{f,i}}} \qquad SI_a = \sum_{f=1}^{2}\sum_{i=1}^{4} t_i.e^{\frac{-Q_{\delta,a}}{RT_{f,i}}} \qquad (1)$$

The calculated severity indexes, reported in Table 2, use the activation energies Qw derived from authors' measurements on commercial barrier films [3] and Qa of oxygen diffusion in the PET, respectively 20 and 29 kJ/mol. Authors conclude that the flat roof without any protection is the riskiest implementation, and even excluding this application, there is less difference between applications with respect to the permeation of air (34%) than that of water (82%).

After aging the apparent conductivity of the core material is given by Eq.2 [4] where the last two terms depend on aging (core moisture τ_w and air and vapor pressures). This can also be expressed by graphs like Fig. 1.

$$\lambda = \lambda_r + (\lambda_{cs0} + B.\tau_W) + \left(\frac{\lambda_{a0}}{1 + \frac{C_a.T}{\phi.P_a}} + \frac{\lambda_{W0}}{1 + \frac{C_w.T}{\phi.P_w}} \right) \qquad (2)$$

4. Interactions between core and envelope

The behavior of the barrier envelope permeability to air and vapor is described by models of solubility, diffusion and ideal layers. This implies a thermal activation. For a laminate consisting of n identical layers, this can be expressed for each gas as Eq.3.

The behavior of the core material is also complex. First there is the influence of the pore size distribution on gaseous conduction. Then there is the influence of humidity on the partial pressure vapor through the sorption isotherm and on the solid conduction (Eq. 2).

$$\Pi = \frac{1}{n.x}\delta_0.e^{-\frac{Q_\delta}{RT}} = \frac{1}{n.x}D_0.e^{-\frac{Q_D}{RT}}.S_0.e^{-\frac{Q_S}{RT}} \qquad (3)$$

Table 1: Nomenclatures

Variables			
B	Conductive impact of moisture	**Constants**	
		R	Gas constant
D	Diffusion coefficient	C	Gas constant in Knudsen's relation
M	Molecular mass		
m	Mass	**Indices**	
n	Number of layer	*a*	air
P	Pressure	*cs*	Solid conduction
Q	Activation energy	*D*	Diffusion
RH	Relative humidity	*f*	Face
S	Solubility coefficient	*g*	Gas
t	Time, duration	*i*	Period
x	Thickness	*r*	radiative
T	Temperature	*max*	Maximum or end of life
λ	Conductivity		
ρ	Density	*S*	Solubility
δ	Permeability	*u*	Use
Π	Permeance	*0*	Reference or Initial
ϕ	Pores size	*W*	Water
τ	Mass humidity	δ	Permeability

Table 2: Maximum service conditions on the hot face and global severity Index of some applications

	Maximum service conditions			Severity Index	
Application	T_U (°C)	RH_U (%)	t (d/y)	SI_a *10^3	SI_W
Internal insulation - wall & floor	30	60	60	2.7	190
Heating floor (wet sceed)	50	90	210	3.4	310
ETICS & ventilated roof	70	70	30	3.5	335
Classic sandwich panel & door	70	30	30	3.5	275
Cladding, roller shutter box	40	55	30	2.7	200
Roof terrace balcony	70	95	60	3.6	900
Hot water tank	60	10	365	10	560
Refrigerator	28	55	60	2.7	185

To illustrate the interaction between core and barrier authors will consider the permeation of air and water vapor separately. For water the life time $t_{W,max}$ is reached when the conductivity equals the permissible limit λ_{max}.

$$t_{W,\max} = \frac{1}{P_W}.x.\frac{\tau_{\max}}{1-\tau_{\max}}.\rho.\frac{1}{\Pi_W}.\frac{1}{2} \qquad (4)$$

For air this corresponds to the pressure P_{max} (Knudsen relationship). Substituting the pressure we obtain:

$$t_{a,\max} = \frac{1}{P_{atm}}.x.\frac{\lambda_{g\max}}{\lambda_{gPatm}-\lambda_{g\max}}.\frac{1}{\phi}.\frac{1}{\Pi_a}.\frac{C.M_a}{2R} \qquad (5)$$

Both equations appear similar with the following terms (in the above order): solicitation, geometry, criterion of end of life, core material and barrier. In both cases authors find the parameters related to the core material and to the barrier film. Then the practical evaluation of the life time is the next step and several methods will be described in the remainder of this paper.

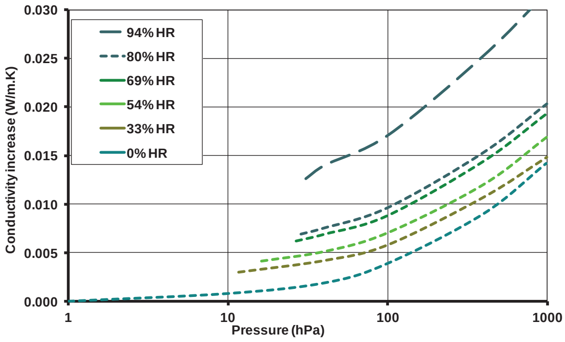

Fig 1: Conductivity increase of a core material as a function of humidity vs. the internal total pressure.

5. Conclusions and outlook

It has been shown that the usual applications of VIP in buildings are not equivalent with respect to aging. Even without considering both extremes, and without corrective measures, some are 40 to 80% more severe than others. Authors have also seen that four components should be considered with regard to life time: authors explained how the characteristics of the core material and those of the barrier envelope interacted with service conditions and the thickness of the panels in estimating the life expectancy. This allows to conclude that any assessment method of life time or declared resistance or conductivity which does not take into account the reality of these four components would be at best unclear and at worst plain wrong and thus unreliable.

Acknowledgements

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NEST – A Holistic, Dynamic and Flexible Research Platform for Sustainable Construction

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Transforming promising research results into market innovations is a difficult challenge for the construction sector. This is mainly due to the complex decision-making process and the high investment risk of construction projects. The NEST project is addressing this challenge (www.empa.ch/nest). It will serve as Living Lab where all players – researchers, industry and users - meet and work together to foster innovation in the construction sector.

NEST will is a flexible research and innovation platform for the development and evaluation of sustain-able solutions for the built environment and for their transfer to practice - with the final goal to develop self-sufficient buildings. NEST is designed in such a way that a maximum of flexibility for the exchange of single components and the reconstruction of entire living units, offices or meeting spaces will be possible at any time. NEST will consist of a basic grid (“the backbone”), which provides the load-bearing structure of the building, access to services, media (electricity, water, etc.), building management and control. The specifications and the design of the building will already take into account the climate changes expected for the coming decades. The fact that NEST is used as a guesthouse with a frequent change of tenants will facilitate this on-going transformation of the building. The living units will be clustered in subgroups with different degrees of flexibility depending on the topics that will be addressed by the respective subgroup. The work will not be limited to the building itself; in a holistic approach it will also include the interaction between the building and its users and the impact of the building on the environment. It is foreseen to open a competition among research and industry groups for the design of the subgroups and for projects addressing the related research topics.

Appropriate measures will be foreseen in order to allow researchers to install sensors, measurement and control systems and other equipment for monitoring of the on-going experiments in situ. It is important that the uniform conditions will allow quantitative comparisons in controlled but realistic environments.

The first wave of research and innovation units will include offices and living rooms. The main topics addressed by the office units are the creation of a flexible and adaptive working environment convey-ing changing forms of collaboration. Furthermore, minimizing the electricity consumption, paperless office, networking and collaborative working forms and optimized communication will be additional topics. The living units will focus on prefabrication, light weight construction and low energy/low CO2 construction.

Visualizations of the NEST building after realization of first innovation units and at a later stage

An energy hub for the supply, conversion and storage of heat, cold and electricity will be implemented and tested within NEST. The supply side will include PV, thermal solar systems and waste heat. The demand side is reflected by offices and apartments with different load profiles. Conversion and storage will include batteries, fuel cells, sorption based storage systems, heat pumps, hydrogen and methane.

NEST is serving as a model for a neighborhood composed of single buildings with different energy demand profiles, namely offices, small apartments and single family houses. Furthermore, the size and character of the neighborhood will constantly change over time as in reality due to the dynamic nature of the NEST platform. Therefore, the design of the energy hub has to be flexible in order to be adaptable to changes in energy flow and to technologies used within the hub.

Application of Vacuum Insulation Panels (VIPs) on Refrigerators

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Abstract:
Vacuum insulation panels (VIPs) offer extremely high thermal resistances properties that can enhance the energy efficiency of the insulating systems and provide savings in energy consumption. They are generally made with porous core materials wrapped, under vacuum, in airtight films. In the construction of VIP, core materials play a crucial role in thermal performance and mechanical properties of the insulation system. Core materials with higher porosity and smaller pore size have greater ability to maintain lower thermal conductivity. The main objective of this study is to investigate the application of VIPs on cold appliances such as refrigerators.

Keywords:
Vacuum insulation panels, refrigerator, thermal conductivity, energy saving.

1. Introduction

Insulation is one of the most important components of every refrigerating appliance. Conventional closed cell polyurethane foam is the most widely used insulating material in refrigerators and freezers (R/Fs). However, increasing ecological concerns and new energy regulations are forcing the refrigeration appliance manufacturers to develop appliances with reduced energy consumption. Since effective thermal insulation can reduce energy consumption rates dramatically in many areas, there is a need to develop materials with enhanced thermal insulation characteristics. Vacuum insulation panel (VIP) technology seems to be one of the most promising solutions for the achievement of reduced energy consumption. Evacuated insulation enables a VIP to have approximately 5 times higher thermal resistance than the conventional insulators [1]. According to the literature and the work done at Arcelik R&D Center, the R/Fs can save energy of 10-30 % and enlarge the effective volume by 20-30% by using VIP technology [2,3]. Therefore, replacing the traditional insulation materials with VIP provides better insulation, which allows energy savings without increasing the insulation thickness. Moreover, it has been observed that vacuum panels are also used in ultra-low temperature freezer and transportation boxes applications.
As illustrated in Figure 1, VIPs are made by placing a core insulation material and a gas/moisture absorber inside of an ultra-high barrier film and evacuating the air from inside of the panel. The core material imparts mechanical strength and thermal insulating capacity by preventing the free flow of the gas/air molecules thereby reducing the ability of heat transfer through air conduction. Furthermore, the gas barrier/facer foil provides the air and vapour-tight enclosure for the core material. The getter/desiccant is added inside the core material to adsorb residual or permeating atmospheric gases or water vapor in the VIP enclosure.

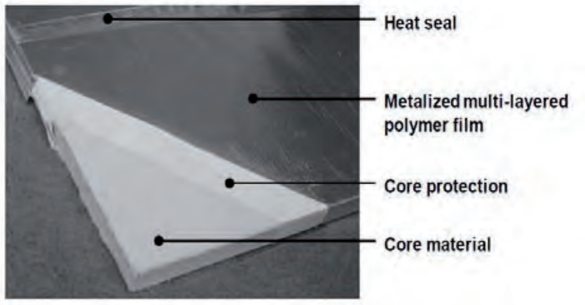


Fig 1: A picture of VIP and its parts

There is a big potential for VIP technology which can directly contribute in the reduction of energy consumption in cold appliances. For instance, a recent survey shows that more than 40 % of the total energy consumption in the European Community is made in buildings [1,4] and the refrigerating appliances are one of the biggest power consumer in many households. A typical old refrigerator may use 900 kWh/year. Refrigerators and freezers (R/Fs) typically make up over 20% of total residential electricity consumption. For instance, European Commission estimated that the total stock of household refrigerating appliances of 307 million units was responsible for 122 billion kWh annual electricity consumption in 2005 in the European Union (EU-27), corresponding to 56 Mt CO_2 equivalent [C(2010) 6481 final]. According to a preparatory study, in refrigerating appliances, each year 60 billion kWh could be saved (after replacing old cold appliances with new energy efficient ones), which is production of about 6 nuclear power plants [5]. Needless to say, high performance thermal insulation is increasingly required to reduce energy consumption and/or to save valuable space. Therefore, reduction of energy consumption in house and refrigerators will also have a big impact on reduction of green house emissions and will contribute to efficient utilization of energy resources.

Increasing ecological concerns and new energy regulations are forcing the refrigeration appliance manufacturers to develop appliances with reduced energy consumption. For example, EU Directive 92/75/EC established a set of energy efficiency classes from A to G (A being the most energy efficient, G the least efficient). To keep up with advances in energy efficiency, A+, A++ and A+++ were later introduced for refrigeration products. While A++ refrigerator uses 120 kWh/year, a comparable appliance of energy class B consumes with 300 kWh/year. Using the latest GfK-data from EU countries, the projection of market share of European cold domestic appliances by efficiency category was plotted in Figure 2. As shown in Figure 2, the market share of cold appliances with VIP usage (A+, A++ and A+++) has a potential to increase sharply and in the future VIP would be used in almost all cold appliances if cheaper VIP could be produced.

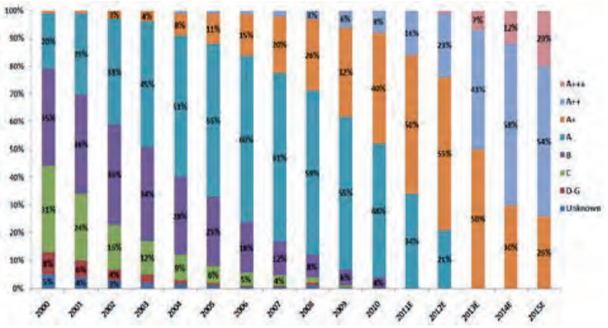


Fig 2: Projection of market share of European domestic appliances by efficiency category.

There are more than 300 million household cold appliances in European Union (EU-25) and according to the GfK-data from 21 European countries approximately 18 million are sold each year. The market for VIP technology will be huge and quantitative estimations on expected market uptake of the VIP technology is given in Table 1.

Table 1: Quantitative estimations on expected cold appliances market of the VIP technology in Europe

Refrigerator & Freezers	Expected Sales values [Million Euro] of VIP in Refrigerators and Freezers			
Energy Level	2012	2013	2014	2015
A+++	36	126	316	660
A++	414	774	1044	972
A+	990	900	540	468
Total (million €)	1440	1800	1900	2100

As it can be seen from Table 1, while the VIP sales were approximately 1440 million Euros in 2012 for R/Fs in EU, it is estimated that there is a potential to be more than 2000 million Euros by 2015 just for refrigerators and freezers industry. As soon as all older cold appliances in households were replaced by higher energy level products (with VIP technology), it is believed that the given numbers would be 4-6 times larger.

2. Experimental Studies

In Arçelik R&D Center, a large number of refrigerator and freezer units with different types of VIPs have been tested. For instance, one of the VIP applications was on the B586 Freezer which has a total of 250 lt volume. The thermal conductivity of VIPs was around 5.0 mW/m.K. Furthermore, the application of VIPs on the freezer is shown in the Figure 3.

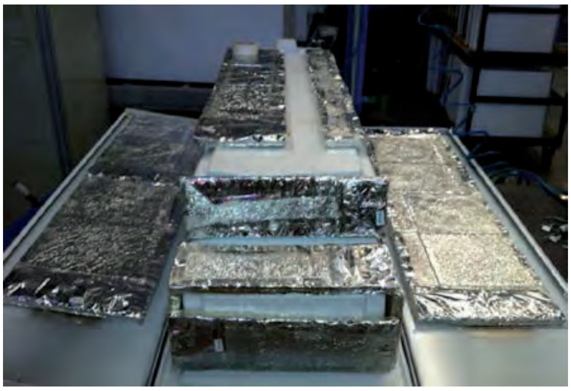
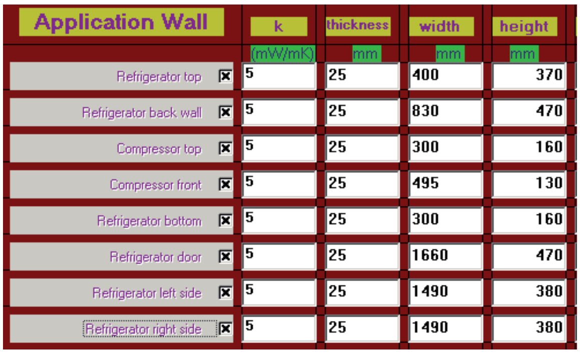


Fig 3: The application of VIPs on the B586 Freezer.

The dimensions and total amount of VIPs used are given in Table 2.

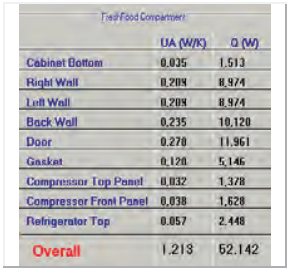
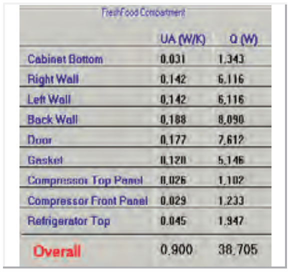
Table 2: Dimensions of VIPs used in B586 Freezer



Application Wall		k	thickness	width	height
		(mW/mK)	mm	mm	mm
Refrigerator top	☒	5	25	400	370
Refrigerator back wall	☒	5	25	830	470
Compressor top	☒	5	25	300	160
Compressor front	☒	5	25	495	130
Refrigerator bottom	☒	5	25	300	160
Refrigerator door	☒	5	25	1660	470
Refrigerator left side	☒	5	25	1490	380
Refrigerator right side	☒	5	25	1490	380

As shown in Table 3, after VIP application approximately 26% energy saving was achieved.

Table 3: Energy consumption and RHL test results

Without VIP	With VIP Applications
	

FreshFood Compartment

	UA (W/K)	Q (W)
Cabinet Bottom	0.035	1.513
Right Wall	0.209	8.974
Left Wall	0.209	8.974
Back Wall	0.235	10.120
Door	0.270	11.961
Gasket	0.120	5.146
Compressor Top Panel	0.032	1.378
Compressor Front Panel	0.038	1.628
Refrigerator Top	0.057	2.448
Overall	1.213	52.142

FreshFood Compartment

	UA (W/K)	Q (W)
Cabinet Bottom	0.031	1.343
Right Wall	0.142	6.116
Left Wall	0.142	6.116
Back Wall	0.188	8.090
Door	0.177	7.612
Gasket	0.120	5.146
Compressor Top Panel	0.026	1.102
Compressor Front Panel	0.029	1.233
Refrigerator Top	0.045	1.947
Overall	0.900	38.705

Similar studies were also performed for a regular home refrigerator which has approximately 400 lt of fresh food volume and 95 lt of freezer volume. In this case, VIPs with thermal conductivity of 4.5 mW/m.K were used. The total amount of VIP used was 2.5 m^2.

Table 4: Energy consumption and RHL test results

	Without VIP	**With VIP Applications**
Inside Temperature (^oC)	5.2	5.2
Outside Temperature(^oC)	25.2	25.2
Temperature Difference	20	20
Cabinet UA (W/K)	1.67	1.16
Total Power Consumption (W)	33.3	23.2

3. Conclusions and outlook

VIPs provide excellent thermal resistance properties that can enhance the energy efficiency of the insulating systems and provide savings in energy consumptions. An optimized combination of VIPs with other energy efficient technologies can allow the appliance manufacturers to create cost-effective solutions that meet the growing pressure from energy legislators through improving, increasingly stringent energy requirements. Besides the economic benefit, the refrigerators with VIP are lighter and smaller. R/Fs require light and thin doors, so using VIP is both technologically and economically meaningful.

Potential impact of VIP for refrigerating appliances is very high. Considerable reduction of costs will boost the application of VIP in cold appliances with high energy level such as A+++, A++ and A+. As a result of this, there will be more energy savings and it will enable developing cold appliances with much higher energy efficient classes. As explained earlier, there are more than 300 million household cold appliances in European Union (EU-25) and according to the GfK-data from 21 European countries, approximately 18 million are sold each year. As it can be seen from Table 5, total of 372 million Euros (1.9 billion kWh) can be saved just in 2013 by using high energy level refrigerating appliances. Furthermore, as soon as all older cold appliances in households are replaced by A++ appliances (after about 15 years), their total energy consumption would be about 60% lower than today which means each year 60 billion kWh could be saved, which is the equivalent production of about 6 nuclear power plants [5].

Table 5. Economical and environmental impact of VIP in the refrigerating appliances.

Energy Level	Estimated Sales Units in 2013 [Million units] (in **Europe**)	Savings kWh/yr (from **1unit**)	Estimated Total Savings in 2013 [million Euros] (electricity cost ≈ 0.20€/kWh)	CO_2 savings kg/yr (from **1unit**)
A+++	1.26	191	48.13	140
A++	7.74	128	198.14	100
A+	9.00	70	126.00	60

Acknowledgements

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Vacuum insulation panels (VIP) in refrigerator room, freezing room & fridge

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Abstract:
With respect to the continuous trend of reduction in energy consumption vacuum insulation panels (VIP) find an increasing application in freezing and cold storage rooms of supermarkets as well as in refrigerators. This implies the investigation of VIP behaviour subject to conditions different from those encountered in building application.

The present contribution deals with the evolution of the internal pressure of VIPs subjected to low and freezing temperature for a period of 5 years confirming the prediction made earlier on its linear increase 0.6 mbar/year in the refrigerator room and 0.10 to 0.26 mbar/year in freezer room depending on the VIP type.

This is a clear indication that the aging process decelerates compared to the standard test condition of VIP due to the low temperature condition.

Further, a refrigerator with different VIP configuration was analysed with respect to their energy performance by means of thermal bridge analysis and possibilities to reduce them.

Keywords:
vacuum insulation panel, pressure increase, aging, floor insulation, low and freezing temperature

1. Introduction

Since the introduction of VIP into the building market at the turn of the millennium, the question of aging and relevant parameter hereof have been addressed by different authors [1-3]. An elaborate report was published by Heinemann on a large number of VIP containing buildings [4] regarding the question of early degradation and showed, that there are no changes of the failure rate values in almost all cases for a period of three years.

Studies on the deterioration on the laminate had been carried out by the authors for the high temperature and high moisture load [5,6]. Assumptions of slow degradation processes in the core material needing long term monitoring (several years) have also been reported [3].

An increasing application of VIP in freezing and cold storage rooms in supermarkets, enabling a more flexible sizing, placing and rearrangement illustrate the need for information on the influence of cooler temperatures on aging relevant parameters. A similar lack of information (in open literature) has been detected regarding energy consumption of VIP containing refrigerators.

2. Experimental

A project for the instrumentation of a cooling / freezing rooms was established on the Empa campus, in the basement of a new office building. Construction plans for a combined cooling / freezing chamber with partition wall could be changed to include a full VIP floor insulation of both the cold (5 °C) and the freezing (-20 °C) section of the double chamber (figure 5). The thickness of the VIP layers was 25 mm in the cooling and 2 x 20 mm (double layer) in the freezing section, and the area about 9 m^2 each. Further details including first year results had already been presented at IVIS2007 including vertical section through the floor [7]

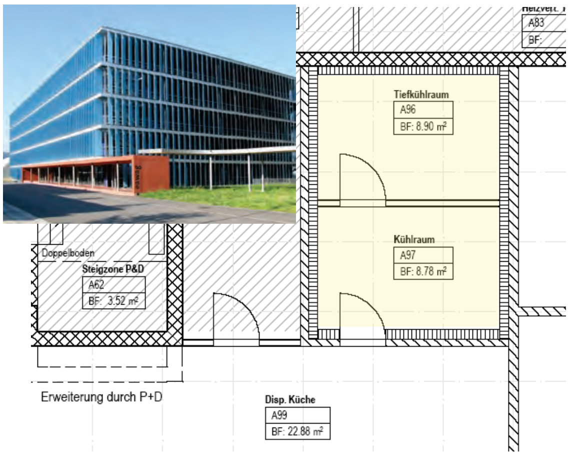

Fig 1: Front view of the near zero energy office building (upper left), the highlighted position of fridge and freezing room in the basement adjacent to the restaurant kitchen (right)

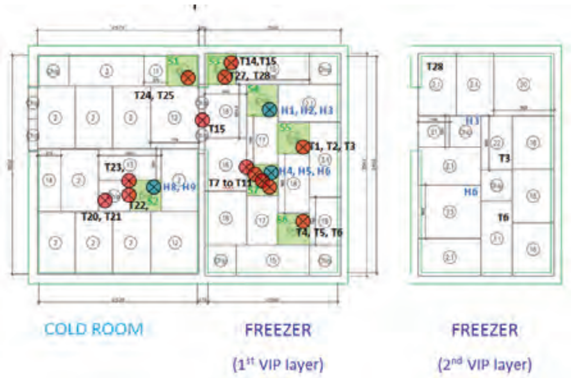

Fig 2: Layout of the VIP's in the refrigerating (single layer) and in the freezing room (double layer). Temperature and humidity sensor are labeled with T and H. Panels with integrated pressure sensor are highlighted in green (or light gray in b&w). Numbers in circle had been from the dimensional planning. Cold storage room CR, Freezer room FR.

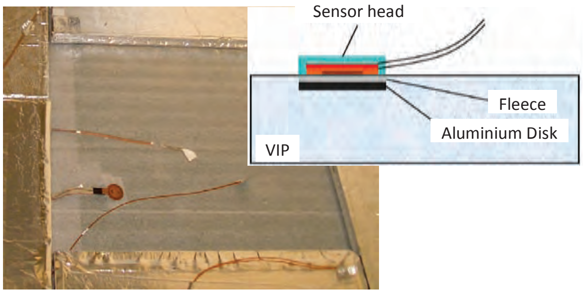

Fig. 3: Principle of the in-situ measurement of the internal pressure (technique va-q-perm , developed by VIP producer va-Q-tec, Würzburg, Germany [8,9]).

3. Results

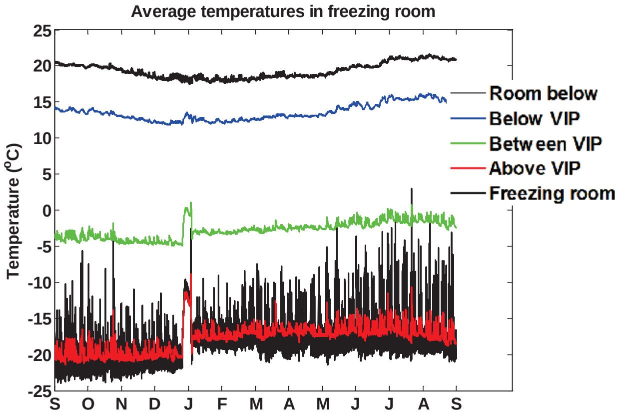

Fig. 4: Average temperature in the freezing room and cold storage room respectively during the period 1 September, 2007 to 31 August, 2008

The every 12 minutes logged data in Fig.4 showed late Dec. 2007 a jump up, that did not occur a year later on next X-mas.

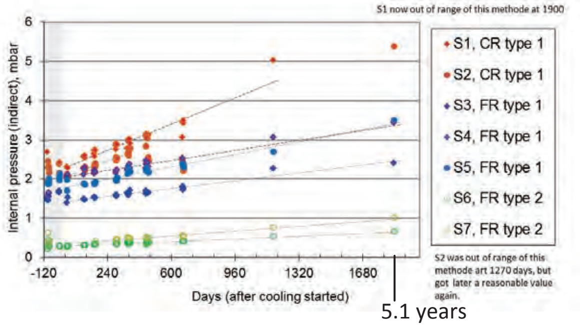

Fig. 5: In-situ measured internal pressure of VIP floor insulation in the cooling / freezing room. The dotted lines indicate the respective linear trends.

According to [9] a measurement range between 0.02 and 10 mbar can be covered with this fleece type. Here the data between 0.2 and 4 mbar well on the linear trend. Values above are less well on the line, and artifacts from the method and not real internal pressure is likely the causation for this.

4. Fridge – house hold sized Refrigerator/Freezer

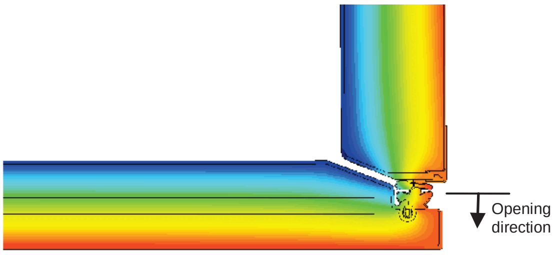

Fig. 6: 2D-Thermal simulation of VIP in a freezer door.

5. Discussions

Conclusions from former IVIS2007 with 25-year-extrapolation in such cold and dry environment: $\Delta\lambda < 0.5\cdot10^{-3}$ W/(m K) will have to be check in a future project in respect the first result of several years in a real roof applications [3] where the 8 year value of $6.6\cdot10^{-3}$ W/(m K) is a hint to a moisture influence doubling of $\Delta\lambda$. The hypothesis, that in dry and one side only cold condition this effect could be small should to be investigated in (a) future project(s).

Acknowledgements

Bruno Binder for the simulation of fridge, Matthias Koebel, to the industrial partners and for the financial support Swiss Federal Office of Energy (SFOE).

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Thermal conductivity measured at center of panel – that is only half the truth !

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Abstract:
The lifetime and performance of Vacuum Insulation Panels (VIP) depends upon the ability of the barrier film or envelope material to maintain a defined vacuum level during lifetime. The major criteria in the selection of the appropriate barrier material for a particular VIP application is the compromise between the permeability of the barrier material itself, its cost and its thermal edge performance effects. Thermal edge effects result from relatively high thermal transport region in the barrier material around the vacuum panel. This occurs to some extent with any barrier composition and thickness. The effective thermal conductivity of a vacuum panel is always greater than the value measured at the center of the panel. The “center-of-panel” (COP) value is the thermal conductivity value that is often and usually reported by VIP manufacturers and suppliers since it is much easier to measure than effective thermal conductivity. However, the effective conductivity is what describes the actual and real performance of the VIP in the final application. For that reason: the COP thermal conductivity value is only half the truth !
Besides all the high insulation performance discussions the aspect of sustainability of the insulation products to get the energy saving thinking and raw material and energy input in the right balance concerning environmental aspects has to be considered. Eco-balance or environmental product declaration (EPD) are examples of the scientific examination of environmental factors such as Global Warming Impact (GWP) or Ozone Depletion Potential (ODP).

Keywords:
Vacuum insulation panels, thermal edge effect, effective thermal conductivity λ_{eff}, linear heat transmittance Ψ, environmental product declaration (EPD)

1. Introduction

Thermal edge effects, also known as thermal shunting or thermal short-circuiting, arise because the thermal performance of the vacuum insulation panel inserts are very high as compared to the dense barrier materials.
This thermal edge effect is schematically illustrated below.

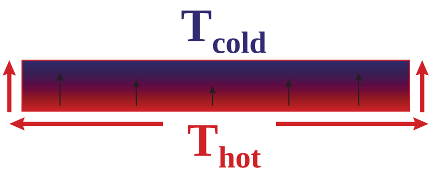

Fig 1: The graph indicates the relative magnitude of the heat or energy flow by size of the flux arrows. Thus the flux at the panel’s center point is the lowest which implies that the VIP thermal performance is the highest at the center.

In general, the barrier materials of VIP can be selected from either plastics, metallized plastics, metal foil / plastic composites produced by lamination or welded metal foils.
In most cases the barrier film structure is typically multilayer produced by lamination in order to impart a range of functionality (water and gas permeability, heat sealing, mechanical properties, etc.) to the laminate. For barriers using metal foil, aluminum foil is the metal of choice because of its ductility, availability and cost. However, aluminum has a very high thermal conductivity. In fact, the thermal conductivity of aluminum is approximately 1,000 times greater than that of common plastics used in barriers and 20,000 to 100,000 times greater than that of typical VIP core materials. [1]

2. Thermal conductivity λ_{COP} vs. pressure

Caused by different structures and pore sizes the VIP insert materials show among each other a total varied behavior regarding the relation of thermal conductivity λ_{COP} versus pressure.

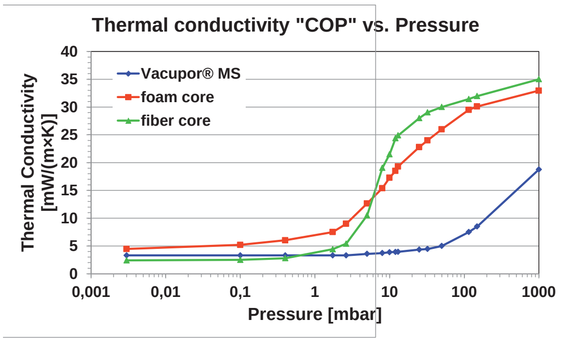

Fig 2: The graph shows the measured dependency of λ_{COP} on pressure for fumed silica, foam and fiber inserts. [2]

To be able to guarantee an increase of inner pressure of a VIP which does not effect in a dramatic increase of thermal conductivity λ_{COP} you have to choose the right barrier material for each used insert material. In view of Fig. 2 for fumed silica it is possible to use metallized laminated films because of the good-natured behavior of thermal conductivity vs. pressure whereas for the foam and fiber material you have to use aluminum foils.

3. Influence of barrier film on effective thermal conductivity λ_{eff}

The effective thermal conductivity λ_{eff} is calculated with the following equation [3]:

$$\lambda_{eff} = \lambda_{COP} + \lambda_{edge} = \lambda_{eff} + \Psi \times d \times \frac{P_{VIP}}{A_{VIP}}$$

where

P_{VIP} = perimeter of VIP
A_{VIP} = area of VIP
d = thickness of VIP
Ψ = linear thermal transmittance

The influence of linear thermal transmittance on thermal conductivity of VIP is calculated for a VIP type with two sealed seams on the surface of the VIP.

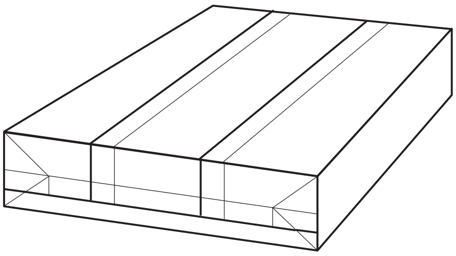

Fig. 3: The picture shows a schematic design of the considered VIP.

Caused by the VIP design the linear thermal transmittance values for the short and the long edges of the VIP are different. For a VIP with a fumed silica core and a metallized laminated film with total 240 nm aluminum the Ψ-values are 0.00796 W/(m×K) (short edge) and 0.00520 W/(m×K) (long edge). Considering a VIP with a fiber core material and an aluminum film (4 µm Al) the Ψ-values are 0.04434 W/(m×K) (short edge) and 0.03613 W/(m×K) (long edge). [4]

Table 1: Calculated effective thermal conductivity for different VIP dimensions with thickness t = 20 mm

VIP Dimensions [mm]	**VIP Core Material**	**λ_{COP} [mW/(m×K)]**	**λ_{eff} [mW/(m×K)]**	**Increase [%]**
1700 × 560	Fumed Silica	3.3	3.6	9.1
	Fiber	2.5	4.3	72
820 × 420	Fumed Silica	3.3	3.7	12
	Fiber	2.5	5.3	112
390 × 150	Fumed Silica	3.3	4.4	33
	Fiber	2.5	9.6	284

4. Results and discussions

The results of effective thermal conductivity shown in table 1 explain impressively why considering for vacuum insulation panels only the thermal conductivity value in the center-of-panel is only half the truth. It is very important to know for the user which kind of barrier envelope is used for the vacuum insulation panel.

Especially in case of aluminum foil is employed for VIPs, the edge effect caused by the total thickness of aluminum changes the thermal conductivity value of the heat insulation product tremendously.

For that reason it is absolutely necessary to consider for each vacuum insulation panel the increase of thermal conductivity by thermal edge effect of barrier material.

This cognition has to be integrated in standards for vacuum insulation panels prepared in the future. Actually the CEN / TC 88 / WG 11 and ISO / TC 163 / WG 5 are working on standards for VIP and VISE (**V**acuum **I**nsulated **S**andwich **E**lement) for building and construction applications. It is broad agreement of the members of the mentioned working groups that the thermal edge effect and its influence on resulting thermal conductivity have to be considered.

The important information for the user with view on its insulation application is at the end of the day the effective thermal conductivity respectively the U-value calculated by dividing the effective thermal conductivity value by the thickness value of VIP.

5. Conclusions and outlook

Besides the discussion about all the right declaration of thermal insulation properties the sustainability of heat insulation products will become more and more important. For insulation products in building and construction industry environmental product declarations (EPD) according to ISO 14025 and EN 15804 are already prepared and published.

Acknowledgements

The author is thankful to Christoph Sprengard / FIW München for calculating the linear thermal transmittance values Ψ.

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Vacuum insulation panels in thermal packaging solutions - functioning, application, solutions

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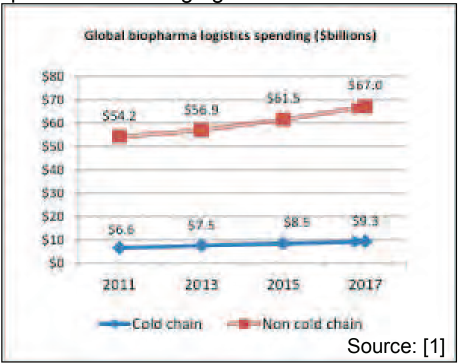
Abstract:
The global market for the transportation of temperature sensitive and precious cargo grows every year, while the value of the precious cargo increases as well. Due to this trend more and more high performance thermal packaging solutions are required to protect these products sufficiently against temperature excursions. In many of these high performance packaging solutions vacuum insulation panels (VIP) are already used. These solutions range in size from from small boxes up to airfreight containers. Different combinations of core materials and high barrier foils can be used depending on the requirements of the products and of the transport routes. To achieve a reliable solution proper VIP protection is necessary, too. This article and the according presentation at the IVIS2013 provides an overview of the current challenges and solutions.

Keywords:
Vacuum insulation panels, thermal packaging solutions, transport

1. Introduction

The value of one container load of temperature sensitive and precious cargo is often several million USD and these sensitive products are transported around the globe. The market for high performance thermal packaging solutions grows every year. Driving factors of this growth are for example the increasing amount of biotec products in pharma industry and stricter regulations for the temperature control of cold chain products in emerging markets.



Source: [1]

Fig.1: Global Biopharma logistics spending

This trend is not only limited to the transports of pharmaceuticals. Similar trends can be seen for transport of foods, fine arts, …

In the past ten years this has lead to the current situation, where vacuum insulation panels are used in many logistics applications and transport containers either to elongate the potential transport time or to reduce the energy consumption during transport or to provide a high level of protection against ambient temperature peaks. Depending on the transport and product requirements different VIP types are used.

2. Requirements and current container solutions

The most important requirement is to maintain a fix inner temperature for a certain transport duration taking into account extreme and varying climatic conditions on international transport routes. These climate conditions during transport are simulated by ambient temperature test profiles and according test procedures. Target of these tests is to qualify a maximal transport duration.

There are two main categories of packaging solutions, which are able to achieve these requirements for a transport duration of more than 3 days: Active and passive containers.

The active containers comprise an insulation and a control unit, which maintains the required container temperature actively by using electronic heating and cooling devices. These solutions usually have a battery and additionally a power cable. Until the batteries are emptied, the containers can be used independently of an additional power source. In such solutions VIPs elongate the period of independency and thus reduce the power consumption during transport.

Passive thermal transport containers maintain the required inner temperature by using insulation and temperature stabilization materials (phase change materials, PCM). The use of VIPs in such solutions increases the qualified transport duration but requires very accurate PCM solutions comprising a large amount of latent heat at the required transport temperature of the product which is to be shipped. One way shippers including VIPs are always passive due to their low price.

3. Main VIP components

Mainly the following VIP core materials are used in packaging solutions:

Silica, Glassfiber or Polyurethane foam

In addition to the required transport duration, driving benchmarks for the choice of materials for transport containers is weight, wall thickness and lifetime.

Core materials	Fumed Silica	Glassfiber	Polyurethane
Weight per R-value and per square meter $\mathrm{kg} / [\mathrm{m}^2 * (\mathrm{m}^2 * \mathrm{K} / \mathrm{W})]$	0,88	0,77	0,59
Effective thermal conductivity λ (wall thickness per R-value) $\mathrm{W} / (\mathrm{m} * \mathrm{K})$	< 0,005	< 0,0035	< 0,009
Density of the core material $\mathrm{kg} / \mathrm{m}^3$	195	220	65
Lifetime years	> 10	> 0.5	> 1

Tab.1: numbers based on va-Q-tec product descriptions

It is easy to see that the PUR core is the best choice regarding weight, while in regards of container volume the open cell Microfleece would be the best option. These core materials also provide an attractive price. Unfortunately they yield a low qualified lifetime due to the large cell sizes. Thus these core materials are mainly used for one-way shippers.

Lifetime and stability are important for each packaging solution, but of course it´s even more important for packaging solutions which are used many times on global transport routes. Thus the Silica core material is the choice in many of the current packaging solutions, because it provides a good ratio between lifetime and volume reduction, even if it is the worst in regards of weight and price. The lifetime of silica based VIPs and their relatively high insensitivity against micro leakages are key properties for using VIPs in a transport container multiple times without loosing the qualified performance. Nevertheless proper protection for the VIPs and/or quality check options (like va-Q-check [2]) should be available if the containers are used several times.

Usage of metal foil/plastic composites instead of plastic or metallised plastic films could increase the lifetime of the other core types, but especially for smaller boxes below 200 Liter net volume thermal edge effects would lead to a significant performance reduction. A reduction of more than 30% was observed in a 24 Liter net volume packaging solution, if a metal foil/plastic composite in comparison to a metallized film was used.

4. Protection and quality control of VIPs in packaging solutions

One of the major challenges by including VIPs into packaging solutions is to provide sufficient protection for the VIPs. Keeping in mind that a damaged VIP may lead to a massive container performance reduction, the VIP protection is a protection for the precious and temperature sensitive cargo of the container user.

For the large shipping containers this protection is provided by solid walls and according shock absorption layers [3] or by including the VIPs into a layer of foam.

For the smaller containers up to approximately 100 Liter net volume, more lightweight and space reducing protection layers are required and already available to the market.

Nevertheless using VIPs in thermal packaging solutions makes a regular quality check mandatory, preferably before every shipment. A container (24L inner volume) will loose approx. 30% or more of its performance even if only 1 VIP is punctured/damaged. Moreover, the entire container qualification documents are completely misleading and wrong in such a case, because the qualified performance is not given anymore.

In many cases there is not even a quality check for every VIP after VIP production or during assembly of the container. Consequently, we could find many VIP containers on the market, where more than 1 VIP is defect, leading to a complete under-performance of the box. This is the case, even if the protection of the VIPs seems to be sufficient.

5. Results and discussions

As one representative example of a VIP insulated container we want to present a test result of a 24 Liter one-way shipper with 35mm PUR VIPs and according PCM. The target was to achieve more than 96hrs with an inner temperature of 2°C…8°C. The box tare weight was less than 20 kg.

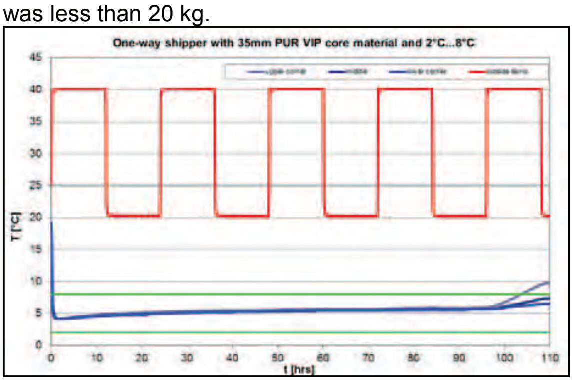


Fig.2: va-Q-Tcon12 performance data

The result was a performance of more than 100hrs under an extreme ambient temperature profile.

Such performances are only possible to achieve with premium insulation materials like VIPs.

6. Conclusion and outlook

Performance of the current solutions are already fulfilling the requirements of the market. Quality control systems are available, too, but currently not used in all solutions up to now. Nevertheless the use of vacuum insulation panels in packaging solutions is only a niche in regards of the global cold chain market. They are mainly used for very sensitive and precious cargo. So there is a lot of potential for the coming years. Additionally to the quality control issue, which is described above, one of the future challenges to achieve a deeper market penetration, is to reduce the price of the VIP based solutions. This would open new sectors of the cold chain logistics market..

Acknowledgements

The authors appreciate the support of the va-Q-tec engineering team, which had part at the various developments in regards of VIPs and packaging solutions over the last years.

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Development and applications of VIP using fiber based core material

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Abstract:
Two routes of heat fluxes, (1) Center of panel, (2) Edge of envelope were scrutinized carefully to minimize the overall thermal transmission in the viewpoint of material technology for VIP. Effective thermal conductivity could be improved by controlling fiber geometry as well as orientation of glass fiber in core material. Furthermore, thermal edge effect as well as long term stability could be minimized by the advanced design of multilayered barrier film of the VIP envelopes.

Keywords: Glass fiber, core material, Effective thermal conductivity, Thermal edge effect

1. Introduction

As the world has become seriously concerned on the energy saving issues in these days, laws and regulations related to energy efficiency are becoming strict and thus thermal insulation materials with higher efficiency are demanded in many industrial fields such as home appliance, construction and automobiles.

Especially, reduction of energy consumption is a crucial marketing point among the refrigerator manufacture since customers are carefully interested in the electric bills.

Therefore, manufacturers are competing for the quick release of a new generation of refrigerator with higher energy efficiency achieved by novel mechanical design and new insulation materials, i.e. vacuum insulation panels (VIP).

VIP is undoubtedly the most efficient insulation material having 8~10 times higher efficiency than homogeneous insulators like bulky glass wool, EPS, polyurethane foam [1-2].

There are many issues causing keen competition in VIP business, including performance, price, etc. and it is no exaggeration to say that selection of proper material of VIP component is the main key to give solution on all those issues in engineering aspect.

In this paper, I'd like to talk about why we chose glass fiber and aluminum-coated film as core material and envelop in our VIP product, respectively and how we made efforts to overcome their inherent handicaps and thus improve the performance of the VIP.

2. Effective thermal conductivity

There are two routes of heat flux that can be divided into in the conventional structure of VIP: (1) Center of panel, (2) Edge of envelope (linear thermal transmittance conductivity) and the effective thermal conductivity of VIP considering these is expressed below as sum of these two terms [3].

$\lambda_{eff} = \lambda_{cop} + \psi(d) \times d \times p/A$ (1)

where cop is center-of-panel, d is the thickness of the VIP (in the heat flux direction) (m), A is the surface area of the VIP (perpendicular to the heat flux direction) m^2 and p is the perimeter of the surface A (m)

2-1. Improvement of λcop

λcop mostly depends on the type of core material. In the case of glass fiber, details such as diameter, length and orientation of fiber should be considered as a variable of λ_{cop}

As shown in Fig.1, the λcop is disproportional to the diameter of the fibers on both fiber-fabrication method, centrifugal and melt spinning. The fiber diameter >9 μm shows lower λ_{cop} value than the fiber diameter <6 μm.

This result indicates that the improved arrangement to the perpendicular to heat flux direction is achieved due to the high length of fiber and this is more effective structure to induce the low λcop, at least within the range of the diameter below 13 μm.

Additionally the physical and forced ways to get better arrangements of fiber in the board also contribute to decrease the λ_{cop} value, comparing to the common wet method.

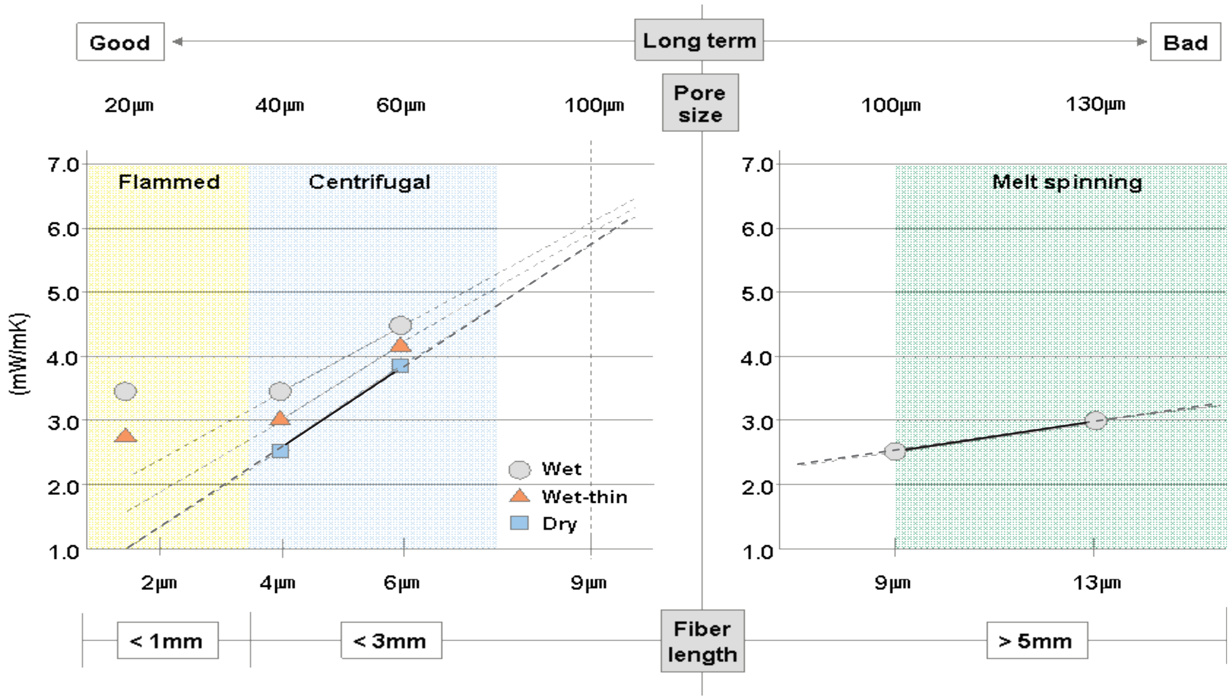

Fig. 1: The effect of fiber diameters and the arrangements

2-2. Thermal Edge effect

Depending on the types of envelopes, the heat flux through the edge is changed. Al foil film showed around 17mW/m K, whereas Al coated polymer film type has only 7mW/m K as shown Fig 2. The total energy loss could be postulated by the integration of the area below the line.

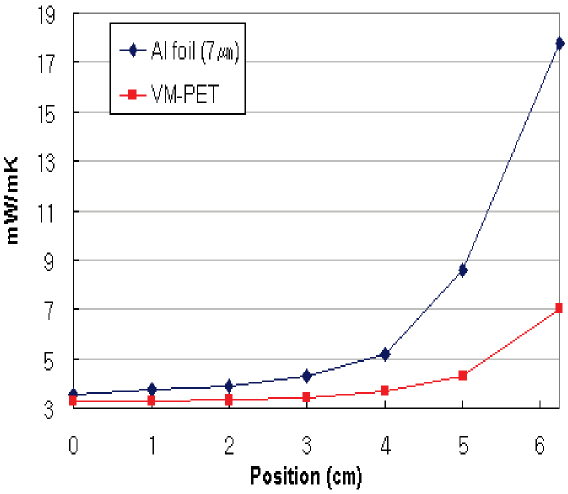

Fig. 2: Heat Edge effect depending on the film kinds

To decrease the thermal bridge effect of edge, several attempts have been carried out such as ; (1) the use of Al foil film and Al coated polymer film in each opposite lateral, (2) the partially Al foil film attached structure, (3) the modified layered structure

As the use of Al coated polymer film may lead to the deterioration of the long term stability, the seam protecting film and the modified layer are simultaneously applied to the commercial product. Until now, these films have satisfied the long term stability tests in the worst stress condition of 70°C, 90%RH.

3. Applications

Nowadays, we can find many home appliances to which VIPs were applied. We are also investigating the possibility of VIP application to electrical vehicle (EV), which is attractive energy-saving solution for efficient heating and cooling of EV.

Implementation to facade and the internal insulation system of building have been realized partially. However, the high price, poor long term stability and workability are still considered as drawback and should be resolved in near future for mass-production.

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Thermal performance of two different glass fibers based vacuum insulation panels: a comparative study

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Abstract:

Thermal insulation mechanism of the ordered filament and wool-type glassfibers based vacuum insulation panels (VIPs) was investigated. The experimental results showed that the thermal performance of ordered filament glassfiber based VIPs was better than that of wool-type glassfiber based VIPs due to different paths of heat transfer for the ordered filament and wool-type glassfibers owing to heat transport along different fiber orientations. The core material should have a homogenous diameter of ordered filament glassfiber, resulting in a stable and highly effective thermal performance of VIPs.

Keywords:

Heat transfer; Glass fiber; Vacuum insulation panel VIP; Thermal performance

1. Introduction

Glass fiber is commonly utilized as an insulation composite material. Glass fiber is generally produced in two basic forms namely: wool-type fibers (Fig.1a), commonly referred to as glass wool or glass fiber insulation by the centrifugal or aerocor blowing technology, and continuous filament glass fibers (Fig.1b), produced in long, continuous filaments by crucible remelt method. VIP is composed of a core material with a micro-porous structure, a vacuum-tight envelope to maintain the inner vacuum and a getter or desiccant to adsorb various gases flowing into the vacuum [1]. At present, the wool-type fibers are usually used as the core material. To Effective thermal conductivity at center-of-panel of VIPs with glass fiber used as core materials ranges from 1-3 mWm^{-1}K^{-1} [2, 3]. The insulation performance of VIP is a typical factor of five to ten times better than that of conventional insulation materials. The VIP with wool-type fibers as core material has a low thermal conductivity due to the high vacuum state, hence widely utilized in aerospace, refrigerator, transport, container and building applications [4].

The equivalent overall thermal conductivity λ_e is considered to be the sum of the four distinct modes:

$$\lambda_e = \lambda_s + \lambda_r + \lambda_g + \lambda_c \qquad (1)$$

where λ_s is solid conduction, λ_r is radiation, λ_g is gas conduction and λ_c is gas convection. Various formulations for heat transfer through fibrous materials have been investigated, and most of the models have been validated with experimental results. Songa et al. [5] studied the effective heat conductivity of polymeric fibrous assemblies. Also, by using a developed surface-to-surface radiation model, Qashou et al. [6] studied the effect of fiber diameter, solid volume faction and thickness in suppressing radiative heat transfer in nonwoven polymeric fibers. Thermal transport mechanisms in non-evacuated alumina-silica fibers were described by Hager and Steere [7]. In addition, some researchers have numerically and experimentally studied heat transfer through insulation systems, although most of the studies have been based on fumed silica core materials. Stark and Fricke [8] developed improved heat transfer models for predicting the thermal conductivity of evacuated and gas-filled fibrous insulations. They stated there was no natural convection in fibrous insulations with densities larger than 20 kgm^{-3} because the fibers subdivided the gas into sufficiently small pores. In this paper, the insulation performance and mechanism of the VIPs with two kinds of glass fibers as core material are investigated.

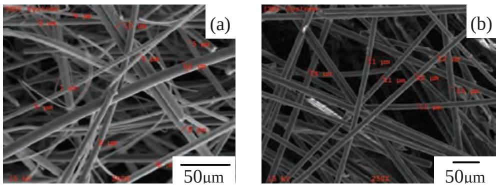

Fig 1: SEM micrographs of two kinds of glass fibers.
(a) Wool-type fibers, (b) Short filament glass fibers.

2. Experimental procedure

In this paper, the two kinds of glass fibers were used as the core materials in VIP. One was the wool-type fibers, and the other was short filament glass fiber (FF). Mean diameter, length and composition of glass fibers are shown in Table 1. The VIP core material was prepared by wet process. Parameters of six samples are shown in Table 2. The as-prepared core materials were dried in an oven at 150 ^{o}C for 30 min to remove moisture. Afterwards, the dried core materials were bagged in barrier envelopes composed of PET, Al and PE thin films, and then vacuum compressed to 0.1 Pa to form high performance thermal insulating material of VIP. The thermal conductivities for the VIPs were determined by heat flow meter thermal conductivity instrumentation (Netzsch HFM 436). The thermal conductivity was measured at mean temperature of 23.78 °C, with 37.7 °C on the hot plate and 10°C on the cold plate. The size of VIP was 300 mm ×300 mm×25 mm.

Table 1: Mean diameter, length and composition of glass fibers.

Properties	CF	AF	FF
Diameter (d, μm)	3.8	1.9	8, 10, 13
Length (l, mm)	50	8	15
Composition (EDS, at.%)			
O	37.39	40.74	46.74
Na	11.18	8.99	-
Mg	1.92	1.76	0.80
Al	0.48	1.00	7.86
Si	42.93	38.96	28.39
Ca	6.10	8.50	16.21

Note: CF- centrifugal glass fiber, AF- aerocor glass fiber, FF- short filament glass fibers.

Table 2: Parameters of six VIP samples.

Sample	Glass fiber	d (μm)	T (mm)	L	λ (mWm^{-1}K^{-1})
#1	70%CF+30%AF	1.9~3.8	0.5	20	1.8
#2	70%CF+30%AF	1.9~3.8	1	10	2.1
#3	70%CF+30%AF	1.9~3.8	3	3	2.5
#4	FF	8	0.5	20	1.9
#5	FF	10	0.5	20	2.0
#6	FF	13	0.5	20	3.4

Note: T-thickness of core material, L- number of layers, λ-thermal conductivity.

3. Results and discussion

From Table 1, the thermal conductivities of VIP for samples 1, 2 and 3 decreased with decreasing core thickness. For the FF glass fiber, the thermal conductivities of VIP decreased with decreasing fiber diameter. In this experiment, the λ_c achieves its limit value. Equation (1) can then be reduced to the first three terms:

$$\lambda_e = \lambda_s + \lambda_r + \lambda_g \tag{2}$$

For the same thick VIP, the number of layer for the thin core material was much more than that of the thicker core material. Layers could stop or deteriorate the heat transfer at the interface between the layers. Fig.2 shows the model of the path of heat transfer for two different glassfiber based VIPs. The paths of heat transfer for the disordered glass fiber are mainly along the longitudinal fibers themselves, interfaces and contacts point, and radiation. However, the paths of heat transfer for the ordered glass fiber are mainly along interface contact between transverse fibers and radiation. The path of heat transfer for the ordered glass fiber was much longer than that of heat transfer for disordered glass fiber. Assuming the same thickness for VIP, it can be inferred that multilayer cores in a VIP with ordered glass fibers can increase thermal insulation performance. Here, the radiation of the array fiber has an important influence on heat transfer of VIP observed from Equation (2). It is assumed that the fiber diameter is so large that diffraction effects are avoided and transmission through the fiber is negligible. Furthermore, the vertical aligned structure of glass fibers could create a continuous thermal path from the hot surface to the cold surface, and hence give rise to an inherently high conductivity in the VIP.

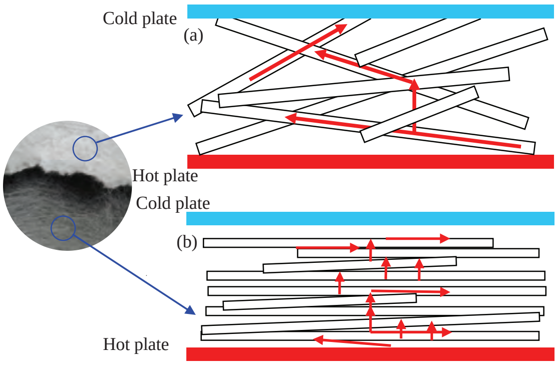

Fig 2: Model of the path of heat transfer for two different glassfiber based VIPs. (a) Disordered wool-type glassfiber based VIP, (b) Ordered filament glassfiber based VIP.

Assuming that fiber diameter is small and there is perfect contact between fibers, the heat conducted through one layer is equivalent to that conducted by a number of parallel paths equal to twice the number of junctions between adjacent layers; each path has cross-sectional area equal to that of the fiber and length equal to half the distance between the fibers in a layer. For VIP with multilayer FF cores, decreasing fiber diameter resulted in decreased thermal conductivities of VIPs whereas for VIP with multilayer wool-type glass fiber cores, decreasing discrete core layer thickness resulted in decreased thermal conductivities of VIPs. Sample 1 and 5 recorded nearly the same thermal conductivities. The result corroborates with the conclusions of reference [9], who resolved that samples prepared as layers with most of the fibers perpendicular to heat flow demonstrated lower conductivities than samples with random laid fibers at similar fiber diameters. The equivalent conductivities can be attributed to sample 1 having a small fiber diameter while sample 5 had a fiber diameter of 8 μm. The center-of-panel thermal conductivities of both types of fibrous insulation decreased with decreasing fiber diameter and thickness of single core layer. This may contrast with conventional correlations between physical properties such as density in which an equal change in fiber diameter results in differences in thermal conductivity measurements of 25% or greater [10]. One of the major parameters of its thermal insulation quality is the fiber diameter. Decreasing the variance in the fiber diameter will consequently decrease the variance of the thermal conductivity. It indicates that the fiber diameter had an influence on the heat transfer of VIP. The connections between fibers increased with the decrease of average diameter, so that the heat conduction of glass fiber increased with the decrease of average diameter.

4. Conclusions

Increasing the number of constituent core material layers resulted in a decreased thermal conductivity because most of the fibers had orientation perpendicular to the heat flux. The thermal conductivities of VIP with ordered glass fiber core material decreased with decreasing fiber diameter. The thermal conductivity of both types of fibrous insulation decreased with decreasing fiber diameter and thickness of single core layer.

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Glass fiber based vacuum insulation panels – comparative study of properties and aging

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Abstract:
The Kyoto Protocol agreement under the auspices of The United Nations has been extended to the year 2020 due to the glaring impact of greenhouse gas emissions from energy usage on world climate and environment. Over the past decade, the world has increasingly focused on the need for improved energy efficiency within the built environment which singularly accounts for a greater percentage of total global greenhouse gas emissions. Conventional energy efficient vacuum insulation panel (VIP) with fumed silica core and metalized envelope has been extensively investigated in other literature. In this study, the basic properties, aging and durability issues related to glass fiber core VIPs of different core compositions and multilayered envelope have been investigated experimentally under varied heat and moisture loads. Analogous comparison is made between the different core and envelope materials. Fiber architecture had pronounced effect on thermal conductivity. VIP with fiberglass cloth as outer protective layer showed slower aging rate.

Keywords:
Vacuum insulation panel (VIP), glass fiber core, properties, aging, fiberglass cloth.

1. Introduction

Heating, ventilation, and air conditioning singularly accounts for the largest energy end-use sector in the world energy consumption [1]. In the absence of abatement measures, global emissions from buildings are forecasted to grow by 1.7% annually, increasing by 53% overall in 2005-2030 [2]. While the heating demand will reduce due to global warming in the coming decades, the cooling demand for buildings will increase respectively; hence the importance of thermal insulation of existing and new buildings will remain [3]. Vacuum insulation panel (VIP) consisting of an evacuated porous load-bearing core material, multilayer envelope and supplemented with desiccant or getter is a high-performance insulation material to curtail energy losses [4, 5]. VIPs had been widely used in refrigeration and cryogenics for a long time until the brink of the millennium where building applications soared. One key issue for building application is to ensure a service life in the order of several decades under typical thermo and hygric effects [6]. For the present study, hygro-thermal aging of VIPs with two glass fiber core material types and two Al-laminate envelope types have been investigated for several months. The intention is to estimate the service life from experimental results as well as calculate the effective thermal conductivity including edge effect and aging for VIPs with glass fiber core material and Al-laminate envelope.

2. Experimental description

The manufacturing process of the glass fiber core material has been reported elsewhere [7]. Panels with centrifugal glass fiber (CF) and aerocor glass fiber (AF) as core materials were investigated. The Al-laminate envelope was prepared by heat lamination using polyurethane glue. Al-laminates designated: AL1 was composed of 50~55 µm LDPE/7 µm Al/12 µm metalized PET/15 µm PA, and AL2 was composed of 80 µm mLLDPE/15 µm PA/7 µm Al/12 µm PET/340~350 µm FGC; where LDPE is low density polyethylene, Al is aluminium foil, PET is polyethylene terephthalate, PA is polyamine, mLLDPE is metallocene catalyzed linear LDPE, and FGC is fiberglass cloth. The panels were formed by simultaneous evacuation and sealing in a depressurization chamber. In this study, the fibrous core material was evacuated to inner pressure ranging 0.001-0.1 mbar. Sample compositions and inner pressures during manufacturing are described in section 3. With exception of samples 3-6, all others had getters incorporated. Aging of VIPs was investigated using a climatic chamber (Fig.1). After initial determination of thermal conductivity, samples1-4;7-10 were exposed to varying thermo-hygro conditions: partial exposures at 23°C, 50% (for 130-187 days); 80°C, 80% (for 14 days); 23°C, 50% (for 45 days), 80°C, 5% (for 21 days) and 20°C, 45% (for 130 days). Samples 5 and 6 were first exposed to ambient outdoor conditions for 137 days, and then at 80°C, 80% (for 14 days); 23°C, 50% (for 45 days), 80°C, 5% (for 21 days) and 20°C, 45% (for 130 days). Thermal conductivity measurements were performed using a heat flow meter (Netzsch HFM 436) with overall sample size of 300×300 mm^2 and metering area of 100×100 mm^2. Moisture content (%-mass/year) was measured periodically. Inner pressure was measured with an instrument that operates on similar principle as the Pirani thermal conductivity vacuum gauge [1].

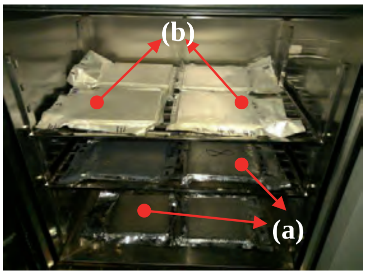

Fig.1: Apparatus for aging test showing VIPs with: (a) AL1 and (b) AL2 laminates.

3. Results and discussion

3.1 Hygro-thermal aging mechanism and properties

For as-prepared VIPs at 0.001 mbar with AF core material, Fig.2a shows clearly the correlation of thermal conductivity and the respective envelopes with aging time. VIPs 7 and 8 showed lower initial thermal conductivities but aged at a more rapid rate than VIPs 1 and 2. The latter aged slowly, adding only about 0.0003 W/(m·K) close to the 280th day after accelerated aging. The water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) for AL1 was measured to be < 0.05 $g/(m^2 \cdot d)$ and < 0.005 $cm^3(STP)/(m^2 \cdot d)$, respectively. WVTR and OTR for AL2 is not easy to determine due to the outer layer FGC. In reality they may be even lower than the threshold values of the standardized measuring methods. Only in actual applications or accelerated aging can one realize the laminates performance. The heat seal strength (HSS) of AL2 is about 2.5 times higher than the HSS of AL1; chiefly attributed to the intrinsic properties of mLLDPE sealing layer. Literally, high HSS will oppose permeating gases around the heat sealed flanges. Even at 0.01 mbar inner pressure, VIPs 9 and 10 showed thermal conductivities lower than 0.0045 W/(m·K) (see Fig.2b). In comparison, thermal conductivities of VIPs 3 and 4 were high at about 0.012 W/(m·K). The difference is attributed to two main reasons. Firstly, VIPs 9 and 10 had getters incorporated while VIPs 3 and 4 had none. Getters absorbed permeating gases to maintain the inner vacuum especially during the infant stage of the panel. Secondly, the fiber architecture of AF and GF differ significantly. The constituent fibers of AF can be considered as somewhat orderly arranged as compared to disoriented GF constituents. Thus the heat transfer path of GF is much shorter and simpler than that of AF; with the former yielding a fairly higher thermal conductivity than the latter. A similar trend with higher thermal conductivity values was measured for VIPs 5 and 6 (not shown).

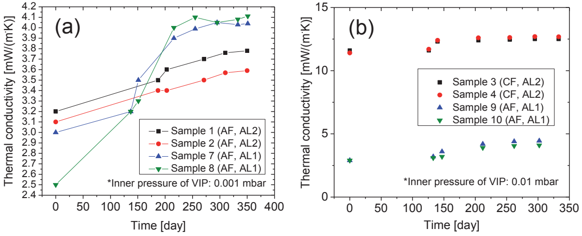

Fig.2: Aging results of thermal conductivity versus time for as-prepared VIPs at (a) 0.001 mbar and (b) 0.01 mbar. Inserted legend shows sample number and composition (core material, laminate envelope).

3.2 Determination of effective thermal conductivity

Edge effect (Δ_{edge}) was estimated by measuring heat loss at the edge (Ψ) to augment the center-of-panel thermal conductivity (λ_{cop}). For a VIP area (A) and perimeter (p), the effective thermal conductivity (λ_{eff}) is calculated by [8]:

$$\lambda_{eff} = \lambda_{cop} + \Delta_{edge} = \lambda_{cop} + \psi(d) \times p/A \tag{1}$$

Table 1: Results of thermal bridge measurements.

VIP	d_{vip}(m)	Ψ_{edge} with seal W/(m·K)	$\lambda_{cop,90\%}$ W/(m·K)	$\lambda_{cop,25yrs,90\%}$ W/(m·K)	$\lambda_{eff,25yrs}$ W/(m·K)
Type A	0.03	0.023	0.0030	0.00645	0.00746
Type B	0.03	0.032	0.0035	0.00695	0.00692

The results are listed in Table 1. VIP type A in Table 1 has same composition as samples 7 and 8 in Fig.2a. Also, VIP type B in Table 1 has same composition as samples 1 and 2 in Fig.2a. Again, 90%-fractile $\lambda_{cop,90\%}$ and $\lambda_{cop,25yrs,90\%}$ have same designation as reported elsewhere [9]. However, $\lambda_{eff,25yrs}$ reported here includes edge effect and aging but does not include 90%-fractile values; which may add another 0.0004.

3.3 Service life estimation

Service life is defined as a time period after which the maximum limiting thermal conductivity (λ_{lim}) is reached. That is:

$$\lambda_{eff}\Big|_{t=t_{SL}} = \lambda_{\lim} \tag{2}$$

As well known, pressure increase and moisture accumulation are the major aging parameters. Assuming the pressure and water content are thermal resistances in parallel (as in reality they oppose thermal conductivity at same time), then they can be superimposed independently as [6]:

$$\frac{\partial\lambda}{\partial t} = \frac{\partial\lambda}{\partial p}\frac{\partial p}{\partial t}(T,\varphi) + \frac{\partial\lambda}{\partial X_W}\frac{\partial X_W}{\partial t}(T,\varphi) \tag{3}$$

where $\partial\lambda/\partial t$, $\partial\lambda/\partial p$, $\partial p/\partial t$, $\partial\lambda/\partial X_w$, $\partial X_W/\partial t$, T and φ are: change in thermal conductivity with time 10^{-3}[W/(m·K·yr)], change in thermal conductivity due to pressure W/(m·K·bar), pressure increase rate (mbar/yr), change in thermal conductivity due to humidity [mW/(m·K·M-%)], moisture accumulation rate (%-mass/yr), temperature (K), and humidity (%), respectively. For the VIPs, $\partial\lambda/\partial p$ was about 0.029 W/m·K·bar, $\partial\lambda/\partial X_w$ was about 0.80 mW/m·K·M-% with an annual mass increase of 0.1%-mass/yr (extrapolated from 300 days weight measurements). Assuming a constant pressure increase of 2 mbar/yr, the effective thermal conductivity λ_{eff} and service life are estimated according to equation 3 and listed in Tables 1 and 2.

Table 2: Calculated service life for VIP (30 cm ×30 cm × 3 cm) with aerocor glass fiber core material and different Al-laminates.

$\lambda_{\lim}$,(starting from $\lambda_{cop,90\%}$) W/(m·K)	Service life (years)	
	TYPE A	TYPE B
$\lambda_{\lim}$ = 0.006	21	18
$\lambda_{\lim}$ = 0.008	36	32
$\lambda_{\lim}$ = 0.010	51	47

4. Conclusions and outlook

Glass fiber core VIPs have been studied under various temperature and moisture environments to investigate the aging mechanism and service life. AL2 laminate with outer fiberglass cloth showed slower aging rate compared to AL1. λ_{eff}, was measured to be < 0.0075 W/(m·K) (including edge effect and aging) after 25 years. All parameters altering thermal conductivity were experimentally determined except increase in pressure per year which was assumed to be 2 mbar/yr. This may be on the high side as AL foil laminates have been reported to have lower permeation rates [1]. To further reduce Δ_{edge} and λ_{eff}, big sized panels will be studied in the future. Again, glass fiber core VIPs with center-of-panel thermal conductivity lower than 0.0018 W/(m·K) are now emerging on the Asian market. With such VIPs, service life of about 30 years and 45 years maybe predicted for $\lambda_{\lim}$ of 0.006 W/(m·K) and 0.008 W/(m·K), respectively.

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Synthesis and characterization of melamine – formaldehyde rigid foams

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Abstract:
A novel core material for vacuum thermal insulation, the melamine-formaldehyde (MF) rigid foam was processed from an emulsion of the melamine-formaldehyde resin at temperatures between 130°C and 150°C, using pentane as the blowing agent. Optimization of the synthesis resulted in the base thermal conductivity of only 0.006 W m^{-1} K^{-1} and an extremely low outgassing rate. The average pore size was between 0.03 an 0.1 mm as determined directly by SEM and indirectly by measuring the thermal conductivity in a wide pressure range from 10^{-3} mbar to the atmosphere. The long-term pressure-rise measurements using the spinning rotor gauge indicated very low values which means that these MF rigid foams could be applied as the core material in Vacuum Insulating Panels (VIPs). Their outstanding performances are comparable to selected inorganic core materials as they can withstand thermal treatment up to 200°C.

Keywords:
Vacuum insulation panel, new organic core material, melamine-formaldehyde rigid foam.

1. Introduction

Core materials for Vacuum Insulation Panels (VIPs) must fulfill several specific requirements. They should have a high porosity with small interconnected open pores and structural stability, since they must withstand the high mechanical load exerted by the atmospheric pressure. Small pores are desired since the same low thermal conductivity can be maintained at higher internal pressure compared to the same bulk material with larger pores. Beside this, chemical stability, expressed by low outgassing rates over the projected operational time, must be achieved, too. The requirements seem to be the stringent in VIPs for building applications where the expected service lifetime is ~100 years [1, 2].

2. Foam synthesis

For preparation of the rigid foams, a reacting mixture was formed from an emulsion of Meldur®MP (melamine - formaldehyde resin partially soluble in water with the concentration range between 60 % - 65 %), n-pentane, sodium lauryl ether sulphate (SLES) and formic acid. Foam density was controlled by variation of the pentane content in the emulsion and with different heating schedules. Foaming and curing proceeded with heating in a conventional oven in the range of temperatures between 130°C and 150°C for 30 minutes. Final curing and water removal was carried out at temperatures from 170°C to 190°C.

3. Foam characterization

The range of densities achieved on several ten samples was between 30 kg m^{-3} and 115 kg m^{-3}, but the acceptable foam density range for VIP turned out to be between 55 and 75 kg m^{-3}. Samples with densities below 55 kg m^{-3}, although with an acceptable low outgassing rate, were discarded because the mechanical stiffness could not sustain the atmospheric pressure exposed on the VIP. Different density of foams is clearly manifested in the micro-structure presented on SEM images. Foams with different densities at 200x and 1000x magnification, cut perpendicularly to the direction of the foam rising, are shown in Fig. 1. The open-cell structure is clearly observed, regardless of the density.

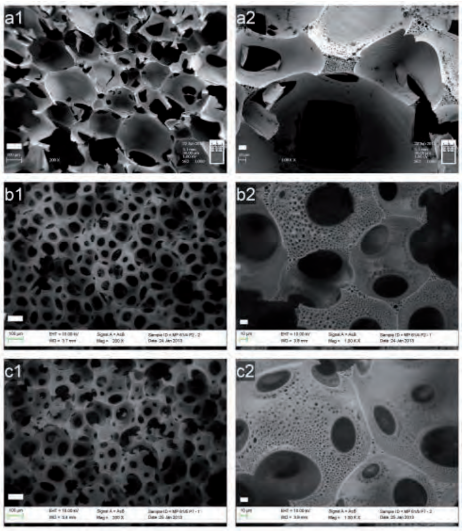

Fig. 1: SEM images of melamine foams processed from the unmodified melamine-formaldehyde resin with different densities (a1, a2 - 30 kg m^{-3}; b1, b2 – 60 kg m^{-3}; c1, c2 – 85 kg m^{-3}).

The outgassing rate of the foam was determined according to the recommended practices using the spinning rotor gauge, [3]. Two appendages, the Cu tube and SRG thimble, were welded to the stainless steel frame forming a small VIP having the size ~200 x 200 x 24 mm^3.

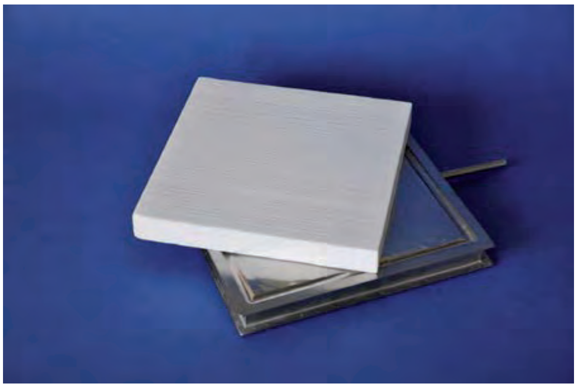

Fig. 2: A MF foam sample before mounted into the stainless steel envelope.

Each foam sample was dried at 150°C in air for 17 h before mounting into the VIP. The pressure rise was monitored by the SRG at R.T. for up to 24 h after pinch-off. On average, the pressure and its rate of change were low enough to enable measurements of the base thermal conductivity λ_0 at conditions $p < 10^{-3}$ mbar where the contribution of the gaseous thermal conductivity could be ignored. This envelope design allows also occasional recording of the *dp/dt* over weeks and months until the upper SRG range limit is approached ~10^{-2} mbar.

4. Results and discussions

The atmospheric thermal conductivity λ_{atm} and compression strength versus foam density is presented in Fig. 3.

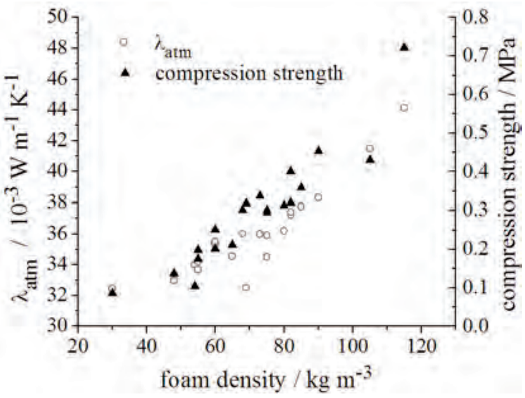

Fig. 3: The atmospheric thermal conductivity and compressions strength of several MF foam samples.

The range of densities suitable for VIP is between 50 and 75 kg m^{-3}. Lower density results in low compression strength while higher density has higher bulk thermal conductivity.

The main result of our research is expressed in the values of *dp/dt* and base thermal conductivity λ_0 measured on 6 different MF foams with different density. Data are collected in Table 1.

Table 1: MF foam density, corresponding *dp/dt* and base thermal conductivity λ_0.

Sample number	density kg m^{-3}	*dp/dt* x10^{-9} mbar s^{-1}	λ_0 x10^{-3} W m^{-1} K^{-1}
1	55	4.9	5.9
2	60	4.7	6.2
3	68	4.4	5.9
4	73	2.8	6.9
5	75	2.2	6.6
6	82	2.9	7.6

5. Conclusions and outlook

Our data indicate that MF rigid foams are serious candidates as the core material in VIPs. After intense thermal treatment their low outgassing rates may result in a projected service lifetime of the order of some ten years. Further optimization towards lower pore sizes is in progress. This parameter anyhow releases the requirements for maintenance of low pressure inside the VIP. So far, requirements for a low flammability and an acceptable VIP service life could be only fulfilled by using inorganic core materials.

Acknowledgements

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Effect of Radiative Scattering Pattern on Insulation Performance of VIP Filler Materials

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Abstract:
Radiation is a significant heat transfer mode for vacuum insulation panel (VIP) since it has a strong influence on insulation performance of VIP. In this study, radiative heat transfer is investigated for each of isotropic and backward scattering media to evaluate the effect of each scattering pattern on the insulation performance of VIP. A statistical formulation proposed in this paper, a diffusion approximation, Monte Carlo method and discrete ordinate interpolation method (DOIM) are used and compared to calculate the radiative thermal conductivity. The results show that the insulation performance of the VIP can be enhanced by increasing the optical thickness or decreasing the wall emissivity. It is also found that the backward scattering is superior to the isotropic scattering especially when the medium is optically thick.

Keywords:
Isotropic scattering, Backward scattering, Statistical formulation, radiative thermal conductivity.

1. Introduction

Vacuum insulation panel (VIP) is an outstanding insulation method to save the energy consumption for buildings. It has a lower thermal conductivity than those of the conventional insulators since its core material is evacuated [1]. To improve the insulation performance of the VIP, it is important to investigate not only the conduction but also radiative heat transfer through the filler material. The previous studies show that the radiative properties such as absorption and scattering coefficients have an effect on the radiative heat transfer in the insulation materials [2]. Further, Jang et al. [3] predicted the radiative heat transfer in pure isotropic and backward scattering media using a Monte Carlo method and found that the backward scattering is more desirable in VIP. In this study, the scattering effect of filler material on the insulation performance is examined for pure isotropic and backward scattering. A statistical formulation is proposed to get the exact solutions and it is validated against the Monte Carlo method. For various optical thicknesses and wall emissivities, the radiative conductivity is calculated and compared to find the maximum insulation condition of the scattering phenomena.

2. Analysis

A filler material of a VIP is considered as a one-dimensional pure scattering medium with height H between two walls. The temperatures of upper and lower walls are T_1 and T_2. Both walls are diffuse and have the same emissivity ε_w. The medium is gray with a constant scattering coefficient σ_s. In this problem, there is only radiative heat transfer and the medium is at a radiative equilibrium. For the isotropic scattering, the photon can be scattered in arbitrary direction with uniform probability. On the contrary, for the backward scattering, the photon is always scattered to the opposite direction and its polar angle is not changed like specular reflection.

Monte-Carlo method used in this study is presented earlier by the authors [3]. It traces a random sample of photons from emission to absorption.

The Discrete Ordinate Interpolation Method (DOIM) is a modification of the Discrete Ordinate Method (DOM) by Cheong and Song [4]. In the DOIM, the intensity at a grid point is calculated using the upstream value.

The modified diffusion approximation enables to obtain the radiative conductivity easily for a gray medium between parallel walls. It is expressed as [5],

$$k_{r,diffusion} = \frac{4\sigma T_m^3 H}{3\sigma_s H/4 + (2/\varepsilon_w - 1)}, \qquad (1)$$

where T_m is the mean temperature and σ is the Stefan-Boltzman constant.

The proposed statistical formulation is based on the probability that the emitted photon at a wall arrives at the opposite wall. Let the probability that a photon emitted from one wall with strength 1 arrives at the opposite wall is R_0 and the probability that the photon comes back to the original wall is S_0 (i.e., $R_0+S_0=1$). The heat flux q_r'' obtained by considering all the possible sequences until the photon emitted at surface 1 is finally absorbed at surface 2 is expressed as,

$$q_r'' = \frac{\varepsilon_w R_0}{(1+\rho_w R_0 - \rho_w S_0)}(\sigma T_1^4 - \sigma T_2^4), \qquad (2)$$

where ρ_w is reflectivity of the walls. Certainly, R_0 depends on the polar angle measured from the surface normal vector. It can be written as

$$R_0 = \frac{\int_0^{\pi/2} R_\theta \cos\theta \sin\theta d\theta}{\int_0^{\pi/2} \cos\theta \sin\theta d\theta}, \qquad (3)$$

where R_θ is the probability that the photon launched in direction θ at surface 1 arrives at surface 2 and it is expressed as

$$R_\theta = e^{-\tau_L/\cos\theta} + \int_0^{\tau_L} P(\tau) e^{-\tau/\cos\theta} \frac{d\tau}{\cos\theta}, \qquad (4)$$

where τ is the non-dimensional optical thickness, $\tau_L = \sigma_s H$ and $P(\tau)$ is the probability that the photon scattered at τ arrives at surface 2.

For isotropic scattering, by using the exponential integral function, $P(\tau)$ is given as

$$P(\tau) = \frac{1}{2} E_2\left(\tau_L - \tau\right) + \frac{1}{2}\int_0^{\tau_L} P(\tau') E_1\left(\left|\tau_L' - \tau\right|\right) d\tau'. \qquad (5)$$

For the backward sc attering, P is dependent on the direction cosine μ contrary to the isotropic scattering. The probability $P(\tau)$ is defined as

$$P(\tau) = \int_0^1 \int_0^\tau \left(1 - P(\tau_L - \tau')\right) \frac{e^{-(\tau-\tau')/\mu}}{\mu} d\tau' d\mu. \qquad (6)$$

3. Results and discussions

3.1 Isotropic scattering medium

Table 2 shows the radiative thermal conductivity k_r for various optical thicknesses and wall emissivities. The mean temperature T_m is 300 K and H is 0.01 m. The relative error of the statistical formulation to the Monte Carlo results is less than 1% here. Table 2 also shows that the radiative conductivity decreases with increasing $\sigma_s H$ and decreasing ε_w. To improve the insulation performance, therefore, it is recommended to insert radiation shields of low emissivity or use filler material with high scattering coefficient.

Table 1 : Comparison of radiative thermal conductivities with varying optical thicknesses and emissivities for the isotropic scattering medium (H=0.01 m).

	Optical thickness ($\tau=\sigma_s H$)			0.01	0.1	1	10
k_r (mW/m·K)	**Statistical formulation**	ε_w	**0.1**	3.22	3.21	3.09	2.31
			0.5	20.3	19.8	16.1	5.86
			0.9	49.7	46.6	30.2	7.06
	Monte Carlo	ε_w	**0.1**	3.22	3.21	3.09	2.30
			0.5	20.3	19.8	16.1	5.82
			0.9	49.7	46.5	30.2	7.00
	DOIM	ε_w	**0.1**	3.22	3.20	3.09	2.32
			0.5	20.3	19.8	16.0	5.80
			0.9	49.7	46.5	30.0	6.96
	Diffusion Approx. (Eq. 1)	ε_w	**0.1**	3.22	3.21	3.10	2.31
			0.5	20.4	19.9	16.3	5.83
			0.9	49.8	47.2	31.0	7.02

3.1 Backward scattering medium

Table 3 shows the radiative thermal conductivity in a backward scattering medium. It is also found important to not olny increase the optical thickness but also decrease the wall emissivity, which is in common with the isotropic scattering. From the results, it is found that the radiative thermal conductivity of the backward scattering medium is about half that of the isotropic one when the medium is optically thick. By adding specular metal scales in the filler material, the insulation performance can be improved. The relative error of the statistical formulation results to the Monte Carlo result is also below 1%

Table 2: Comparison of radiative thermal conductivities with varying optical thicknesses and emissivities for the backward scattering medium (H=0.01 m).

	Optical thickness ($\tau=\sigma_s H$)			0.01	0.1	1	10
k_r (mW/m·K)	**Statistical formulation**	ε_w	**0.1**	3.22	3.19	2.97	1.79
			0.5	20.3	19.3	13.4	3.37
			0.9	49.3	43.7	21.8	3.73
	Monte Carlo	ε_w	**0.1**	3.22	3.19	2.97	1.79
			0.5	20.3	19.2	13.3	3.39
			0.9	49.3	43.6	21.8	3.71
	DOIM	ε_w	**0.1**	3.22	3.19	2.97	1.80
			0.5	20.3	19.2	13.3	3.38
			0.9	49.3	43.5	21.6	3.74
	Diffsuion Approx. (Eq. 1)	ε_w	**0.1**	3.22	3.20	2.99	1.80
			0.5	20.3	19.4	13.6	3.40
			0.9	49.5	44.6	22.5	3.77

4. Conclusions

Radiative thermal conductivities of isotropic and backward scattering media are investigated to evaluate the scattering effect of filler material on the insulation performance. A statistical formulation is proposed in this study. Other numerical solutions are obtained using the Monte Carlo method, DOIM and diffusion approximation. The results of statistical formulation, Monte Carlo method and DOIM agree well with each other within 1% error.

The results show that radiative heat transfer can be reduced by decreasing the surface emissivity or by increasing the optical thickness of the filler material for both of isotropic and backward scattering media. Also, it is found that the backward scattering medium decreases the radiative heat transfer more effectively than the isotropic scattering one.

Acknowledgements

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Getter pumping of vacuum sealed devices

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Abstract:

Since more than 100 years the vacuum inside sealed devices is maintained by Getters. About 30 years ago a Getter pump was used, for the first time, to provide a large linear pumping for a particle Accelerator (the Large Electron Positron collider, LEP, at CERN). Getter pumping, in the form of a thin film coated on the internal surface of vacuum chambers, is presently used for the Large Hadron Collider (LHC) at CERN.

A thin Getter film coated on an Al foil is also used in the evacuated flat solar thermal collector produced by SRB Energy. This same approach could be extended to improve the thermal insulation of windows and panels.

Keywords:

Vacuum insulation, NEG pumping, Particle Accelerators, evacuated Solar Collectors, Windows and Panels.

1. Getters and gettering.

Getters are materials (metal alloys) able to react chemically with gas molecules so as to fix them in the form of stable chemical compounds. Doing so, the getter surface is progressively covered and finally the pumping action is lost. The attractive property of Non Evaporable Getters (NEG) is the possibility of restoring the pumping action by heating. Heating provides the energy required to diffuse the adsorbed gases from the surface into the getter bulk.

The most important property of NEGs is the ability to react with all the gas species usually present in a vacuum system, although the rare gases, non-reactive by definition, cannot be pumped. Also important is the temperature to activate the NEG after exposure to ambient air or to regenerate its pumping in operation. The lower are these temperatures, the wider is the range of the NEG possible applications.

Getters are commonly used by industry to maintain the vacuum inside electron tubes, light bulbs, TV screens etc. Therefore it was natural to envisage their application for the pumping of LEP at CERN, which, after all, is a large electron tube…

2. NEG pumping for LEP at CERN.

In a Storage Ring Accelerator like LEP, particles may be kept circulating for hours at a speed close to the speed of light. To minimize particle interaction during such a long travel, pressures as low as 10^{-11} Torr are needed. Maintaining these low pressures in operating conditions is problematic because of the large amount of gas produced by the circulating beam (due to synchrotron radiation and/or charged particle bombardment of the chamber walls) and of the small conductance of the accelerator chamber, which limits the access of the gas molecules to the pumps. For this latter reason, a large and linearly distributed pumping must be adopted (1). In the case of LEP linear pumping was supplied by a NEG strip subtended all along the accelerator chambers, for a total length of about 23 km. This solution was adopted after showing that NEG operation at these unusually low pressures was feasible (2). About 2000 chambers, most of them 12 m long and equipped with a NEG strip, able to reach an ultimate pressure lower than $2x10^{-11}$ Torr were finally installed in the machine. The vacuum behavior of LEP was fully satisfactory during the 10 years of its life (3).

3. NEG coatings for LHC at CERN.

For the pumping of LHC an additional difficulty consisted in the lack of space for the NEG pump inside the vacuum chamber. To solve this problem, thin film NEG coatings were developed and applied by sputtering to the chamber internal surfaces (4). However, in this case heating the whole chamber up to the NEG activation temperature is required, and Al chambers cannot be heated above 200°C not to deteriorate their mechanical strength. Since NEGs with such a low activation temperature were not known, about 20 different NEG alloys were tested before finding an adequate material. At present about 7 km of LHC chambers (all those at ambient temperature, outside the superconducting magnets) are coated with a film of TiZrV alloy, which provides the required vacuum stability in presence of high intensity proton beams.

4. Vacuum for thermal insulation.

Heat transmission in evacuated devices results from combined effects of gas conduction and radiation exchange. For any given design, an upper limit of the gas pressure may be defined to make the gas conduction negligible with respect to the contribution of radiation. Whenever NEG pumping is envisaged, two different situations are possible. If periodic NEG heating is feasible, the installed NEG amount must be sufficient to absorb in its bulk the total outgassing produced during the operating life of the device. If heating is not feasible, the NEG amount must be large enough to accommodate the gas load only on its surface. If this is not done, after some time the pressure will increase above the target figure, and the thermal performance of the device will progressively deteriorate. In the following paragraphs a few practical cases will be discussed in view of these general considerations.

4.1. Evacuated Solar Collectors.

In this case the radiation losses are large because of the high operation temperatures and a pressure lower than 10^{-4} Torr is sufficient. The required amount of NEG is reasonably small if a proper choice is made of the collector construction materials (only metal and glass, no organics). In the case of the solar collector produced by SRB Energy, the NEG pump is heated by sun and pressures lower than 10^{-5} Torr are consistently achieved (5). Thanks to vacuum, this collector may reach a stagnation temperature higher than 300°C even without the help of focusing mirrors. These mirrors cannot transmit the diffuse component of the solar light, which in Central Europe may exceed 50% of the total light available.

4.2. Evacuated Windows.

A window operates at temperatures lower than those of solar collectors, therefore the radiation losses are smaller and the required pressures correspondingly lower by 1 to 2 orders of magnitude. Thanks to vacuum, a thermal transmission 3-4 times lower than that of the best windows commercially available could be achieved. However, additional difficulties exist with respect to the solar collector, namely the mechanical spacers should not be visible, a metal structure does not exist to receive the pumping port, little space is available for the NEG and its activation is problematic.

4.3. Insulating Panels.

The case of an evacuated empty panel is in all respects of an easier solution as compared to a window. A heat transmission factor, thickness independent, of about 0.3 W/m^2 K could be maintained during the panel life. If a low thermal conductivity material is inserted in the panel, the thermal losses may be lower initially, but both the NEG heating and the evaluation of the total gas load become very problematic, leading to probable pressure drift and performance deterioration during the life of the panel.

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Hollow Silica Nanospheres as a Superinsulating Material

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Abstract:
A simple, mild, and effective template approach has been used to produce hollow silica nanospheres with controlled sizes ranging from 40 to 150 nanometers. The obtained powders reported herein showed systematic variations in measured thermal conductivity, with values typically between 0.040 to 0.090 W/(mK) before further optimization, with an expressed goal to reach below 0.020 W/(mK). Surface hydrophobization was successfully performed. Thus, hollow silica nanospheres are considered to be promising building blocks for new hydrophobic, superinsulating materials.

Keywords:
Hollow nanospheres, superinsulation, Knudsen effect, hydrophobic, thermal conductivity

1. Introduction

Thermal insulation requirements for building envelopes are increasing. When traditional insulation materials such as glass wool or expanded polystyrene (EPS) are used, the insulation thickness must be increased. In applications where space is an issue, state-of-the-art materials and solutions with low thermal conductivities, such as aerogels and vacuum insulation panels (VIP), are of interest. They are, however, costly and high embodied energy solutions and may not be suitable at the moment for large-scale building applications. Furthermore, the VIPs will lose their vacuum gradually by air and moisture penetration by diffusion, and may also lose their vacuum abruptly by various punctures.

A major aim within the industry and research community is to develop less expensive, robust thermal insulation materials with as low thermal conductivity values as possible. Another concern is the carbon footprint, since the ultimate goal is buildings that have limited or no CO_2 emissions.

On this background, the development of nano insulation materials (NIM) has been proposed. The NIMs are envisaged to be homogeneous materials with a closed or open nanopore structure. The aim is an overall thermal conductivity equal or less than 0.004 W/(mK) in the pristine condition.

Our efforts have so far been devoted to production of hollow silica nanospheres with controlled diameters and wall thicknesses by template-based processes. Silica was chosen as shell material due to its low thermal conductivity (~ 1.4 W/(mK)), ease of preparation, and abundance in nature.

The starting point for the concept of hollow nanosphere NIMs is shown in Fig.1. The overall property of hollow nanosphere NIMs depends on several parameters, such as the inner diameter (D) and shell thickness (L) of the hollow spheres, the chemical composition of the shell materials, the type of gas within the structure, and the packing manner/density of the hollow spheres. It should be possible to control the thermal properties of hollow nanosphere NIMs by adjusting these structural and/or compositional parameters.

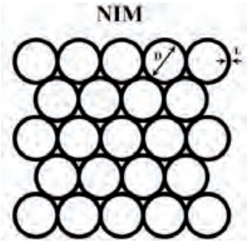

Fig.1: Schematic illustration of a close-packed NIM.

2. The Knudsen effect

The low gas thermal conductivity in NIMs is caused by the Knudsen effect, which is of importance when the pore diameter is of the same order or smaller than the mean free path of the gas molecules. In this case, a gas molecule inside a pore is more likely to hit the pore wall than hitting another gas molecule, hence the thermal gas thermal transport is decreased. The resulting gas thermal conductivity λ_{gas} as a function of pore diameter and air pressure is based on the following simplified expression:

$$\lambda_{gas} = \frac{\lambda_{gas,0}}{1+2\beta Kn} = \frac{\lambda_{gas,0}}{1+\frac{\sqrt{2}\beta k_B T}{\pi d^2 p \delta}} \qquad (1)$$

where λ_{gas} = gas thermal conductivity in the pores, $\lambda_{gas,0}$ = gas thermal conductivity at STP, β = coefficient characterizing the molecule wall collision energy transfer efficiency, Kn = Knudsen coefficient, k_B = Boltzmann's constant, T = temperature, d = gas molecule collision diameter, p = gas pressure in pores, and δ = characteristic pore diameter. That is, pores with very small diameters (e.g. nanoscale) will result in a very large Knudsen coefficient, i.e. a very low λ_{gas}.

3. Experimental

Two different template methods were used for nanosphere synthesis: polyelectrolyte agglomerates (i.e. polyacrylic acid, PAA) [1] and polystyrene (PS) nanoparticles [2]. PAA agglomerates were prepared by dispersing the polyelectrolyte in an ethanol/ammonia mixture. PS nanoparticles were prepared by the polymerization of styrene under controlled conditions. These templates were coated with silica by controlled hydrolysis and condensation of tetraethoxysilane (TEOS). Then the templates were removed either by washing (PAA) or heating (PS). The hollow core size, wall thickness, wall morphology and particle packing were varied by changing the template size, the concentration of NH_4OH and/or the amount of TEOS.

Hollow silica nanospheres are subject to capillary condensation of atmospheric water, which will lead to an increase in thermal conductivity. This can be avoided by making the nanospheres hydrophobic. Two methods were tried: direct production of hydrophobic nanospheres by adding organosilanes to TEOS when making the shell and post-treatment with vapour-phase organosilanes. The thermal conductivity of the obtained materials was analyzed by using a Hot Disk Thermal Constants Analyzer (TPS 2500S).

4. Results and discussion

Typical transmission electron microscope (TEM) images of the hollow SiO_2 nanospheres prepared with PAA and PS templates are shown in Fig.2.

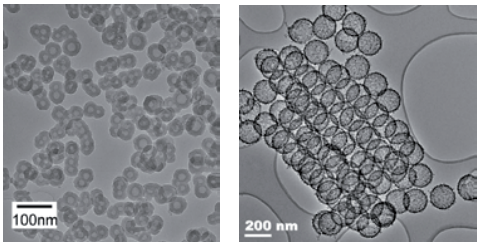

Fig.2: TEM images of hollow silica nanospheres prepared with PAA (left) and PS (right) templates.

The thermal properties of the as-prepared and hydrophobic hollow silica nanospheres are given in Table 1. Solid silica nanoparticles with similar dimensions (diameter: ~ 250 nm) and a commercial aerogel sample from PCAS [3] were also measured and the results are included for comparison.

A significant decrease in thermal conductivity was observed when the particle size was decreased or the porosity increased. The thermal conductivity was essentially unaltered with hydrophobic treatment. However, sample stability in humid environment must be determined for practical applications.

Table 1: Measured thermal conductivity for different materials and nanospheres.

Inner diameter D (nm)	Shell thickness L (nm)	Sample (powder) density (kg/dm^3)	Template	Measured effective thermal conductivity (W/(mK))
Bulk silica				1.2-1.4
Silica nanoparticles				0.090
PCAS aerogel [3]				0.023
10	20	0.37	PAA	0.089
25	12	0.20	PAA	0.065
25	12	0.20	PAA, hydrophobic	0.062
100	12	0.33	PAA	0.076
150	15	0.27	PS	0.040

The preliminary synthesis and characterization results indicate that hollow silica nanoparticles can be used to prepare advanced insulation materials, and that it is important to control both nanosphere dimensions and their packing density.

A life cycle assessment (LCA) of the PS-based process showed that alternative synthesis methods must be developed in order to use the material in zero emission buildings [2], where further work is being carried out.

5. Conclusions and outlook

Hollow nanospheres represent a promising candidate for thermal building insulation applications. Ongoing experiments aim at manufacturing hollow silica nanospheres with as low thermal conductivity as possible.

Acknowledgements

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Buildings (ZEB).

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A methodology for thermal performance testing of Vacuum Insulation Panel (VIP)

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Abstract:

Centre of panel thermal conductivity of Vacuum Insulation Panels (VIPs) comprises solid conductivity, gaseous conductivity and radiative conductivity. Lab testing of thermal performance is an essential part of the development of VIPs, however not much has been reported to date about developing a simplistic methodology to analyse and predict the thermal performance of VIPs. Methodology should be such as to minimise the number and simplifies the nature of tests required for testing, hence saving the precious resources spent on comprehensive testing procedures and sophisticated expensive equipment. In this paper, a sequential methodology to test each component of thermal conductivity of VIPs has been proposed and to demonstrate its effectiveness applied to silica based VIP. Prevalent test techniques and mathematical correlations to interpret the results were identified to measure the gaseous, radiative, solid and center of panel thermal conductivities of VIPs. Gaseous thermal conductivity and radiative conductivity using Mercury intrusion porosimetry and Fourier transform infrared techniques respectively were employed to confirm the validity of this approach. The results suggest that this methodology can allow rapid testing and would be a valuable tool to analyse the each component of thermal conductivity of VIPs with minimal testing involved.

Keywords:
Vacuum Insulation Panel, Center of Panel Thermal conductivity, Radiative conductivity, Mercury Intrusion Porosimetry (MIP), Fourier Transform Infrared (FT-IR)

1. Introduction

Thermal performance of VIPs is measured by measuring the center of panel thermal conductivity($\boldsymbol{\lambda_{cop}}$) of VIPs. To date testing of center panel thermal conductivity of VIPs is performed with expensive guarded hot plate or Heat flow meters [1] and [2]. These methods of testing are limited to measure overall center of panel thermal conductivity of VIPs and not able to measure the different components of $\boldsymbol{\lambda_{cop}}$. However, for optimization of thermal performance estimation of individual components of center of panel thermal conductivity $\boldsymbol{\lambda_{cop}}$ are required.

In this research work a sequential methodology based on heat transfer theory across VIPs was adopted to estimate the different components of $\boldsymbol{\lambda_{cop}}$ by measuring the simple characteristics of materials. Subsequently, an experimental study was carried out to validate the theoretical estimation of center of these components.

2. Theoretical

λ_{cop} of a VIP is a summation of the solid thermal conductivity (λ_S), radiative thermal conductivity (λ_R), gaseous conductivity (λ_G) as given in equation (1) [3]

$$\lambda_{cop} = \lambda_S + \lambda_R + \lambda_G + \lambda_{coup} \qquad (1)$$

Here λ_{coup} is the thermal conductivity for powder materials. Gaseous thermal conductivity at different vacuum levels can be estimated from the pore size data measured using Mercury Intrusion Porosimetry (MIP) by equation (2).

$$\lambda_{\text{G}} = \lambda_0/(1 + (0.032/\text{P}\Phi)) \qquad (2)$$

where (λ_0) is the thermal conductivity of air at atmospheric pressure ($\text{Wm}^{-1}\text{K}^{-1}$) at 25 °C, P is the pressure (Pa) and Φ is the pore width of the porous insulation material (m).MIP is based on the capillary law governing liquid penetration into small pores. This law in case of a non-wetting, non-reacting liquid like mercury and cylindrical pores, is expressed by Washburn equation (3)

$$D = -(4\gamma\cos\theta)/P \qquad (3)$$

where D is the pore diameter, P the applied pressure [Pa], γ the surface tension [Nm^{-1}] θ the contact angle

Sample percent porosity is then calculated from bulk volume and pore volume using the equation (4).

$$P\,\% = (V_{pore}/V_{Bulk}) \times 100 \qquad (4)$$

where $P\,\%$ percent porosity is, V_{pore} is volume of pores, V_{Bulk} is sample bulk volume

Opacifying properties was calculated using transmission spectrum obtained by Fourier Transform Infrared (FT-IR) (Perkin Elmer Spectrum One) and equation (5)

$$\lambda_R = (16n^2\sigma T^3)/(3E(T)) \tag{5}$$

where n is the refractive index, σ is the Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$), T is the medium local temperature (K), and E is the extinction coefficient (m^{-1}). The combined thermal conductivity, λ_C, the sum of λ_S and λ_{coup}, was calculated from λ_{cop} at 1 atm and λ_R and λ_G using equation (6)

$$\lambda_C = \lambda_{cop} - (\lambda_R + \lambda_G) \tag{6}$$

3. Experimental work

For experimental purpose fumed silica, expanded perlite, SiC (opacifier) and reinforcing polyester fiber composites were prepared and their porosity, pore size distribution, and densities were measured Using Micromeritics Autopore IV mercury porosimeter [4]. Gaseous thermal conductivity of samples was estimated from the pore size data obtained using MIP, radiative conductivity was measured using Fourier Transform Infrared (FT-IR) (Perkin Elmer Spectrum One) with KBr method. Core boards (100mm×100 mm × 15 mm) made of composite samples using Instron Universal Testing Machine were prepared at Brunel University Labs. Centre of panel thermal conductivity at a range of pressures was measured by using a small guarded hot plate device at Empa labs Switzerland. λ_C was calculated using equation (6).

4. Results and discussion

- The center of panel thermal conductivity with 30% expanded perlite content in the composite sample was measured as 0.0076 $Wm^{-1}K^{-1}$ at 0.5 mbar pressure and 0.028 $Wm^{-1}K^{-1}$ at a pressure of 1 atm as shown in Figure 1.
- Radiative conductivity was calculated to be 0.0011 $Wm^{-1}K^{-1}$ using measured data from FT-IR at 300K. Gaseous conductivity was calculated to be 1.25 × 10^{-5} $Wm^{-1}K^{-1}$ at 1 mbar pressure.
- The combined thermal conductivity, λ_C, was calculated to be 0.0196 $Wm^{-1}K^{-1}$ at a pressure of 1 atm.

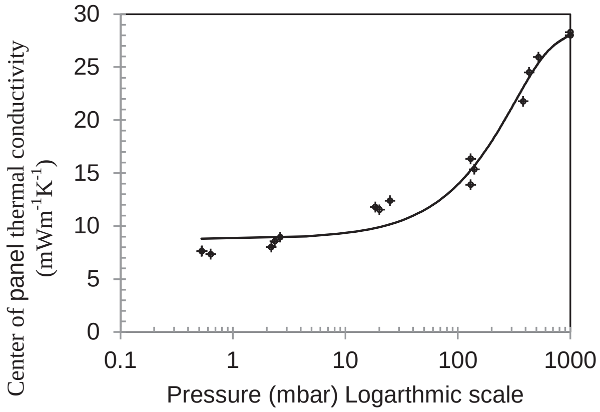

Fig 1 Measured center of panel thermal conductivity of composite samples

5. Conclusions

A methodology to estimate different components of λ_{cop} involving simple material properties tests has been presented and employed to evaluate the performance of a fumed silica-perlite mixture VIP core. The tests employed were MIP for pore size data measurement and FT- IR for Opacifying properties of silica based materials. Gaseous conductivity was calculated from MIP data and radiative conductivity from FT-IR. Radiative and gaseouse thermal conductivity values for the sample were 0.0011 $Wm^{-1}K^{-1}$ using measured data from FT-IR at 300K and 1.25 × 10^{-5} $Wm^{-1}K^{-1}$ at 1 mbar respectively. Measured values of λ_{cop} was used to estimate the combined thermal conductivity and was calculated to be 0.0196 $Wm^{-1}K^{-1}$ at a pressure of 1 atm.

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Thermal high performance walls made with precast concrete sandwich panels

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Abstract:
The scope of this research includes the development of load-bearing, thin, composite concrete facade elements having high performance thermal insulation. It applies to elements of factory-produced precast concrete and is optimized around five points in particular: construction, production, economic and environmental requirements, and flexibility in planning. A pilot project [1] of a detached house has been completed. This approach has garnered attention from the *Senatverwaltung für Stadtentwicklung und Umwelt* in Berlin which is planning an international construction exhibit in 2020 [2], the year for which the city has planned the building of 70'000 dwellings, i.e., 2,000,000 m^2 of opaque and insulated facade. In the context of a new construction method using VIP (vacuum insulated panel) insulation, we intend to refine our product in order to respond effectively to a request for mass-production in the future.

Keywords:
facade wall, precast concrete sandwich panel, wall with high performance thermal insulation, vacuum insulated panel (VIP), expanded polystyrene with graphite (EPS-graphite) insulation

1. Introduction

For a sustainable future, the concept of the *2000 Watt Society* relies on two key arguments: the depletion of fossil resources and occurrence of global warming. The issue at stake for the future of architecture is a real paradigm shift that will reduce our demand for energy and move towards the greater use of up-and-coming resources, such as renewable energies. For a building, this paradigm shift can be achieved by using heat traps [3]. This idea is to thermally insulate the building so that inevitable heat losses do not exceed heat gains coming from both inside and, above all, outside the building.

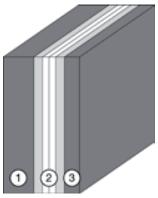

Fig. 1 : cross section of a precast concrete wall:

1. load-bearing strata
2. *composite insulation*
3. exterior covering strata

2. Requirements and justification

The walls that we developed include three distinct strata: a layer of load-bearing concrete, an intermediate layer (insulation), and a completion layer of concrete (exterior covering). The objective is to find a new construction method which takes into account the new thermal insulation requirements recommended as standards for the *2000 Watt Society*. The challenges to overcome are: a considerable volume of raw material, complications in handling, transport, and installation, as well as, a loss of useable space inside the building. At the level of planning, uncertainty about the nature and thickness of the facade wall and the type of insulation used is a drawback from the perspective of the use of space, as well as, of the construction, throughout the building process. The move towards a standardized insulation thickness simplifies the planning and production. On the basis of this first observation, we recommend a mixture of two insulations, a high performance one, such as the VIP, and a more traditional one, in order to meet the thermal performance standards of *Minergie-P*, an overall heat transfer coefficient (U value) of about 0.1 W/m^{2}K. Therefore, it is not simply a matter of substituting traditional insulation with high performance insulation, but creating, by mixing, an ideal *composite insulation* for any type of construction.

The choice of the *composite insulation* thickness is based on the following arguments:

- from a heat transfer point of view, the thicker the wall, the weaker the thermal bridges between *composite insulation* panels;
- from a construction point of view, the current principles of detail design (concrete window side jamb, concrete window sill, and shutter chamber), which guarantee the quality of the product, are preserved; and
- from a production point of view, the fundamentals of the manufacturing process are not questioned.

On the basis of these points argued above, we have shown that the optimal thickness for a *composite insulation* is 14 cm. This construction optimum should be considered during the preliminary drafting and planning stage and, then once chosen, can no longer change throughout the construction process.

3. Pilot project

On the basis of this choice for thickness, we carried out, in collaboration with the architectural firm Bassi-Carella, a pilot project for a detached house consisting of sandwich panels containing *composite insulation* (4 cm EPS-graphite / 2 × 3 cm VIP / 4 cm EPS-graphite). This project work has enabled us to concretely verify all together the planning phase, as well as, the manufacturing process.

Only two formats of *composite insulation* were used. For construction, 3 of these panels were stacked vertically and their height corresponded to one-third of that of a single story, 96 cm high. Their horizontal width of the *composite insulation* panels was 60 cm for the center part of the prefabricated concrete element and only 30 cm for its edges. This arrangement of the *composite insulation* is buried between two strata of concrete (load-bearing and exterior covering) and synthetic fiber connections provide stability to the ensemble without degrading the VIP panels. The 11 precast concrete parts weigh on average 9 tons and have a size of about 3 × 8 m. They were produced in 11 days and have been assembled in situ in two days.

4. Results and discussions

This project work demonstrated that a wall constructed from precast concrete with high performance thermal insulation is achievable without disrupting traditional production methods exploited in Switzerland. The optimal thermal and construction properties fall into the criteria set for a *2000 Watt Society*. The change to the more important specifications, e.g., urban buildings having greater than 1000 m^2 of opaque facade surface, obliges us to optimize also the important and implied parameters mentioned in the Berlin comparative analysis [4]: the cost of the product, its ecological impact, and its architectural flexibility.

- From an economic point of view, we seek a *composite insulation* with a thickness of 14 cm to obtain a U value of 0.1 W/m^2K at a reasonable price, knowing that the VIP proposed in catalogues is a material of higher quality and expense than necessary for the facade.
- From an ecological point of view, the Environmental Load Units (ELU) are still undecided, knowing that thin walls require a higher value due to the greater technological complexity which increases the ELU. In addition, recycling strategies in the VIP sector are still unknown.
- At the architectural level, the flexibility of the *composite insulation* format depends on two factors: height and width. For the height factor, one must be able to make the *composite insulation* elements in proportion to the project, according to a division of the story height in equal parts. For the width factor, on the other hand, one uses 15/30/60 cm modules which can meet the spatial requirements of office or housing types.

Therefore, it is important that the quality, price, as well as, the format, are suitable for an architecture of facades, a condition which presents additional requirements compared to the typical placement of VIP in floors or its use in cold rooms.

In a Swiss urban context and in some European cities, land prices are quite high and the integration of these types of *composite insulation* panels into building architecture is a realistic goal. We are looking for partners ready to develop this *composite insulation* in order to decrease its cost, lower its environmental impact, and increase its flexibility for use in facade design, all of which would make the use of these insulation panels more competitive and attractive for the mass production of housing and offices, as planned for the IBA Berlin 2020.

5. Conclusions and outlook

The use of sandwich panels with high-performance thermal insulation is feasible and now realistic without increasing costs for supporting technology, but it includes a more expensive *composite insulation*. The use of VIP in the facade will depend on the price and appropriate quality, a smaller ELU, and a flexibility which allows its adaption to a range of different formats usable for facades.

Acknowledgements

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In Situ Performance Assessment of a Composite Insulation System Consisting of Mineral Wool and Vacuum Insulation Panels

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Abstract:
In the present paper, heat flux, temperature and moisture monitoring data simultaneously obtained over a period of one year, at several locations of the envelope of a small scale (4x4x7m) demonstration house (situated in the NTUA premises) are presented and analyzed. Three walls of this house use conventional polystyrene insulation and the fourth north wall, a composite insulation system consisting of VIPs, mineral wool (mineral wool – VIP – mineral wool) and thermo-insulating render. The U-Value of the walls is theoretically and experimentally determined. The discussion focuses, via comparative assessment, on the key issues of thermal and hygrothermal performance of the examined walls that incorporate either EPS or a VIP composite assembly as an external thermal insulation system.

Keywords:
Vacuum insulation panels, Monitoring, Building envelope, Hygrothermal behavior

1. Introduction

Insulation of building envelope is a critical factor affecting the total energy consumption of a building. Conventional insulation materials have thermal conductivity values not less than ca. 0,03 W/mK. Vacuum Insulation Panels (VIPs) can have a thermal conductivity up to 10 times less than polystyrene boards. They can thus form a promising insulation solution, especially in cases of limited space.

Several experimental studies [1] have been carried out regarding the deterioration of VIP panels due to moisture accumulation and internal pressure increase. Also, thermal bridges occurring at the connection line of the panels on a wall assembly are well known to increase the effective thermal conductivity [2].
In this study the thermal performance of a wall insulated with VIP panels is assessed and compared to the same wall configuration insulated with EPS. At the same time, the two critical factors that affect the service life of VIP panels, temperature and relative humidity inside the wall assembly (surrounding the VIP panels), are measured continuously for several months.

2. Test site, construction and materials

The test site is located inside the campus of the National Technical University of Athens. It is a demonstration two-storey, dry-wall construction house. The envelope is based on a cavity wall system with external insulation. The construction methodology follows the same rules applied to real scale houses of this type.
The envelope of the house was initially insulated with EPS panels. After two years of monitoring, the insulation of the north wall of the house was replaced with a composite panel consisting of mineral wool (λ=0.045 W/m•K) and VIP finished with insulating render (λ=0.065 W/m•K) (Figure 1).

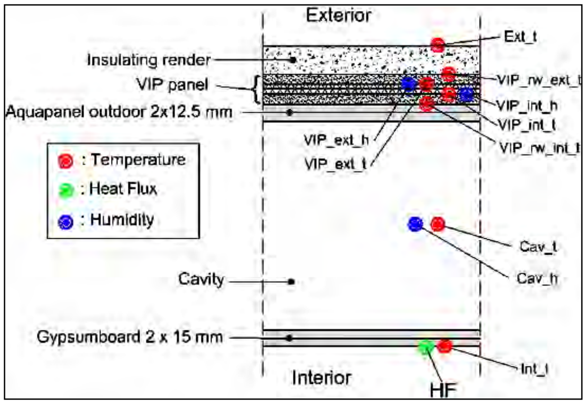

Fig 1: Measuring locations shown at a section of the north wall.

3. Theoretical calculations and experimental methodology/equipment

The thermal conductivity of the materials used for the construction of the walls has been measured with a guarded hot plate apparatus. The apparent density was measured according to the ISO standards and the specific heat capacity was either measured by DSC or provided from tables. The R-value was theoretically calculated according to ISO 6946 standard. The effective thermal conductivity of the VIPs (taking into account thermal bridges at the joints) was estimated with the procedure described by Ghazi Wakili et al [2].
For the in–situ measurement of the thermal resistance a dedicated device was used (Hukseflux, model

TRSYS01) and the dynamic method described in ISO 9869.

For the monitoring of the overall hygrothermal performance, a data acquisition system was used. Temperature, humidity and heat flux values were collected at several locations on the envelope.

4. Results and discussion

Table 1 presents the theoretical and experimental R-values for the two walls (EPS and VIP insulation).

	Thickness [mm]	Theoretical R-value [$m^2 \cdot K/W$]	Experimental R-value [$m^2 \cdot K/W$]
EPS Wall	300	1.695	1.786
VIP Wall	382	5.263	3.846

Table 1: Theoretical and experimental R-values

The thickness of the insulation layer of the VIP and EPS walls is 110mm and 50mm, respectively. The achieved overall improvement of the thermal resistance of the wall is approximately 115%, which is less than the initially expected theoretical value (ca. 210%). This can be attributed to the construction irregularities and quality of workmanship that appear to introduce significant thermal bridges. Also, based on detailed 3D modeling (ANSYS CFX) of the behavior of the cavity - not presented here - it can be suggested that the convection effect inside the wall cavity may be underestimated in the R-value calculations.

Temperature and relative humidity at the two surfaces of the VIPs are continuously monitored, since the construction of the wall at the north side of the model. Focusing on the most important findings of the monitoring results(figures 2,3), it is observed that high relative humidity values and presence of water occur during the first weeks after installation due to the initial moisture of the adhesive mortar. The elevated summer temperatures accelerate the drying of the wall. During winter months, the wall of the upper floor shows higher RH values and prolonged periods of saturated vapor presence. Introduction of heating system in the ground floor reduces the humidity level and eliminates the condensation at the internal surface of the panels.

5. Conclusions and outlook

The extensive monitoring of the hygrothermal behavior of VIP insulated envelope revealed the degree of thermal performance improvement as well as the risk of water vapor condensation inside the wall. The presence of high humidity values and liquid water on the VIP surfaces for prolonged periods can drastically reduce the service life of the panels.

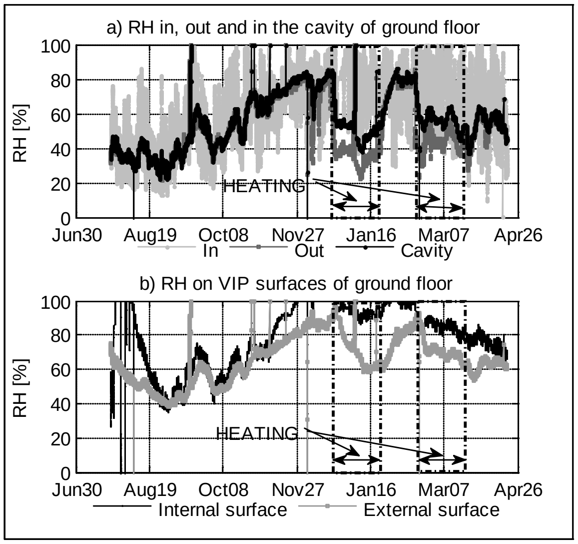

Fig 2: Measurements of Relative Humidity of the ground floor.

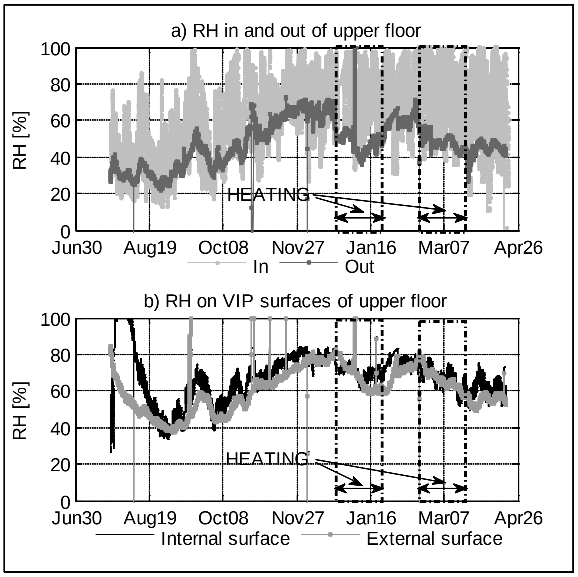

Fig 3: Measurements of Relative Humidity of the upper floor.

Acknowledgements

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In-Situ Performance of Residential Wood-Frame Construction Retrofitted Using VIPs

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Abstract: The National Research Council of Canada's Construction (NRC-Construction) investigated the energy strategies to retrofit conventional wall assemblies with a new generation of insulation made of Vacuum Insulated Panels (VIPs). The objective of this work was to develop recommended construction specifications and guidelines for assembling next generation building envelope systems with the ultimate goal of encouraging their use in building practices. Tests to assess the thermal performance and energy usage of wall assemblies incorporating VIPs were performed in NRC-Construction's Field Exposure of Walls test Facility (FEWF). These performance assessment tests were conducted for one year over which period the wall assemblies were exposed to outdoor natural weathering conditions. The intent of the performance assessment exercise was to examine exterior retrofit options and compare these to a standard retrofit method.

Keywords:
Vacuum insulation panels, Modelling, Wood construction, retrofit, residential

1. Introduction

To achieve high levels of energy performance with existing wall systems and materials, the wall systems would need to be considerably thicker and this may be less acceptable to consumers because of the loss of usable floor area, greater weight, increase in costs due to transportation, and time of construction, as well as new challenges for the structure associated with greatly increased wall thickness. To maintain reasonable envelope thickness while having high thermal performance, a promising recent innovation in building technology was investigated within the context of its application using Vacuum Insulation Panel (VIP) systems. VIPs are of interest owing to their exceptional insulating R-value, up to R-60 per inch or even higher. The VIP technology can be used in new construction as well for retrofitting existing homes [1].

2. Objectives

The main objectives were to: (1) develop recommended construction specifications and guidelines for assembling VIP walls; (2) encourage their use in building practice, and; (3) assess their thermal and energy performance.

3. Retrofitted Wall description

Tests to assess the thermal performance and energy usage of wall assemblies incorporating VIPs were performed in the FEWF. Three side-by-side 2 x 6 wood-frame wall assemblies (4 ft x 6 ft), two of which incorporated VIPs within either an XPS Tongue and Groove (T&G) configuration or VIPs within an XPS Clip-On (C-O) configuration, and a third assembly incorporating only XPS. These performance assessment tests were conducted for one year over which period the wall assemblies were exposed to outdoor natural weathering conditions (i.e. May 2011 to May 2012). The intent of the performance assessment exercise was to examine exterior retrofit options and compare these to a standard retrofit method. The backup wall for all three retrofit strategies consisted of interior drywall (1/2 inch thick), polyethylene air barrier (6 mil thick), 2 x 6 wood-frame having friction-fit glass fibre batt insulation installed between vertical studs, OSB (7/16 inch thick), and Tyvek sheathing membrane (Figure 1). The backup wall was retrofitted by adding different configurations of external insulation. The first wall (W1) was retrofitted by adding an XPS layer (2 inch thick) between the sheathing membrane and vinyl siding. The other two walls were retrofitted with Vacuum Insulation Panels (VIPs) using two concepts as described below. In the second retrofit concept (W3), each VIP having a nominal thickness of 15 mm (5 panels in total), was sandwiched between two XPS boards, the exterior board being 1 inch thick and the interior board 5/8 inch thick (Figure 1). To protect the VIP, a hollow piece of XPS of the same thickness as the VIP was cut and the VIP panel was placed inside the opening such that the VIP would be protected by the XPS surround.

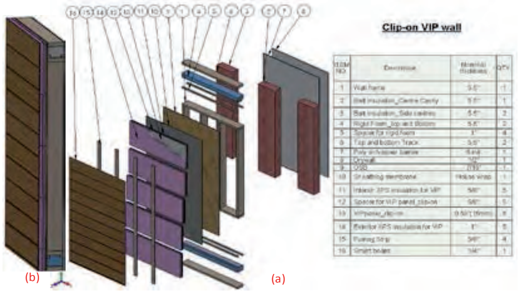

Figure 1 - Schematic of XPS retrofit wall assembly (W2)

In the second retrofit concept (W2) five VIP sandwiches were assembled using clips; hence, the retrofitted wall specimen was called "Clip-On" (C-O) VIP. Vertical furring strips (16 inch o.c. and 5/8 inch thick) were attached to metal clips, which supported the C-O VIP assembly and provided the nailing surface to which the smart board was attached.

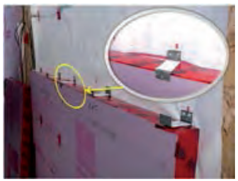

Figure 2 - Installation of VIP panel with Clip-on concept (W2) – S-shape clips.

Figure 3 - Installation of VIP Panel (W3) with T&G Concept

The assembly (W3), consisting of the VIP and XPS surround, was placed between the exterior and interior XPS layers to form a "Tongue and Groove (T&G)" VIP "sandwich" [2].

4. Results and discussions

Figure 4 and Figure 5 show temperature profiles of exterior surface of the sheathing board of the different walls, respectively W1, W2 and W3. Figure 5 shows the temperature difference over time across the added insulation (XPS and VIP panels) of the different wall assemblies W1, W2 and W3.

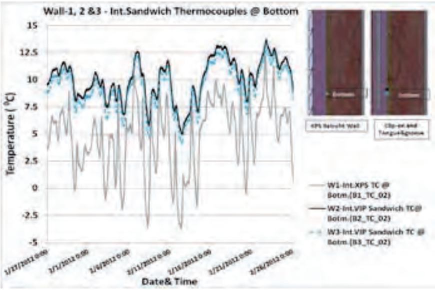

Figure 4 - Temperature profile of each layer of wall the three retrofitted walls W1, W2 and W3

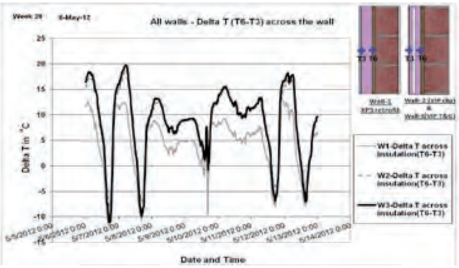

Figure 5 - Temperature gradient through the added insulation of wall W1, W2 and W3

Figure 6 shows the heat flux measurement of the three wall assemblies. The comparison between those walls assemblies were done at the interior face of the added insulation using heat flux transducer #2. The comparison shows that walls W2 and W3 are similar in terms of heat flux across the VIP panel and the interior surface of the VIP panel is less sensitive to changes in exterior climatic conditions. The heat flux across W1 has a greater number of fluctuations as compared to those determined for W2 and W3; this is not surprising given that W1 had the least thermal resistance of the three walls under evaluation. This was due to the thermal resistance of the wall systems and the additional exterior insulation. In Figure 6 is shown the apparent shift in response of W2 and W3. This delay in response was due to the overall thermal mass and thermal resistance of the respective wall systems.

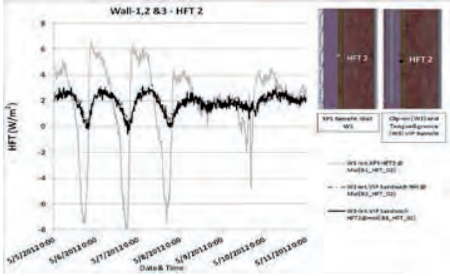

Figure 6 - W1, W2 and W3 Heat fluxes

5. Conclusions

The main objective of this study was to assess the overall thermal performance of side-by-side retrofitted wall assemblies. These walls were retrofitted by adding insulation on the exterior of the sheathing board. The interior surface temperatures of the VIP at the interface with the sheathing board (W2 and W3) are warmer than W1; this will decrease the risk of condensation on the sheathing board (OSB), since the surface temperatures of the OSB are above the dewpoint. One of the objectives of this project was to investigate the degree of difficulties in practice in using a pre-fabricated insulation sandwich panel with VIP insulation as compared to the traditional method of retrofit. Two concepts of installation for retrofit were assessed in this study (W2 and W3) having the same nominal thermal resistance of the added insulation. The comparison in terms of energy performance of wall assemblies W2 and W3shows that the two walls, one using Clip-on (W2) and the other Tongue & Groove (W3) concept, have close thermal performance with W2 having an additional degree of thermal resistance of R ~2; this was due to the effect of air space between the insulation and the exterior cladding [3]. The thermal gradients across W2 and W3 that included the thermal insulation in the stud cavity were very similar. Not surprisingly, the thermal gradients were different from W1, given that W1 did not include VIP exterior insulation but only rigid insulation XPS. The experimental data helped benchmark the model hygIRC-C as described in reference [4].

Acknowledgements

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Permeation of water vapor through high performance laminates for VIP

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Abstract:
The question of maintaining the long term performance of VIP has been and continues to be the focus of many technical and scientific investigations. The performance of the barrier foil is of course decisive, especially its capability of maintaining the vacuum level as well as its resistance to the permeation of water vapor. This presentation presents an overview of the methods used for the determination of the permeance of the barrier films as well as of the finished VIP. The test results obtained on a selection of commercially available products through the different methods are reviewed and the relevance of these methods for characterizing the performance of finished VIP discussed.

Keywords:
Vacuum insulation panels, Barrier films, Permeability, Permeance

1. Introduction

Regarding the long term performance of VIP the expectations of the end-users and the manufacturers of the panels remain very similar. These two players need to have methods at their disposal to evaluate the performance of the barrier films already used or for a future use in order to obtain a clear idea of the technical value of the barrier films proposed by various manufacturers.

There exist various techniques, either direct measurements on the barrier foils or an indirect measurement on VIP. The former methods are applied to the components of the multilayered films as well as to the complete multi-layer structure in order to separate the influence of the metallization from the laminating operation.

2. Barrier films

For the evaluation of barrier films - either on the individual single layer or on the multilayer structure - several methods can be applied. These include the manometric method, the cup method and the use of tritiated water.

In the first method - described in the ASTM D-1434 and ISO 15105-1 norms - an initial pressure difference between the two sides of the material to be evaluated is established and the increase of the total pressure downstream in time upon the influx of water vapor in the upstream chamber of the equipment is monitored (Fig. 1).
Measurements can be carried out as a function of temperature and relative humidity; degassing of the samples before the measurement is also an option.

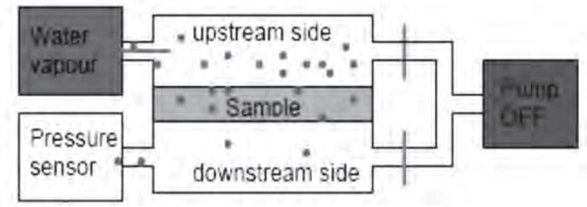

Fig.1 Principle of the manometric measurement technique

The permeance of the material (in kg/(m².s.Pa)) can be obtained from the following equation :

$$\Pi = j / \Delta P \qquad (Eq.1)$$

where

Π = permeance
j = flux density
ΔP = partial pressure difference

and where the flux density can be determined once the measurement has reached a steady state.

Another approach to measure the permeance of films concerns the so-called cup method - referred to in the ISO 12572 and 2528, and ASTM E 96M-05 norms - in which the amount of water vapor absorbed or evaporated by a saline solution in the interior of the cup is monitored. This way the quantity of water vapor going through the film sample can easily be defined through the measurement of the weight change. Once the steady state has been reached during the measurement, the slope of the curve indicating the weight increase as a function of time represents the flux density and therefore the permeance can also be easily determined with Eq.1.

A third method implies the use of radioactive tracer, namely tritiated water. In order to quantify the flux through the sample a very small part of the water molecules on one side of the film are marked through the addition of tritium thereby not fundamentally changing the permeating behavior of the fluid. In a two-chamber experimental set-up the concentration of tritiated water molecules is measured after their passage through the film sample. As in the previous techniques the slope of the curve representing concentration changes as a function of time leads to the calculation of the flux, and thus of the permeance.

3. Vacuum insulation panels

The barrier performance of the film covering the core of a VIP can also be examined through an indirect measurement on the insulation material itself. For this purpose the VIP are aged in an environmental chamber at selected temperature and relative humidity conditions, e.g. at 50 °C or 70 °C at 90 % RH, and the weight gain due to the water vapor uptake recorded at regular intervals. A set of experimental data is graphically represented in Fig. 2.

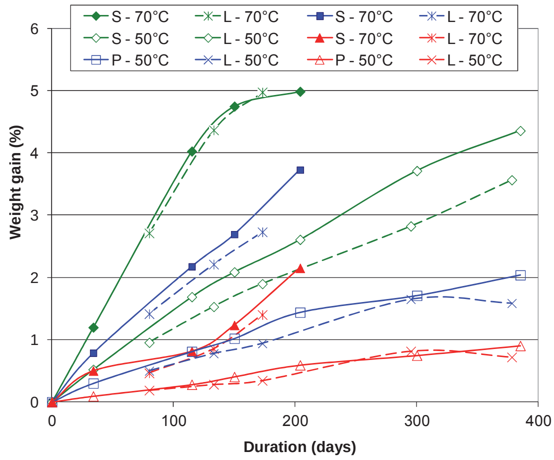

Fig.2 Aging data of 3 references at varying T at 90 % RH; weight gain as a function of duration and sample size (L 0.25 m^2 and S 0.04 m^2)

As in the previous techniques the flux through the surface of the VIP can be determined and thus the permeance of the barrier film, but this time as a component of a finished VIP.

4. Results and discussions

In Table 1 the results of the measurement of the permeance of commercially available barrier films - as such and in a VIP - are summarized. For sample A the results between the cup method and the one based on tritiated water generally seem to be in good agreement.

However the cup method falls short of the required accuracy limit. On the other hand the agreement between the manometric method and the results obtained on VIP appear very satisfactory. It should be noted that the permeance values measured on VIP often exceed the values obtained via the manometric method due to possible damage incurred during the manufacture of the VIP and water vapour influx through the seals. This explains that the indirect measurement on VIP constitutes our reference approach today.

Table 1: Permeance of commercially available barrier films.

	Deltaperm			Tritiated Water / Cup			VIP		
	T (°C)	HR	Π (kg/(m².s.Pa))	T (°C)	HR	Π (kg/(m².s.Pa))	T (°C)	HR	Π (kg/(m².s.Pa))
A	25	0.4	1.5E-14	23	0.6	3.3E-13			
	40	0.4	2.6E-14						
	50	0.9	3.5E-14	25	0.9	1.8E-13	50	0.9	3.8E-14
	70	0.9	4.3E-14				70	0.9	5.4E-14
B				23	0.6	3.3E-14	50	0.9	1.1E-13
							70	0.9	1.2E-13

Regarding the relevance of the individual methods w.r.t. the evaluation of barrier films one can conclude that the manometric method reproduces the best the loading conditions to which the barrier film is being subjected. Furthermore the temperature can easily be adjusted. The same holds true for the cup method, although this technique appears less suitable in light of the superior barrier performance of these films, i.e. very low values of the permeance. The temperature range which can be covered by the cup method and the approach based on tritiated water also remains more limited. In addition the latter method is much more difficult to implement.

5. Conclusions and outlook

The suitability of different measurement techniques aimed at determining the permeance of barrier films as such as well as converted into a VIP has been examined. For the characterization of barrier films the manometric appears to be the most useful and reliable approach as it duplicates the best the real exposure conditions. The good correlation with the current reference method on VIP forms an incentive to further optimize this manometric technique.

Acknowledgements

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Accurate Prediction of the Lifetime Performance of VIPs: Challenges and Working Solutions

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Abstract:

It is generally accepted that the permeation rates of atmospheric gases do not change during the service life of vacuum panels(1). This allows the accurate prediction of the internal pressure at any time along the lifetime of the panel, assuming the long term permeation rate can be determined correctly within the first few weeks of the panel's lifetime. In principle this goal can be achieved by connecting a high resolution pressure gauge to the envelope of the panels. Even then very wrong conclusions concerning the permeation rate can be made due to the transient processes of desorption (outgassing) and adsorption, processes that may cause faster pressure changes than those caused by the permeation processes. Recently Hanita Coatings developed a new permeation measuring unit devoted to solving the problem of lifetime prediction. The mVIP system contains a metallic plate as core for volume reduction, and an easy-to-install vacuum-tight connector that also allows the use of a residual gas analyzer (RGA) for precise assessment of the gas content, and enables high resolution Helium leak testing to ensure absolutely no micro-leaks. The article describes the results of a comprehensive investigation of the transient processes inside the panels using 7 mVIP systems. Recommendations were made on how to achieve reliable prediction of the lifetime performance of VIPs.

Keywords:

Vacuum insulation panels, mVIP, RGA, outgassing, permeation, steady state

Introduction

The best way to predict the insulation performance of VIPs along their service life is to measure the permeation rate of the air molecules, and to use this data to calculate the thermal conductivity of the panels along their service life. In effect, this is very hard to do, because the permeation rates of the nitrogen and oxygen molecules (GTR) are too slow to be measured by any standard means. To overcome this problem the VIP industry has been forced to rely mainly on accelerated thermal conductivity measurements for calculating the permeation rates. In most cases, these tests are made at temperatures much higher than the application temperature. These accelerated tests can take several weeks or even several months. But even more importantly, because they are carried out at high temperatures, it is almost impossible to use their results to accurately predict the rate of change in thermal conductivity along the real service life, because of the large temperature difference.

More than a decade ago, several groups(2) showed that by connecting sensitive pressure gauges to the envelope of the panels, it was possible to measure the tiny pressure changes inside the panels very accurately in a relatively very short time. However this promising technique was abandoned because the sample preparation process was very complicated, and not reliable enough, due to the use of epoxy adhesives to vacuum-tightly connect the pressure gauges to the VIP envelopes. Over the last two years Hanita has developed in-house a new type of vacuum-tight connector based on a double O-ring technique that allows very easy sample preparation in just a few minutes. The high resolution of the pressure measurement enables measuring the permeation rates very accurately at any temperature, and using the measured permeation rate for accurate calculation of the panel performance along its service life.

A photograph of one of the 7 new mVIP systems is shown in Fig.1 below.

Fig 1: A photograph of an mVIP system connected to the envelope of a 25cmX25cm VIP. The system contains Spinning Rotor Gauge (SRG) for measuring the internal pressure, as well as extra an opening for VIP evacuation, He leak checking and RGA measurements.

Sample Preparation Procedure

A schematic diagram of the mVIP system is shown in Fig 2. An Al plate is placed inside the bag, followed by sealing of the fourth edge of the bag. The Al plate serves as a replacement for the standard porous core material. Through a circular hole in the bag, the stainless steel connector equipped with a double O-ring system is tightened against the envelope using the Al plate as a rigid mechanical support. An SRG pressure gauge is connected to one arm of the connector, while the 2nd arm is used to evacuate the system to the required initial pressure as well as to perform He leak checking to ensure there are absolutely no leaks from the seals. The entire system is then placed in a controlled atmosphere chamber (temperature, RH, gas type). This way the permeation rate of air or just O_2 or N_2 can be measured extremely accurately at any needed temperature.

After inventing the mVIP system, we found that the double O-ring connector can work perfectly well with fiberglass core material too. This allows simultaneous measurement on the same panel of the pressure increase due to permeation, and the thermal conductivity. The idea is very simple. A rectangular 30cmX60cm fiberglass panel is produced with the double-O-ring connector mounted on one half, and the second half of the panel is used for simultaneously measuring the thermal conductivity by a standard hot plate device.

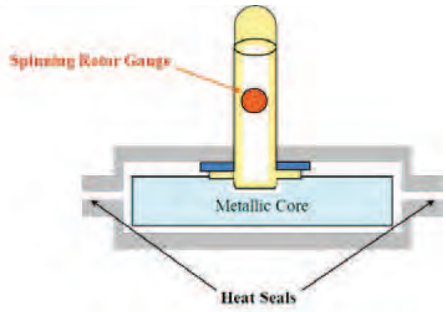

Fig. 2: A schematic diagram of an SRG pressure gauge connected to the envelope of a panel with a metallic plate as core material.

The RGA (Residual Gas Analyzer) Analysis

RGA systems measure the relative concentration of the different species of gas molecules contained in a tested space according to the molecular weight. This mass spectroscopy procedure is performed using the quadrupole technique. The system sucks gas molecules from the tested space and measures the partial pressure of the gas types in the sucked sample. Accordingly, the RGA system does not tell the absolute partial pressures inside the tested volume, but rather provides very accurate measurements of their relative concentrations in the tested volume. By connecting an RGA system to the second outlet of the double O-ring connector, the relative concentration of any gas species can be measured up to a molecular weight of 200 amu at any point along the testing period of time of a VIP. This gives a very clear insight of what occurs inside the panels in terms of outgassing of water molecules or organic molecules. The RGA system can also provide accurate information on the change in the absolute number of molecules of the different gas species along any testing period of time. For that the accurate measurement of the change in the overall pressure ΔP inside the panel by the SRG pressure should be taken into account.

A typical RGA analysis is shown Fig 3 below. A fiberglass panel with metallized film envelope and CaO desiccant was analyzed immediately after a one-hour long evacuation procedure. The predominant gases inside the panel were oxygen and nitrogen (amu 28 and 32 respectively). The amount of water molecules was substantially reduced by the desiccant. It is very important to note that amount of organic molecules outgassed from the envelope was extremely low.

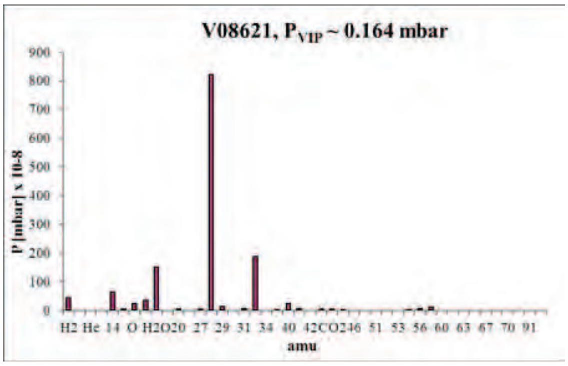

Fig.3: RGA analysis of a fiberglass panel with CaO desiccant immediately after a one-hour long evacuation process. The X axis is the molecular weight of the gas species and the Y axis is the partial pressure of the different gas species in the sample mixture sucked from the inner volume of the panel.

Pressure Measurement – Preliminary Results

Typical results of the mVIP/SRG systems are shown in Fig.4 and Fig.5 where the internal pressure inside two mVIPs panels with two different envelopes and somewhat different experimental set ups was measured. The panels were kept at temperature of 22^{0}C and 30% RH. The slope of the curves in both graphs represents the pressure change inside the panels in one hour in mbars. It can be seen in Fig.4 that the resolution limit of the system is about 10^{-5}mbar/hour, which is equivalent to an annual pressure increase inside the panels of less than 0.1mbar. Fig.4 shows the pressure readings of the SRG pressure gauge when a newly developed metallized bi-laminate was used with metallic core and no desiccant. The fast pressure increase in the first 3 to 4 hours after evacuation can be explained by the quick release of water molecules from the LDPE seal film until some equilibrium conditions are reached. After that, the pressure increase slows down significantly to a level which is very hard to explain when a metallized envelope is used without desiccator. It seems that the PE seal film that was dried out in the long 10 hour evacuation process acted like a very efficient desiccator.

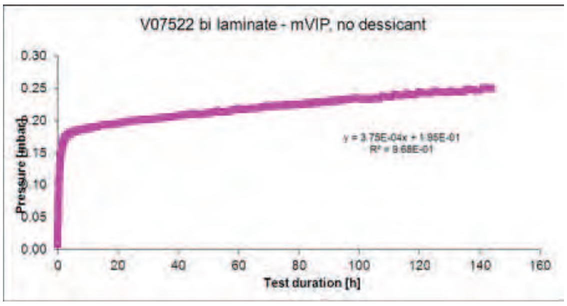

Fig.4 Pressure Vs. Time inside an mVIP. The envelope used was a newly developed metallized bi-laminate. No desiccant used. T=220C, 30% RH

Fig.5 describes a somewhat different setup where 1mm thick fiberglass cloth was inserted between the envelope and the metallic core in order to separate the envelope from the metal plate, and allow a free permeation process and faster pressure equilibration. In this case, Al-foil based laminate was used without desiccant. Comparing Fig.4 and Fig.5, one can see very clearly the huge effect of adding a porous material with a very large surface area into the evacuated space. It can be seen that due to some outgassing, the pressure increase rate was about 10 times faster than in Fig.4. 65 hours after evacuation, the system was still very far from steady state conditions where the pressure increase rate is influenced only by the skin and the side permeation through the envelope only.

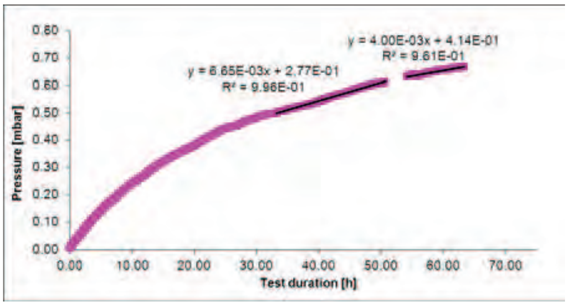

Fig. 5 Pressure Vs Time (hours) inside an mVIP with thin fiberglass cloth for separating the envelope from the metal core material. V08311P Al foil based laminate. No desiccant used. T=22^{0}C, 30% RH

Conclusions and Outlook

- The mVIP system was proven to be a very powerful and reliable tool for measuring the pressure inside the evacuated space of panels
- The detection limit of the mVIP system is about 10^{-5}mbar/hour or 0.1mbar/year. This enables determination of the permeation rate into panels even at low temperatures, and when Al foil laminates are used **assuming steady state conditions have been reached**
- Adding RGA analysis to the SRG pressure measurements can be very helpful in understanding the absorption and desorption processes inside panels before they reach steady state conditions.
- More work with the mVIP/SRD and RGA systems has to be done in order to understand how long it takes for the panels to reach steady state conditions. Once this has been determined, the mVIP would become an excellent technology for calculating the longevity of any type of VIP in any type of application.

Acknowledgements

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Physical characterization of sorption and diffusion of water vapor through ultra barrier for VIP

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Abstract:
The barrier property of the multilayer film against water vapor is a key factor of the durability performance of Vacuum Insulation Panels (VIPs). It is characterized by the permeance of the multilayer film. The model commonly used for the membrane permeance defines it as the product of the solubility coefficient and the diffusion coefficient, divided by the thickness, assuming the validity of Henry's law. To check this hypothesis, an experimental campaign was carried out to establish the sorption isotherms of multilayer films for VIP, but also on single layer films (films to be metalized and sealed). The dependence of the solubility coefficient on the temperature and the humidity was also investigated. In parallel, the diffusion coefficient was estimated indirectly.

Keywords:
Vacuum insulation panels (VIPs), Water vapor, Permeance, Solubility, Diffusion

1. Introduction

The model commonly used for gaseous transfer in a membrane is the solution-diffusion (SD) model, considering adsorption and dissolution on the top side, then diffusion through the membrane, and desorption on the bottom side. It is a linear model of mass transfer established for the polymeric homogeneous membranes. Fick's law is used for the diffusion in the membrane and Henry's law for the solubility.

The permeance in a polymeric membrane is defined as the product of the diffusion coefficient (*D*) and the solubility coefficient (*s*), divided by the thickness (*e*):

$$\Pi = \frac{D.s}{e} \quad (\text{kg.m}^{2}.\text{s}^{-1}.\text{Pa}^{-1}). \qquad \text{(Eq. 1)}$$

For a multilayer film (made from both metalized polymer and sealing layers), the previous equation was extended replacing *D* and *s* by the equivalent diffusion and solubility coefficients, and a stacking model was used (verified by measurements) [1, 2]:

$$\Pi = \frac{1}{\sum_{i=1}^{n} \frac{1}{\Pi_i}} = \frac{1}{\sum_{i=1}^{n} \left(\frac{e_i}{D_i . s_i} \right)} \qquad \text{(Eq. 2)}$$

where

Π_i = permeance of each layer
e_i = thickness of each layer
D_i = diffusion coefficient of each layer
s_i = solubility coefficient of each layer

The solubility is a volume parameter, thus it can be extended to a coated membrane. The diffusion coefficient of the metalized polymer layers is the equivalent diffusion coefficient, controlled by the aluminum layer (barrier function against gas transfer).

The aim of this paper is dual:

- first to check the validity of Henry's law;
- then to determine the influence of temperature and relative humidity (RH) on the solubility and on the diffusion coefficients, and to obtain some quantitative data for polymer - aluminum multilayer films to be used in models (D_0, s_0, Q_D, Q_S).

2. Experimental

Samples

Simple films (PET / sealing polymers) and multilayer films, whose typical architecture is composed of 2 or 3 metalized aluminum layers (often on 12 µm thick PET) and one sealing layer (> 50 µm), were studied.

Methods

The permeance of the films was measured by two methods: a direct measurement on foils by manometric method (*Technolox*, Deltaperm tester) and an indirect one on VIP by weight increase measurement. The solubility coefficients were determined from water vapor sorption isotherms (*Bel Japan*, Belsorp Aqua). The diffusion coefficients were indirectly determined from permeance and solubility measurements, and by dynamic water vapor sorption measurements (*Hiden Isochema*, IGAsorp DVS).

3. Results and discussion

Water vapor sorption

Influence of relative humidity

For the tested PET films, the sorption isotherms follow Henry's law in the tested RH range (C = f(p) is linear up to 82% RH). For the sealing and the multilayer films, there is however a deviation from Henry's law above 50 - 55% RH. This mismatch on multilayer films can be explained by the one observed on the polyolefins.

This influence of RH on the solubility has to be moderated by an assessment of the humidity that is seen by the different layers for a typical multilayer. As shown in Fig. 1, calculated with real material properties at 50°C and 90% RH, only the external PET layer is exposed to RH above 50%. So the sealing layer never sees such a high RH in a VIP.

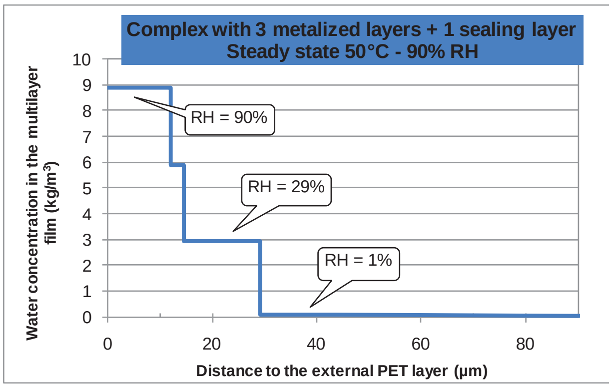

Figure 1: assessment of the relative humidity in the different layers of a multilayer film

The solubility coefficients measured at 25°C are given in Table 1. The solubility coefficients of the tested PET are similar, more than ten times higher than the one of the sealing layers. The same PET film, metalized or not, has the same solubility coefficient, indicating no influence of the metallic layer, but also no influence of the metallization on the polymer crystallinity. The significant difference between the sealing layers has a limited influence on the solubility of the multilayer (law of mixtures).
For a multilayer film, the solubility coefficient was calculated from the coefficients of the constituting layers by a law of mixtures: it was very close to the value obtained from the sorption isotherm of the multilayer film.

Table 1: Solubility coefficient for different films at 25°C

		s (10^{-4} kg.m^{-3}.Pa^{-1})	HR validity interval
PET (met. or not)		around 25	< 82%
Sealing layer	PE	1,5	< 55%
	PP	1	< 55%
Multilayer		5 - 10	< 55 or 75%

Influence of temperature
The solubility coefficient depends on temperature according to an Arrhenius' law [3, 4]:

$$s\,(T) = s_0 . e^{-\frac{Q_s}{RT}} \qquad \text{(Eq. 3)}$$

where
s_0 = limit value of the solubility coefficient for an infinite molecular agitation (T → ∞)
Q_s = apparent heat of solution
R = universal gas constant (8,314 J.mol^{-1}.K^{-1})

For simple films (PET and sealing), Q_s and s_0 were determined from experimental results between 25 and 70°C (Table 2). As Q_s is negative, a decrease in the solubility is observed with an increasing temperature.

Table 2: determination of s_0 and Q_s for simple films

	s_0 (kg.m^{-3}.Pa^{-1})	Q_S (kJ.mol^{-1})
PET1 (met.)	7.10^{-9}	-32
PET2 (met.)	1.10^{-9}	-36
PET2 (without Al)	1.10^{-9}	-36
Sealing layer (PE)	4.10^{-8}	-20
Sealing layer (PP)	2.10^{-6}	-9

Water vapor diffusion

Influence of relative humidity
No influence of relative humidity was shown. Direct measurements are necessary to confirm this point.

Influence of temperature
For 4 multilayer films, the diffusion coefficient was deduced from permeance measurements and sorption isotherms (Eq. 1). D_0 and Q_D (activation energy) were determined from the experimental results on multilayer films at different temperatures (23 to 70°C). The same activation energy for the diffusion process was found: 54 kJ.mol^{-1}.

4. Conclusions and outlook

In this study, the solubility coefficient was determined for PET and sealing films, and also for a multilayer film. The law of mixtures allowed to estimate the multilayer solubility, in good agreement with the measurements. As for the PET the sorption isotherm is linear up to high RH, this is not the case for the sealing layers, and as a consequence for the multilayer films. But this deviation does not impact the multilayer films used as VIP envelope because only the external PET layer is exposed to high RH. Some quantitative data of solubility and diffusion coefficients and of their activation energies are given for multilayer films, but they have to be consolidated, particularly concerning diffusion.

Acknowledgements

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Degradations of barrier multilayer films exposed to high temperature and/ or humidity

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Abstract:
The effect of hydrothermal ageing at 70 °C, 90 % RH on metallized polyethylene terephthalate (PET) was investigated using complementary techniques at different scales. The physical properties of both components are largely altered over time in the aggressive environment. Within the polymer, an increase in the ability to crystallize was attributed to the reduction of molecular weight by chain scissions. The thin aluminium layer was in most cases strongly degraded by oxidation. The influence of aluminium thickness and treatments applied to PET substrate will be described. The paper also furnishes the time dependence of structural changes together with some degradation mechanism.

Keywords:
Vacuum insulation panel (VIP), Polymer/metal, Multiscale analysis; Hygrothermal ageing; Durabilty.

1. Introduction

The service life of a VIP is mainly governed by the maximum tolerable gas pressure within the core. The latter should remain below 100 mbar, even after 30–50 years [1]. Gas and water permeation through the envelope increases the internal pressure and degrades the thermal insulation of the SiO2 [2].
The ageing of the envelope components alters the PET (polyethylene terephthalate) through chain scission and depolymerization mechanisms [3]: The degradation of the polymer substrate may induce severe alteration of the composite and even a decohesion with the metallic component and thereby the loss of the barrier effectiveness. As a result, a comprehensive knowledge of the changes in physical properties of all the components after ageing is required for the application. The purpose of this paper is to contribute to the understanding of the effect of hygrothermal ageing on aluminized PET thanks to a multiscale analysis of the different steps of the damage process. This study thus concerns the structural changes within the polymer substrate as well as the effects induced on the mechanical and barrier properties.

2. Experimental

Materials used in this study were obtained from Rexor company. The model films are bimaterials layers of PET covered with one or two aluminium layers of different thicknesses by Physical Vapour Deposition (PVD). The interface properties between polymer and aluminium coatings are expected to alter the final properties [4]. To improve the adhesion between polymer and metallic layers, some surfaces were treated before the deposition of the metallic coating either by "chemical treatment" with an acrylic coating (thin layer of 0.3 µm) or with a corona treatment resulting in a chemically activated surface more likely to provide good adhesion to the metallic layer.

The films were aged up to six months in a climatic chamber regulated at 70°C and 90%RH.

The characterization consisted of recording thermograms with a DSC 7 (Perkin Elmer) from 20 to 275 °C @ 10 °C/min under the nitrogen. The heat of fusion for PET was taken at 125 J/g [5].

The thin aluminium layers were observed with optical microscop Leica-DMLM in transmission mode.

Tensile testing were performed in accordance to NF ISO 6239 standard using an Adamel Lhomargy universal testing machine, at room temperature and at 50 mm/min, with an initial gauge length of 30 mm.

3. Results and discussion

Effect of ageing on PET

The DSC thermograms of PET as received and aged 192 days is shown in Fig. 1.

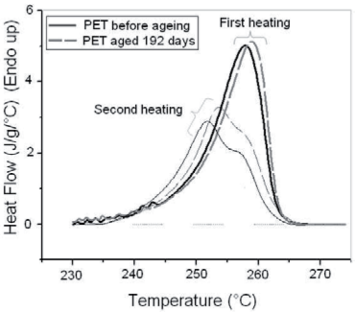

Fig. 1 : DSC thermograms of PET as-received and aged 192 days

The thermogram reveals that the second heating is shifted towards lower temperature and presents a smaller area. The melting temperature and degree of crystallinity increased with ageing (31 w% to 34 w%). The high accuracy of the DSC and quality of the baseline make these changes meaningful. In addition the noticeable shift in the thermograms indicates a chemical modification within the PET structure. For this peculiar polymer that crystallizes slowly [6] , an increase in crystallinity may indeed be the signature of a reduction in the molecular weight. Smaller PET chains indeed present an enhanced mobility and are therefore expected to crystallize more easily. As shown in Fig. 2 the second heating ramp is more sensitive to these structural modifications because the differences in mobility remained hidden at room temperature, i.e. below Tg, but are revealed during the crystallization process.

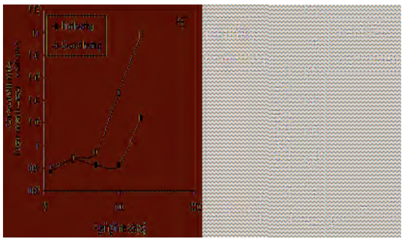

Fig. 2: PET crystallinity as a function of ageing time under 70°C and 90%RH.

The reduction in molecular weight of the PET, was estimated with literature data [7], by plotting the molecular weight (Mn) as a function of the crystallinity (χ): a linear decrease was observed were Mn~2.4 10^4 – 390 χ , Fig. 3.

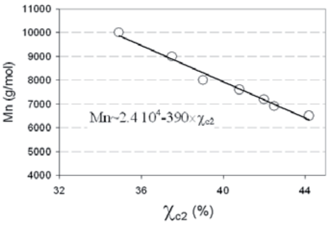

Fig 3: Molecular weight as a function of crystallinity extracted from [7], and linear extrapolation.

Using this equation as a calibration curve, the reduction in the molecular weight of PET in the present study may be estimated to be close to 20 % after 192 days of hydrothermal ageing. Attempts to detect the chemical changes using infrared transmittance were unsuccessful.

Barrier properties

The quality of the barrier property was evaluated with the help of optical microscopy [8]. The amount of aluminum decreased with ageing time for all the studied composites. PET film metallized with 40 nm on two sides is the most efficient barrier, as measured by transparency to visible light, and probably so in terms of vapour permeability.

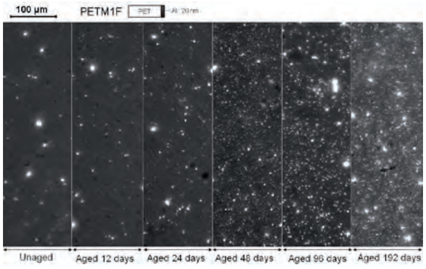

Fig. 3: OM (Optical microscope in transmission mode to characterize the aluminum barrier layer over ageing time.

Conclusions

For all the investigated materials, the physical properties are degraded during hydrothermal ageing at 70 °C and 90 % RH. A chemicrystallization process causes an increase of the crystallinity; the molecular weight of the PET chain was reduced of about 20 % after six months of ageing. The aluminum layer is largely degraded with time. The PET metallized on both surfaces with 40 nm lead to the optimum physical properties over time.

Acknowledgements

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Barrier Development and Testing for Warm Applications

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Abstract:
Vacuum insulation has been primarily used for cold applications. These applications have been rapidly growing over the last several years and will continue to grow. However, there is now growing markets that are interested in vacuum insulation for warm (55ºC to about 100ºC) temperature. For short duration, these temperatures are not a significant issue. For continuous use warm temperature applications, there is a significant challenge to obtain the desired performance over the life of the products. The technology must be developed now in order for this new market area to grow in the next several years.

Keywords:
Vacuum insulation panels, Barrier film, VIP, VIP warm applications

1. Introduction

A significant challenge for vacuum insulation has been to maintain acceptable performance over the desired life of the panel. Higher temperatures decrease the effective vacuum panel performance over time. Thus, the primary focus has been on cold applications. Very substantial progress in vacuum insulation barriers has been made over the years and desired life for most cold applications can now be met.

Interest from new warmer temperature markets (55ºC to about 100ºC) such as hot water heaters is starting to occur. One side of the vacuum panel is typically at about room temperature and the other side is at the higher temperature. Unfortunately maintaining the performance for these warm applications over the desired life is very difficult.

This paper presents a test method to verify the performance over time for warm applications. It also allows the determination of the temperature dependency of the performance change.

2. Warm Application Test Method

In the typical warm temperature application, one side of the vacuum insulation panel is at a warm temperature and the other side is at about room temperature. Due to the length of the test time (weeks to months long) it is desirable to test many panels at once with both the same barrier and with other barrier designs.

The typical test panels were 300 mm x 300 mm and 17 mm thick. The tester was designed to test 6 panels at a time. The test area was 610 mm x 914 mm.

The tester is constructed of a 6.35 mm thick aluminum plate with full coverage electrical heater on the back side of the plate. The aluminum heater plate was supported on a 51 mm thick foam insulation board. The test panels are placed on the top side of the aluminum plate.

Fig 1: Picture of the hot test plate that can test 6 sample panels at one time.

A typical temperature controller could be used to maintain the plate at the desired temperature. However, we found that an adjustable digital DC power supply held the temperature more accurately once the correct voltage was determined.

Fig 2: Adjustable digital DC power supply to the electrical heater.

3. Test Panel Preparation

The Thermal Visions vacuum panels typically have a fibreglass core so we produced all test panels with our typical core. The core is heated in an oven and then put into the vacuum chamber. The panel is sealed at

2.0×10^{-2} torr. To reduce the diffusion through the seals, the seal flaps are all folded to the cold side of the panel. Thus the seals are at the room temperature (21.7ºC).

4. Barrier Films Tested

A commercially available three metalized PET layer barrier was tested. Also a hybrid barrier that was composed of a commercially available aluminum foil based barrier on the hot side and the commercially available three metalized PET layer barrier on the cold side was tested.

A proprietary barrier film with multiple metalized layers and chemical barrier layers was tested.

5. Results and discussions

Thermal conductivity measurements were made before the test and after the test were completed.

The barrier films were tested at 100ºC plate temperature. All barrier films were previously tested at room temperature on each side versus time so that the room temperature change with time was known.

Commercially available three layer metalized PET barrier:
The test duration was 2 weeks and resulted in an average decrease in performance of 19% or 38% per month. The temperature dependence was calculated to be 1.6 times for every 10ºC increase in temperature.

Proprietary barrier film with multiple metalized layers and chemical barrier layers:
The test duration was 2 weeks and resulted in an average decrease in performance of 13% or 26% per month. The temperature dependence was calculated to be 1.8 times for every 10ºC increase in temperature.

Hybrid barrier that was composed of a commercially available aluminum foil based barrier on the hot side and the commercially available three metalized PET layer barrier on the cold side:
The test duration was 4 weeks and resulted in an average decrease in performance of 3% per month. The temperature dependence was calculated to be 1.4 times for every 10ºC increase in temperature.

6. Conclusions and outlook

The commercially available three metalized layer PET barrier shows a decrease in performance at 100ºC that is far higher than most applications could tolerate. Some warm applications are at about 70ºC and the decrease in performance would still be about 110% per year.

The proprietary barrier film with multiple metalized layers and chemical barrier layers at room temperature typically shows 4 times lower change in performance at room temperature than the commercially available three layer metalized but at 100º C it has only about 30% performance advantage. It also shows greater temperature dependence.

The hybrid barrier film shows the best performance at 100ºC. However it still is about 36% per year decrease in performance. It also shows the lowest temperature dependence. Even at 70ºC it will have about 13% decrease in performance per year.

None of the barrier films are at a change in performance with time that would be acceptable for most warm temperature applications. The chemical barrier that works well at room temperature is not very effective at high temperatures. The aluminum foil based barrier has defects (pin holes) in the foil. Some of these defects occur during the rolling of the barrier film and some during the use of the barrier film. The typical method of blocking the foil defects by laminating a metalized layer against the foil is not sufficiently effective for higher temperature.

Typically we think of diffusion through the barrier film. However, actual out gassing by the materials of the barrier film should also be considered at the higher temperatures. This is a mechanism that was not investigated in this test. However in other much higher temperature testing (200ºC), it appeared that there was likely degradation and actual out gassing from the barrier materials.

Clearly more barrier film advancements are needed to be able to provide a long life vacuum panel for continuous warm temperatures.

Development of novel opaque and transparent barrier films for VIP-encapsulation Part-II: Barrier film production for VIPs

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Abstract:
Novel high barrier films for the encapsulation of vacuum insulation panels are developed which contain Al or SiO_x barrier layers in combination with hybrid polymers. These materials are applied by cost efficient roll-to-roll vacuum or liquid phase processes. The developed films have been characterized regarding their oxygen permeabilities and the adhesion strength between their barrier layers.

Keywords:
Vacuum insulation panels, Aluminum, Silicon oxide, Hybrid polymer, Adhesion.

1. Introduction

Novel opaque and transparent VIPs are developed in the NanoInsulate project which are up to six times more energy efficient than current solutions [1]. Their nanoporous core materials consist of nanofoams or composites of silica aerogels with polymers.

The aimed VIP lifetimes are more than 50 years. Therefore the currently used encapsulation materials will be replaced by novel opaque and transparent high barrier films. Their oxygen permeabilities (at 23°C) and water vapor transmission rates (at 23°C, 85% → 0% r.h.) have to be lower than 10^{-3} $cm^3 \cdot m^{-2} \cdot d^{-1} \cdot bar^{-1}$ and 10^{-3} $g \cdot m^{-2} \cdot d^{-1}$, respectively [1].

2. Development of opaque and transparent barrier films for VIP encapsulation

The novel barrier films are laminates of one or two polyethylene terephthalate (PET) substrates coated with a stack of barrier layers together with a polyethylene or polypropylene sealing film. The layer stacks consists of an inorganic layer followed by a hybrid polymeric and possibly a second inorganic layer [2].

The inorganic barrier layers used for opaque or transparent films are deposited by thermal evaporation of aluminum or by electron beam evaporation of SiO_x, respectively [2]. An innovative approach in the field of VIP encapsulation is the combination of these layers with a hybrid polymer (ORMOCER®) [3] applied from the liquid phase. All production steps are performed by cost efficient roll-to-roll processes.

It will be show that an adhesion promoter between the aluminum and hybrid polymeric layers is necessary to reach a sufficient adhesion. This adhesion promoter consists of AlO_x deposited by reactive thermal evaporation of aluminum using oxygen as process gas.

For the transparent barrier film, PET Melinex 401 with a thickness of 50 µm is used as substrate since it was found to be well suited for the application of barrier layers. For the opaque film, however, it was decided to use a thinner (23 µm) and more cost efficient PET variant, denoted as PET 1.

Oxygen permeabilities for the produced barrier films were measured according to DIN 53380, T3 using a MOCON OX-TRAN device having a lower measurement limit of $5 \cdot 10^{-3}$ $cm^3 \cdot m^{-2} \cdot d^{-1} \cdot bar^{-1}$. Additionally an opto-chemical method with a limit of $2 \cdot 10^{-5}$ $cm^3 \cdot m^{-2} \cdot d^{-1} \cdot bar^{-1}$ [4] was used. The adhesion strength between the barrier layers was measured using the EAA peel test [5].

3. Results and discussions

Among the opaque barrier structures only for structure **1** (Fig 1) the adhesion strength of ORMOCER® applied directly on top of Al was sufficient, i.e. larger than 2 N/(15 mm). When PET Melinex was replaced by PET 1 the adhesion strength was significantly lower. For the thinner PET 1 film the strain due to thermo-mechanical load during ORMOCER® curing is larger than for PET Melinex and therefore could explain the delamination. Particles, possibly cyclic oligomers [6], which are formed at the PET 1 surface during thermal treatment are another explanation for the low adhesion. They could be transferred to the barrier layers and cause there a delamination between them.

In order to reach sufficient adhesion of the more favorable ORMOCER® System 1 on Al for each of the PET substrates, an intermediate layer of AlO_x as adhesion promoter was necessary (structures **2** and **3**). In contrast to this additionally deposited AlO_x layer, an AlO_x layer which is formed at the surface of an Al layer in contact with oxygen from the air [7] promotes adhesion much lower. An explanation is given by electrochemical impedance spectroscopy [8] which shows that ORMOCER® might penetrate into the deposited AlO_x layer. This would also be an experimental proof of the synergistic effect of ORMOCER® on top of an oxide layer [3].

Fig 1: Opaque barrier structures **1**–**3** (from left to right)

Since PET 1 is the preferred substrate for opaque barrier films the deposition of the second Al layer was investigated for structure **3**. In contrast to the deposition of this layer directly on top of ORMOCER® (structure **4**, Fig 2) the adhesion was significantly improved when an AlO_x layer as adhesion promoter was also deposited between these layers (structure **5**).

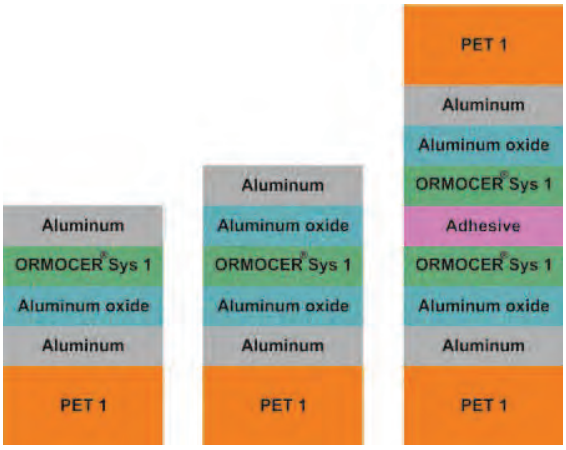

Fig 2: Opaque barrier structures **4**–**6** (from left to right)

The final step is the lamination with the sealing film which will therefore be studied for structure **5** and also for structure **6**. The latter one consists of two structures **3** which contain no Al on top of an ORMOCER® layer and are laminated with their coated surfaces facing together (face-to-face laminate).
The oxygen permeability decreases from structure **3** over **1** to **2** each by a factor of up to 10. The first inequality is due to the higher surface roughness of PET 1 in **3** compared to PET Melinex in **1** [2]. The second one is consistent with the synergistic effect, i.e. the penetration of ORMOCER® into AlO_x [3].
Due to deposition of the second Al layer these differences are not relevant for the application. Aside from few higher values the oxygen permeabilities of the structures **4** and **5** and of a face-to-face laminate of two structures **1** together with LDPE were below $5{\cdot}10^{-3}$ $cm^3{\cdot}m^{-2}{\cdot}d^{-1}{\cdot}bar^{-1}$.
In the case of transparent films the barrier structure PET Melinex / SiO_x / ORMOCER® / SiO_x / ORMOCER® // LDPE was produced. Its oxygen permeability of below $5{\cdot}10^{-3}$ $cm^3{\cdot}m^{-2}{\cdot}d^{-1}{\cdot}bar^{-1}$ was further reduced to a value below $1{\cdot}10^{-4}$ $cm^3{\cdot}m^{-2}{\cdot}d^{-1}{\cdot}bar^{-1}$ by face-to-face lamination.

4. Conclusions and outlook

Different structures of novel opaque and transparent barrier films for VIP encapsulation were presented. These films contain alternating inorganic and hybrid polymeric barrier layers applied in cost efficient roll-to-roll processes.
The measured permeabilities show that the developed films almost meet the requirements regarding oxygen barrier. In the case of opaque films an adhesion promoter is necessary to reach sufficient adhesion between the different materials.
The final step in barrier film development is the optimization of the lamination process between the developped films and the sealing film. In order to evaluate these laminates, VIP panels will be encapsulated with them and the increase of the gas and water vapor pressure within the panels will be measured.

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Thermal Retrofitting of Existing Buildings: The Limits of Conventional Technology and Case for High Performance Vacuum Technology

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Abstract

The imperative to reduce the carbon footprint of buildings will inevitably require higher levels of insulation. Many conventional insulation materials may be unable to practically achieve the anticipated performance standards due either to physical limitations, or their high embodied CO_2.The amount of CO_2 associated with the manufacture of many common conventional insulation materials can significantly offset the operational CO_2 benefits arising from reduced heat losses, or cause a net CO_2 disbenefit. This can, contingent on various factors including service life, entirely negate any rationale for the use of conventional insulation materials in relation to U-values materially lower than those currently specified. Detailed studies carried out at Oxford Brookes University based on aggregated operational and embodied CO_2 analyses suggest significant benefits for vacuum insulation in relation to a broad range of building types and design scenarios, due to the lower embodied CO_2 of equivalent high R-value specifications. Comparisons have been made with mainstream comparator insulation materials including PUR and mineral wool. The aggregated methodology demonstrates particular advantages for vacuum insulation in relation to retrofit applications, which typically have shorter design lives and where the embodied CO_2 investment has to be recovered relatively quickly.

Keywords: Vacuum insulation, embodied CO_2, retrofit, cladding systems.

1. Introduction

The majority of buildings that will be available in 2050 have already been constructed and so, whilst the performance standards of new buildings are important, it is arguably more critical that effective strategies are found for improving the thermal performance of the existing stock. For example, in 2010, over 400,000 existing homes in the UK received cavity wall insulation and over 1 million received loft insulation (DECC, 2011). Despite these statistics, thermal retrofitting of existing buildings appears under-represented in the effort to meet carbon reduction targets.

2. The Current Condition of Building Stock

The built environment accounts for 43% of UK emissions, of which 26% is from residential buildings. It is estimated that about 30% of existing houses do not have cavity walls and around 42% of houses with cavity walls are not insulated (Centre for low carbon futures, 2011). In 2009, 30% of English homes failed the Decent Homes Standard and in approximately a quarter of cases this was due to poor thermal performance. This highlights the importance of thermal refurbishment solutions (DCLG, 2010).

Similarly, in the non-residential sectors only 2% of the UK's existing building stock is less than five years old. These buildings are responsible for 17% of UK emissions. Around 54% of existing commercial buildings were completed prior to 1939 (DCLG, 2000). It has been estimated that 80% of all existing commercial buildings would be rated below C on the Energy Performance Certificate scale (Caleb Management Services, 2009). Retrofitting solutions for non-domestic building stock have not been widely adopted as more than two-thirds of the commercial and industrial properties are owned by short-term tenants. The energy cost is a relatively low proportion of operational costs in many service sector companies (up to 6%) which may discourage owners to undertake the high upfront cost of thermal performance improvements.

3. Combined Operational and Embodied CO_2

Operational energy has in recent decades been assumed to be around 10 times greater than the total embodied energy of buildings. Consequently embodied energy has largely been ignored when framing new regulations. More recently however, with buildings requiring less operational energy due largely to current higher standards of envelope insulation, the ratio of operational to embodied energy is shifting significantly (Yohanis 2002). Future low and zero carbon buildings could see equivalence between operational and embodied energy, or even embodied energy exceeding operational energy. It is essential therefore that embodied energy is factored into refurbishment policies. If so, a compelling case begins to emerge for the development of high performance insulation materials.

This paper supports the case for the development of novel insulation materials such as VIPs that combine higher thermal performance with relatively low embodied energy. The case is particularly strong for retrofit applications where design lives tend to be less than those for new build, and where embodied energy can offset a greater proportion of the total operational energy savings. The analysis presented in this paper however demonstrates that the approach must be an integral part of any holistic appraisal of insulation performance. Recognition of this represents an important and necessary paradigm shift.

4. Results and Discussions

Results for all building sectors support the case that, whilst further reduction in U-values can enhance operational energy thrift, embodied energy issues tend to compromise this gain. For example, combined operational and embodied energy analyses for the refurbishment of common single span portal frame warehouses in the range 1000 to 3000m^2 (which are obvious consumers of both mineral wool and PUR materials, and common in the UK, (UKNS, 2008)), show that whilst increasing the thicknesses of either material beyond the levels currently specified can present some degree of overall energy reduction, far higher savings can be achieved using VIPs. The minimum achievable CO_2 associated with using VIPs in comparison to the investigated conventional insulation materials saves about 400-1000 million tonnes of CO_2 per annum (depending on building size and operation criteria). This is about 8-20% of the CO_2 associated with space heating (DECC, 2012).

5. Conclusions and Outlook

Whilst energy reduction strategies have so far focused on operational energy, the analyses demonstrate that such approaches are not appropriate for future low energy refurbishment solutions. As operational energy reduces the ratio of operational energy to embodied energy becomes relatively evenly balanced. Future thermal refurbishment strategies must therefore focus on combined operational and embodied energy analysis. Such analysis demonstrates optimum net benefit levels for insulation solutions beyond which it is illogical to go as embodied energy burdens exceed the operational energy saved. This provides compelling support for development of novel insulation solutions based on VIPs as conventional solutions cannot be justified in relation to low U-values and relatively short service lives.

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Structure of vacuum insulation panel in building system

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Abstract:
Heating, ventilation and air conditioning of commercial and residential buildings account for more than half of energy consumption. Energy efficient vacuum insulation panel (VIP) offers slim but highly efficient insulating capacities to curtail thermal losses for both new and renovation buildings. This study presents a comprehensive investigation of the advancement of VIP with glass fiber core material in China. Material composition, peculiar procedures, installation method and future outlook have been extensively discussed. Due to its intrinsic properties, the outer barrier layer of fiberglass cloth protects VIPs from localized alkaline cement and mechanical stress. De-bonding of insulation assembly from building walls was curbed by a combination of reinforced fiberglass mesh and plastic spacer. Narrow cavities between the VIP and existing wall created a sort of inward drying model against unforeseen moisture conditions.

Keywords:
Vacuum insulation panel (VIP), glass fiber, building, mechanical stress, condensation.

1. Introduction

Energy usage in residential and commercial buildings is responsible for significant CO_2 emissions. Retrofit measures focused on improving air-tightness of new and existing buildings can achieve significant reductions in heating and cooling energy demands. The vacuum insulation panel (VIP), an energy saving and environmentally friendly thermal insulation system, has been introduced into the Chinese building industry for about half a decade now. VIP is exceptionally useful for space constrained applications owing to low thermal conductivity, allowing a significant reduction in the required minimum thickness [1-4]. Recently, VIP for thermal insulation in buildings is on the ascendency in China owing to safety precautions against other conventional insulation materials that pose as hazard due to burning and release of harmful gases in buildings. Running from early 2009 to early 2011, three major high rise building structures have been destroyed by fire in China (Fig.1); unfortunately resulting in loss of lives and destruction of property worth millions of dollars. Extruded polystyrene board and polyurethane foam were used as insulation materials in Fig.1a and Fig.1b, respectively. Especially in the case of the latter, huge tonnage of toxic hydrocarbons was released into the atmosphere. No known insulation material is reported for situation of Fig.1c.

Fig.1: Fire hazard of other conventional insulation materials [5].

In this paper, we investigate some major installations of VIPs in building structures in China. The peculiar characteristics of the as-produced VIP, installation method being used, condensation and associated mechanical stress effects are also discussed.

2. Material components

As well known, VIP is composed of an evacuated core material encapsulated in a gas-tight barrier envelope supplemented with a getter or desiccant. The widely used core material in China is glass fiber, even though few use fumed silica. The manufacturing process of such glass fiber core material has been reported by Li et al. [6]. A number of top VIP producers in China use the wet processing method [7]. Amorphous glass fiber core material has an open porous internal structure rendering the core material as a highly compressible structure (Fig.2 (left)). The envelope is Al-laminate type composed of 80 μm metallocene linear low density polyethylene (mLLDPE)/15 μm polyamine (PA)/7 μm aluminium foil (Al)/12 μm polyethylene terephthalate (PET)/340~350 μm fiberglass cloth (FGC); laminated together using polyurethane (PU) glue. The dried core materials are bagged in multilayer envelope, simultaneous evacuated and sealed in a depressurization chamber to pressure < 1 Pa to form VIP (Fig.2 (right)).

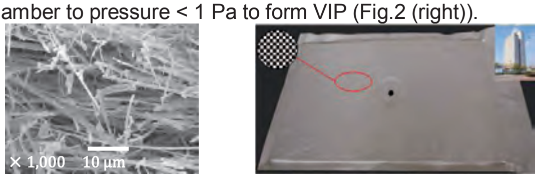


Fig.2: (left) SEM of glass fiber, (right) Sample of VIP: VIP with glass fiber core material, (insert left) schematic of woven structure of outer layer FGC, (insert right) Building façade.

3. Description of construction procedures

The construction procedure is summarized as follows:

1) Grass-roots clean-up which includes removal of pipe fittings; filling, leveling and scraping of building walls.

2) Establish horizontal and vertical reference lines.

3) Foundation wall preparation or surface preparation which includes mixing of adhesive mortar, leveling of dents, apply mortar layer on wall in a guttered design.

4) Pasting of insulation panel, that is: mark and drill blunt hole for spacer; brush adhesive powder on both sides of VIP; paste VIP on wall surface.

5) Evenly coat outer VIP surface with slender mortar.

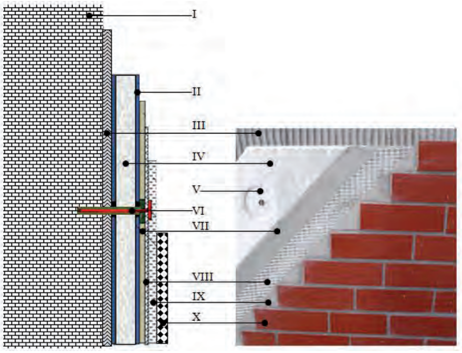
6) Layering of alkali-resistant fiberglass mesh (specification ≥ 160 g/m^2); that is press fit the mesh into the first mortar layer; an overlap width of 200 mm of mesh is used to increase reinforcing strength at corners of buildings. Installations near window and door openings were reinforced with 300 mm × 200 mm mesh along the 45^o direction.

7) Affix plastic spacer through the assembly (in cases where VIPs were prefabricated with spacer hole and walls were drilled to make spacer hole as shown in Fig.3).

8) Coat the outer surface of panel slender mortar. Mortar layers in steps (5) and (8) have thickness of 2~5 mm.

9) Based on local weather conditions, a minimum of 24 hours is allowed for the installation to cure. A quality check is performed by a VIP expert or supervisor from the Municipal Supervision Bureau. The described assembly is shown in Fig.3. Fig.4 and Fig.5 illustrate façade application of the

described installation method. Differences from the described construction procedure are commonly observed. For instance, not all installations incorporate spacers or guttered design (narrow cavities).



(a) (b)

Fig.3: Assembly of vacuum insulation system (a) cross-section and (b) pictorial view of insulated wall.

Nomenclature:

I - Existing wall
II - Interface adhesive powder
III - Bonding mortar (with gutters)
IV - VIP
V - Hole for support
VI - Plastic spacer
VII - Plaster mortar
VIII - Fiberglass mesh
IX - Surface mortar plaster
X - Surface decorations

Fig.4: Wuxi city new commercial building.

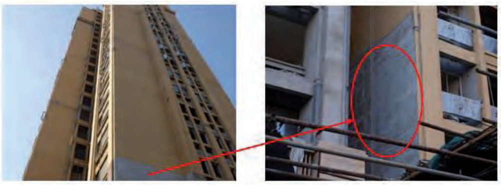


Fig.5: Suzhou Rongqiao renovated commercial building.

4. Results and discussion

Major concerns included protecting the VIPs from mechanical stress (especially during installation) and condensation. Mechanical stress can also occur due to thermal expansion and contraction in response to changes in the ambient outdoor temperature, and due to building shifting. Condensation is the result of moisture built up in an insulated wall. Straube and Schumacher [8] stressed the importance of providing for inward drying as a safety factor against unforeseen moisture problems in a wall assembly. Glover et al. [9] corroborated with a robust installation strategy by incorporating a narrow ventilated depressurized cavity adjacent to a stone wall called negative pressure cavity which provided for inward moisture drying. Moisture build-up problems can occur due to material imperfections, surface cracks and local wet spots.

Very typical of the envelope used is an outer layer of fiberglass cloth (FGC) also called fiberglass textile. FGC is composed of inorganic noncombustible fiberglass woven in a repeated framework. Owing to this interlocking structure, FGC has high tensile strength. Besides, it is inert to sunlight, fungus or bacteria attack, and resistant to attack by most chemicals. VIP with FGC as outer layer showed slower aging rate compared to VIP without FGC outer layer. FGC layer protected the VIP from alkaline cement mortar. Also, it cushioned VIP from mechanical rubbing. In addition, as-produced VIP had excellent dimensional stability because the outer FGC had very low elongation under load. This is particularly important for building applications where real space is limited and cannot be compromised. With other major installations, VIP was well protected between rigid foam on outer surface and polymer barrier on inner surface [9]. However, with the construction procedure described in this paper, the VIP was well protected between two slender mortar plasters. The first mortar layer was applied in stripes and formed gutters or narrow cavities between the VIP and existing wall. This ensured that minimum moisture was in contact with the VIP. Moreover, the narrow cavities could allow vapor to move in either direction, creating a sort of inward drying model. Adhesive powder was brushed on both sides of the VIP to improve adhesion between VIP's smooth surface and wall surface.

De-bonding of insulation panels from the wall surface has been observed in the past. To solve this, firstly, fiberglass mesh was affixed on the assembly, as reinforcement between the two mortar layers. It impacted reinforcement strength, especially to the surface plaster. Secondly, VIPs were prefabricated with holes and plastic spacers fixed in the holes primarily to support the assembly (Fig.4 (right)).

5. Conclusions and outlook

The basic installation procedure and peculiar material components of VIP for building insulation in China has been described. According to the new Chinese Governmental law, the burning requirements for building materials upgrades non 'no flammable' Al which is comparable to French Standard NF P92-510, which can be compared to the 'no flammable' label Al conforming with the new European classification standard EN 13501-1 and EN ISO 1182 [4, 10]. VIP with glass fiber as core material is nonflammable and therefore satisfies the requirements for building insulation materials in China. The in-service performance of VIP does not depend on the structure and properties of the panels only but also on the method or manner in which they are installed. A combination of fiberglass mesh and plastic spacer supported the assembly.

Acknowledgements

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The Preparation and Properties of Silicon Rubber-Vacuum Insulation Panel

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Abstract:
The extensive exploitation range of crude oil calls for a more perfect subsea pipeline system, especially for the heat-insulating ability of the thermal insulation material. Traditional thermal insulation materials like polyurethane-foam used in pipe casing structures for heat insulation has disadvantages such as the requirement for thicker heat insulation layers due to its limited insulation ability, tedious process and huge consumption of manpower during the foaming procedure using large-scale mold. This paper focuses on the preparation and properties of a new kind of pipe insulation material, called silicon rubber-vacuum insulation panel (SR-VIP), which consists of a silicon rubber layer, a VIP layer and silicon rubber layer, making the composite tile sandwich structure. In addition, the tiles can be linked up to each other via a stepwise joint, which ensures reduction of the thermal bridge effect. Compared with traditional foam insulation, the insulation tile possesses superior thermal insulating properties, which will definitely bring substantial economic benefits with the successful slim shape of the pipe and convenient adhesion process under the construction.

Keywords:
Subsea pipeline, thermal insulation material, silicon rubber, vacuum insulation panel, composite tile

1. Introduction

With ever-increasing oil and gas being recovered in deeper, colder water [1], increasing demand for pipelines for passage of oil or gas is required to be insulated to prevent thermal damage to the pipe and the material passing through [2]. Taking oil pipelines for example; as the flow proceeds, the crude oil progressively cools down, drastically changing its kinematic viscosity [3]. Once some problems occur to oil pipelines in the harsh seabed environment, it'll be difficult, expensive and time-consuming to repair. Therefore, insulation materials of a new generation of insulated subsea flow lines [4] should satisfy following requirements: (1) sufficient high strength, stiffness and elasticity to resist various loads in the process of pipe preform and laying; (2) sufficient high compressive strength to resist the static water pressure; (3) low thermal conductivity; (4) small water absorption or non-absorbent; and (5) temperature stability. Currently, pipe in pipe structure is applied to the seabed oil pipeline and its insulation materials are usually organic, inorganic and composite foam materials including epoxy resin foam plastics, expanded perlite, composite silicate products, and so on, of which polyurethane (PU) and polypropylene (PP) foamed plastics are most widely used in China. However, the aforementioned materials have disadvantages such as: (1) the thermal conductivity is not low enough to reduce thickness of the insulation layer, which brings about difficulty during construction; (2) low compressive strength; and (3) a waterproof layer is needed to cover its external surface and to make up for the less than 100% foam obturator rate. In this paper, the preparation and properties of a new kind of pipe insulation material, called silicon rubber-vacuum insulation panel (SR-VIP) has been investigated.

2. Preparation of SR-VIP

The preparation processes are: (1) prepare VIP; (2) clean the mold and smear release agent to the inner wall; (3) bond the silicon rubber block of a fixed thickness around on both sides of the VIP for bracing and making space for pouring liquid silicon rubber (LSR); (4) calculate and weigh the component A and B of LSR according to the mold size; (5) pour the curing agent into the container filled with SR and mix it, then quickly pour it into the mold; (6) quickly put the VIP into the mold and press it; (7) continue to fill the mold with LSR. Then immediately place steps and fix the mold with clamping device; and (8) take off the mold, take out the panel and repair the edges during time of curing at room temperature or by heating. Taking a size of 8-inch SR-VIP as an example, its inner diameter is 330 mm, outer diameter is 371 mm, 21 mm thick and 520 mm high. With 8 mm high steps placed all around the panel, it could join to form a seamless pipeline insulation layer. Fig.1 shows photographs of SR-VIP and how SR-VIPs closely fit the pipeline. Fig.2 shows cross-section view of SR-VIP, which looking from the top down is made up of silicon rubber, aluminium foil, core material, aluminium foil, and silicon rubber.

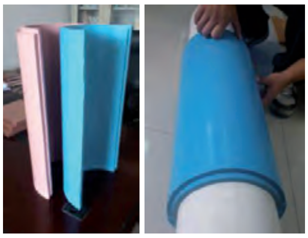


Fig.1 Photographs of SR-VIP.

Fig.2 Cross-section view of SR-VIP.

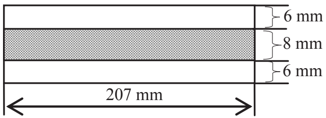


Fig.3 Inner structure and size of a SR-VIP sample.

3. Experimental details

In all nine SR-VIP samples were prepared. Each sample was 207 mm long, 207 mm wide and 20 mm high. Inside, the VIP was 8 mm wide, fitted with 6 mm wide silicon rubber covering on both sides. Fig.3 shows the inner structure and size of a SR-VIP sample. The thermal conductivity was evaluated using a heat flow meter (Netzsch HFM 436). Aging test was performed firstly at temperature values of 40°C, 45 °C, 50°C, 55°C, 60°C, 65°C, 70°C, 75°C and 80°C; coupled with a constant humidity of 95 % using a temperature and humidity chamber (HS-800). Samples were heated for 12 hours at each temperature point and the thermal conductivities were measured. Afterwards, aging at temperature values of 0°C,-5°C,-10°C,-15°C,-20°C,-25°C,-30°C,-35°C and -40°C was performed using a high-low temperature test chamber (GDJ-800). Again, samples were cooled for 12 hours at each temperature point and the thermal conductivities were recorded.

4. Results and discussions

The mean thermal conductivity, λ of SR-VIP samples was 0.01 W/(m·K). Fig.4 shows a comparison of λ of different materials.

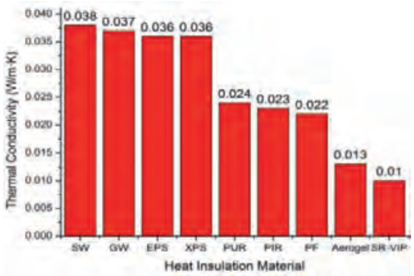
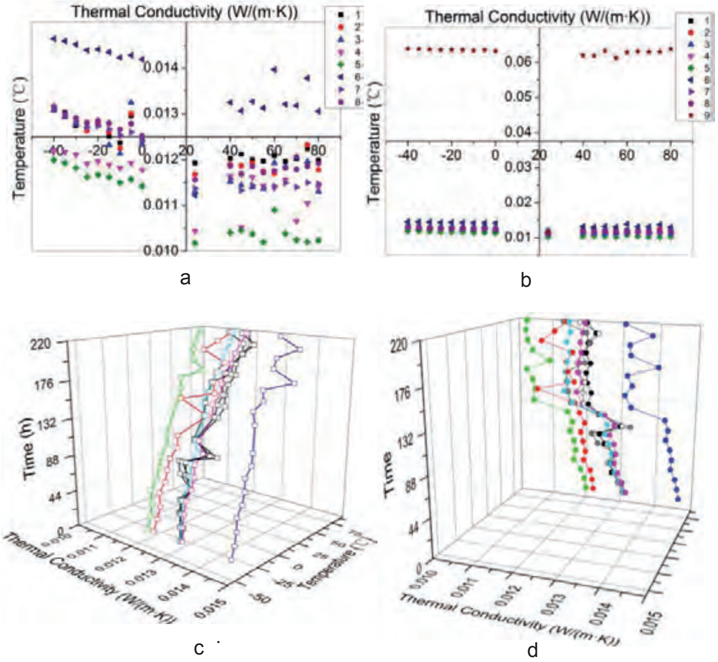


Fig.4 Comparison of thermal conductivity of insulation materials.



a b

c d

Fig.5 Variation of thermal conductivity with temperature

Fig.5 shows how the thermal conductivity of the samples varies as the temperature changes during the aging test. It can be seen from Fig.5a that after being heated for 12 h at 40°C, the thermal conductivity λ_{40} is a little higher than the $\lambda_{original}$ which is tested at room temperature. In addition, except for sample 6 and sample 9, the thermal conductivity of the other samples fluctuates slightly around λ_{40} and stays stable overall. However, the thermal conductivity of sample 6 fluctuates sharply and increases to a high degree since it was heated at 50°C for 12 h, which may have resulted from the joint failure between silicon rubber and the VIP during the experiment while the VIP was undamaged, causing the decline of insulation capability. What is more, it can be found in Fig.5b that the thermal conductivity of sample 9 ascends greatly compared to the other samples, for which the breakage of the VIP, namely the loss of vacuum, makes the insulation layer deteriorate. Moreover, it from Fig.5a, after being cooled for 12 h at 0°C, the thermal conductivity λ_0 is still a little higher than the $\lambda_{original}$. Meanwhile, the insulation capability of sample 6 was weakened, due to the same reason as is mentioned above. And according to Fig.5b, the loss of vacuum in VIP makes sample 9 defective. Except for samples 6 and 9, the other samples with structural integrity have good and stable thermal insulation properties. In addition, a comparison between high-temperature and low-temperature aging tests reveal that the thermal conductivity at low temperature was generally higher than that at high temperature. Therefore, it can be concluded that SR-VIP performs better at high temperature. We thus focus on sample 1 to sample 8, having shown structural integrity. Fig.5c shows how the thermal conductivity spatially changes with both temperature and time. Fig.5d is the projection of the spatial curve in Fig.5c onto the thermal conductivity-time plane, from which we can see clearly how the thermal conductivity of the samples changed as time progressed. Each sample proves a stable performance when cooled at low temperature for the first 108 h and in the process of being heated at high temperature for the next 108 h, the thermal conductivity fluctuated initially on a small scale and then stabilized gradually.

Though SR-VIP is promising, there is the risk of formation of hydrate plugs. However, the silicon rubber serves as a resilient protective layer not only to accommodate deformations in the pipe itself caused by low-temperature gases or oil passing through but also to keep the vacuum degree in VIP for longer time, thus lowers the risk of formation of hydrate plugs. Furthermore, some measures, for example adding low dosage hydrate inhibitors in oil transmission pipelines, transport of hydrate slurries, transient operation through hydrate domain, utilization of hydrate formation kinetics, still have to be taken for certain in practical use.

5. Conclusions and outlook

(1) The thermal conductivity of SR-VIP is about 0.01 W/(m·K). Though bigger than its core material VIP, the composite tile whose thermal conductivity is only 1/3~1/2 of the rigid polyurethane foam shows greater heat insulation performance compared with traditional pipe insulation materials.

(2) Small thermal conductivity variances of SR-VIP after high and low temperature aging tests shows excellent resistance to high and low temperature performance, which greatly reduces replacement frequency of pipeline insulation materials, waste of resources and economic loss.

(3) Combining SR-VIPs outside the pipeline with handy binding during installation simplifies the construction process, in which the following five points should be paid attention to: a) Quality assurance or structural integrity of the products, meaning that no VIP part is exposed. b) Make sure the product seams are wrapped within the pipeline to avoid the failure of the insulation layer due to the thermal motion of gas molecules. In actual construction, adhesives need to be used for stronger bonding, with resin coated glass fiber winded outside the products. c) No torsion or pounding damage. d) Keep at room temperature, without ultraviolet rays. e) Avoid corrosion of oil containers and keep it clean.

Acknowledgements

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Effect of core material layer thickness on thermal conductivity of glassfiber VIPs

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Abstract:

Vacuum insulation panels (VIPs) are the most promising high-performance thermal insulation products on the market today. The quality of core material determines thermal insulation performance of VIPs. In this paper, multiple glassfiber core material layers (CMLs) with thickness of 0.5mm, 1mm, 3mm, and 7mm were paralleled horizontally to form the core of VIPs. Relationship between thermal conductivity of VIPs and interlayer microstructure of core material was investigated. The initial total thermal conductivity of VIPs was lower than 4mW/(m•K) and slightly increased with total thickness of core material, but increased very big with CMLs thickness. Multilayer-structure core material with ultrathin CMLs is the future direction of the core of VIPs.

Keywords:
Vacuum insulation panel, Core material, Thermal conductivity, Glassfiber, Interlayer structure.

1. Introduction

Vacuum insulation panels (VIPs), with up to about 10 times higher thermal resistance than that of conventional insulators like polyurethane foams and polystyrene [1], are the most promising high-performance thermal insulation products on the market today. Due to its characteristics of light weight, low thermal conductivity, and physical and chemical stability, glassfiber VIPs have been increasingly applied to refrigerator insulation to reduce not only energy consumption but also CO_2 emissions.

The quality of core material determines thermal insulation performance of VIPs [2]. Optimizing the microstructure of core material could further reduce thermal conductivity and extend service life of VIPs. However, few literatures have focused on interlayer microstructure of glassfiber core material.

2. Experimental

Fig.1 shows the manufacturing process of glassfiber CMLs. The wet method included the following steps: providing glassfiber slurry; dewatering the slurry to form a wet-laid mat; drying the mat; and cutting the mat to form finished glassfiber CMLs. The length and width of the glassfiber CMLs were both 290 mm, while the thickness was 0.5 mm, 1 mm, 3 mm, and 7 mm, respectively. Multiple CMLs were paralleled horizontally to form the core of VIPs.

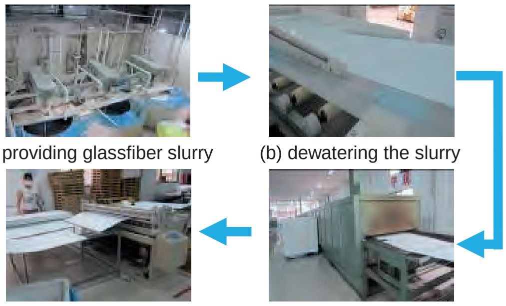

(a) providing glassfiber slurry
(b) dewatering the slurry
(d) cutting the mat
(c) drying the mat

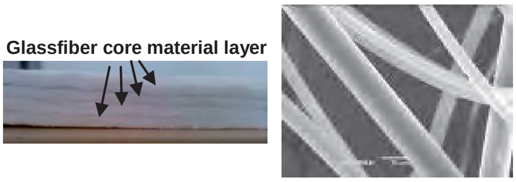
Fig.1 Manufacturing process of glassfiber CMLs.

Firstly, the core materials were dried at 150°C for 60 min, and then bagged in envelope material. Afterwards, the VIPs were produced after simultaneous vacuum and sealing processes. Surface morphology of the core materials was observed by scanning electron microscopy (SEM, JEOL JSM-6360). Thermal conductivities of the as-prepared VIPs were evaluated by heat flow meter (Netzsch HFM 436).

3. Results and discussion

3.1 Microstructure

Fig. 2 shows the morphology of VIP core material. As shown in Fig. 2(a), the invested VIP core material consisted of glassfiber CMLs which were separated by multiple parallel laminates. The mean thickness of the laminates was about 0.1 mm. As shown in Fig. 2(b), the VIP core material consisted of a mass of randomly oriented, super cooled glossy fibers of varying lengths and diameters. The average diameter of the glass fibers was about 2~6 μm.



(a) Macrostructure
(b) SEM micrograph

Fig. 2 Morphology of VIP core material.

3.2 Thermal conductivity analysis

The total thermal conductivity λ_{tot} of VIPs is made up of several contributions in principle [3, 4]:

$$\lambda_{tot} = \lambda_{solid} + \lambda_{gas} + \lambda_{conv} + \lambda_{rad} \qquad (1)$$

where λ_{solid} is the solid thermal conductivity, λ_{gas} is the gas thermal conductivity, λ_{conv} is the convection thermal conductivity, λ_{rad} is the radiation thermal conductivity. Among the contributions, the λ_{conv} is considered to be an ignorable level for cell diameters less than 4 mm [5]. Fig. 3 shows the relationship between thermal conductivity of VIPs and total thickness of core material. In this paper, the λ_{tot} of VIPs possessing CMLs thickness of 0.5mm, 1mm, 3mm, and 7mm was marked as $\lambda_{tot\text{-}0.5mm}$, $\lambda_{tot\text{-}1mm}$, $\lambda_{tot\text{-}3mm}$, and $\lambda_{tot\text{-}7mm}$, respectively. The initial λ_{tot} of VIPs was lower than 4mW/(m•K) and slightly increased with total thickness of core material. Meanwhile, VIPs with low-thickness CMLs possessed lower thermal conductivity.

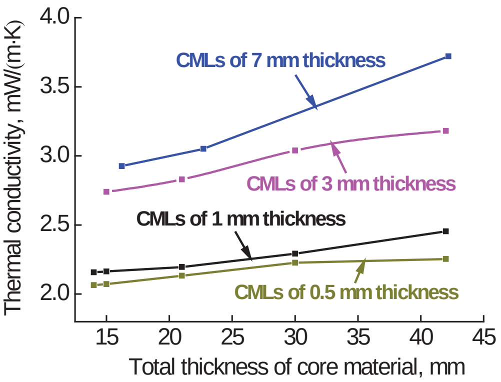


Fig. 3 Relationship between thermal conductivity of VIPs and total thickness of core material.

Fig. 4 shows the interface model between layers. Only a part of CMLs surface was pressed together when two CMLs were horizontally put together because of high surface roughness; and the contact area was a few discrete points separated by relatively large gaps. Some residual gases could lie in the large gaps which was called air gap in this paper. In general, the size of air gap was bigger than that of pores within CMLs.

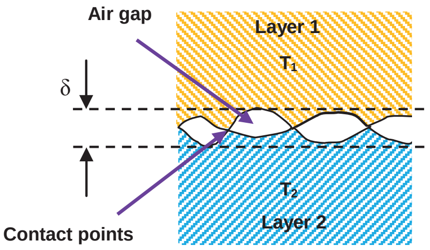


Fig. 4 Interface model between layers.

The pressure within VIP enclosure was much higher than that within vacuum chamber due to extraction resistance. Most of released gases were pulled out of vacuum chamber during vacuum process. However, it was difficult to pump down all of the gases which existed in the VIP enclosure. In addition, multilayer-structure CMLs might release some gases constantly at a slow rate during the service life of VIPs. Hence, a small quantity of gases existed within VIP enclosure. A part of residual gases existed in the pores of CMLs while the other part lied in the air gaps between CMLs. At the initial stage, the inner pressure of VIPs and the mean pore diameter of glassfiber CMLs were about 1 Pa and about 15 μm, respectively. It was reported that the mean free path of air was 5 mm at a pressure of 1 Pa and temperature of 25°C [6]. The micropores within CMLs made by fiber network could effectively block the gas molecules from flowing freely; and thus the convection phenomenon could not occurred in micropores. The large pores, especially for interconnected macropores between CMLs, provided flow channels for residual gases. Therefore, the convection phenomenon mostly occurred between CMLs and thus increased the λ_{tot}. The number of air gap increased with the number of CMLs at the same surface roughness of CMLs. Therefore, the λ_{tot} of VIPs increased with the total thickness of core material with the same-thickness CMLs. It is noteworthy that the proportion of λ_{conv} was not high and the λ_{conv} would not cause great impact on the λ_{tot} of VIPs. Hence, the initial λ_{tot} of VIPs slightly increased with total thickness of core material with the same-thickness CMLs.

The λ_{solid} occupies the most proportion of the λ_{tot} of VIPs. As we know, the solid thermal conductivity of a fibrous structure is greatly influenced by fiber-to-fiber contact area at the fibers' crossover points; and the fiber-to-fiber contact area increased with compression ratio of core material. Arambakam et al. [7] declared that there was no noticeable influence on λ_{tot} of VIPs for in-plane arrangement of fibers. Table 1 shows the density and compression ratio of the four types of CMLs. The compression ratio could be described by the following relation:

$$\alpha = \frac{h_0 - h_1}{h_0} \tag{2}$$

where h_0 is the original thickness of core material, while h_1 is thickness of core material in vacuum environment.

Table 1 Density and compression ratio of the four types of core material layers.

Thickness, mm	Density, kg/m^3	Compression ratio, %
0.5	110	48
1	150	32.7
3	170	21.8
7	172	21.3

The core material was highly compressed due to the huge pressure difference between the outside atmospheric environment and the inner space inside. Fiber parallelism increased under highly compressed samples as the vertical arranged fibers in core material layers were planished; and thus the heat transfer path was extended. Therefore, the λ_{solid} decreased. Core material with 0.5 mm-thickness CMLs possessed the highest compression ratio; and thus the solid thermal conduction λ_{solid} was lowest. As a result, $\lambda_{tot\text{-}0.5mm} < \lambda_{tot\text{-}1mm} < \lambda_{tot\text{-}3mm} < \lambda_{tot\text{-}7mm}$.

4. Conclusions and outlook

VIP core materials were successfully manufactured by wet process. Thermal conductivity of VIPs increased with total thickness of core material and thickness of CMLs. Multilayer-structure core material with ultrathin layers is the future direction of VIPs.

Acknowledgements

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Comparison of methods for evaluating the thermal conductivity of nanoporous silica core materials for vacuum insulation panels (VIPs)

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Abstract:

The superior insulation properties of vacuum insulation panels (VIPs) provide new opportunities for the building industry. A typical VIP consists of an envelope and a core of fumed silica. For economic reasons, new methods for producing aerogel core materials with properties comparable to those of fumed silica are being investigated. This calls for fast and reliable methods for measurements of thermal properties. This study compares alternative methods for evaluating the thermal conductivity of core materials in terms of time, sample size and boundary conditions. The thermal transmissivity is studied through stationary measurements with a hot plate apparatus and with the Transient Hot Bridge method as well as with the Transient Plane Source method. There are small differences in the results while the preconditions of the measurements are different. In addition the dynamic measurement methods allow for the determination of the thermal diffusivity of the samples.

Keywords:
Vacuum insulation panels (VIPs), Core material, Nanoporous materials, Silica aerogel, Thermal conductivity measurements

1. Introduction

Vacuum insulation panels (VIPs) provide new opportunities for obtaining excellent thermal insulation material with light and slender constructions as well as with a thermal resistance that is about 10 times better than conventional insulation materials. A typical VIP, as known today, consists of a core of fumed silica enclosed with a multilayer aluminum polyester film envelope, while the air is evacuated from the inside. (Cremers 2005)

The mechanisms of thermal transfer across the VIPs core material include gaseous and solid conductions as well as radiation, with negligible gaseous convection due to extremely small pore sizes and low pressure. Radiative heat exchange between the interior surfaces is reduced by the use of opacifiers. Conduction through the collision of gas molecules can be diminished by using core material with pore size less than the mean free path of the gas molecules. Nanoporous materials make excellent candidates for core material. Aerogel, fumed silica and precipitated silica offer some of lowest thermal conductivity ranges owing to low density, large surface area and small pores in Nanoscale range [1, 2]. Silica aerogel material has therefore been suggested as VIP core material.

Aerogel for example, has a large surface area (~1600 $m^2 \cdot g^{-1}$) and pores in the range between 5 and 100 nm [3]. These pores occupy about 80 to 99.8% of their total bulk volume. A bulk density as low as 0.003 $g \cdot cm^{-3}$ has been reported, while for typical application aerogel with values of about 0.07-0.15 $g \cdot cm^{-3}$ is used. A low thermal conductivity of 0.017-0.021 $W \cdot m^{-1} \cdot K^{-1}$ at ambient pressure has been established (Hüsing 1998 and Baetens 2010). Fumed silica on the other hand has porosity greater than 90% and a bulk density in the range of 0.06-0.22 $g \cdot cm^{-3}$. The material also has a specific surface area in the range of 100-400 $m^2 \cdot g^{-1}$ which varies with the particle size and a maximum pore size value of about 300 nm has been reported by Gun'ko [4]. A thermal conductivity of about 0.02 $W \cdot m^{-1} \cdot K^{-1}$ at atmospheric pressure has been proven [5, 6].

A good insulation material is the one where the sum of the contributions from radiation and solid conduction is at a minimum. This in addition to the gas (air) conduction 0.026 $W \cdot m^{-1} \cdot K^{-1}$ for conventional insulation gives a total thermal conduction down to a minimum around 0.030 $W \cdot m^{-1} \cdot K^{-1}$. For nanoporous material such as aerogel or fumed silica the gas conduction may be reduced to 0.015 $W \cdot m^{-1} \cdot K^{-1}$ or below, even at atmospheric pressure owing to their nanoscale pores. Despite their obvious technical advantages, their utilization in building industry is limited due to their high market price [2-5]. The current manufacturing processes of silica aerogel thermal insulating materials is laborious and uneconomical [4, 7]. New and economical methods for producing aerogels with properties comparable to those of fumed silica are therefore being pursued.

2. Measuring methods

Thermal conductivity measurements can be carried out with steady state or transient laboratory measurements. When no heat is stored in or generated from a body the temperature in each point will remain constant with time and the conditions are defined as steady-state. The thermal transmissivity can then be studied through stationary measurements with a plate apparatus. In this study the apparatus consists of two independent flat tanks of stainless steel, in which Glytherm-10 is circulated in order to keep the surfaces at constant temperatures. The lower warmer tank is connected to a temperature controlled liquid vessel (Lauda K4R) where the temperature is kept constant with an accuracy of ±0.2 °C, while the colder tank on top is connected to a temperature control unit (Kebo-Grave) that keeps the temperature constant with an accuracy of ±1°C. The dimensions of the lower and upper tanks are 500×1000 mm^2 and 500×500 mm^2 respectively, while the samples are placed in a cylindrical void in the center of a low conductive insulation material consisting of a hard polyurethane sheet with a size of 400×400×20 mm^3. The report of Björk et al. [8] gives further account of the method.

This work also contains the thermal conductivity measurements based on transient theory with the Transient Hot Bridge (THB) method (DIN EN 993-14, DIN EN 993-15) as well as with a Transient Plane Source (TPS) method, (TPS 2500S-ISO/DIS 22007-2.2). The TPS method developed by Gustafsson [9, 10] is a modified version of the Transient Hot Strip method [11]. The TPS method has been described in detail by Log et al. [12], with theoretical considerations having been summarized by He [13]. The measuring procedure is similar to that of the THB method with both methods being based on the transient temperature increase caused by heat supply over a circular surface, but a difference can be observed between the measurement probes. In the TPS technique (recognized in ISO 22007-2), a constant electric power is passed through a double metal spiral between two layers of 25 µm thick Kapton metal. This sensor acts both as a heat source for increasing the temperature of the sample and a "resistance thermometer" for recording the time dependent temperature increase. In the case of both the TPS and the THB method, the voltage across the "meander spiral" is registered during the measurement. The temperature rise can be related to the thermal transport properties of the surrounding materials. The rate of change in the registered voltage corresponds to the resistance variation of the metal spiral when the electric power is held constant. This gives both The thermal conductivity and thermal diffusivity of the sample.

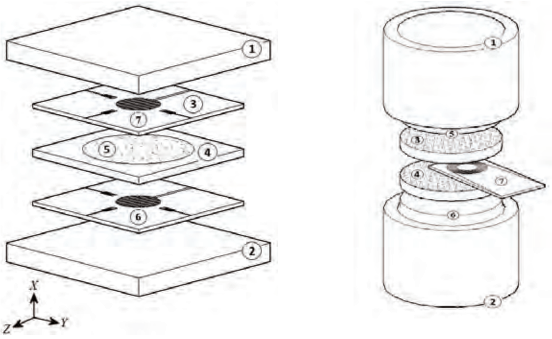

Fig. 1: The arrangement of the Hot plate apparatus at the left hand side and a self-made apparatus applied with TPS method at the right side.

3. Result and discussions

The transient measurements were carried out with a sample temperature of 25°C while the hot plate measurements had an average plate temperature of 25°C. The duration of the transient measurements were in the range of 45-60 seconds for the THB method and the TPS method had a measurement time of 160 s, while an initial time of up to 20 minutes is needed for the sample to achieve the desired test temperature. The steady state measurements lasted 12 hours, the duration of which is based on observation of the variations in the monitored data from the temperature sensors as well as heat flow meters at the initial experiment times. Hence, the calculation of the mean value did not include the initial transient for the temperature changes when the heat capacity in the samples has an influence on the recorded data.

Table 1: The thermal transport properties measured with Hot Plate Apparatus (HPA^a), THB and TPS methods.

Samples	Thermal conductivity mW/m·K		Thermal diffusivity mm/s
A -P100	HPA^a	19.801	-
	THB	23.48	0.1183
	TPS	21.52	0.1827
B	HPA^a	35.958	-
	THB	36.38	0.2509
	TPS	36.01	0.2386
C	HPA^a	34.146	-
	THB	38.57	0.2071
	TPS	34.80	0.1822

4. Conclusions and outlook

The methods give results with a greatest difference of about 15% between hot plate method and THB method. While the stationary hot plate method might be considered somewhat simpler to conduct, the transient methods offer other possibilities. Not only do they offer significantly less measurement time but the possibility to use a much smaller test sample, the latter giving an advantage when producing new materials in the laboratory. In addition, the transient methods provide information about the thermal diffusion coefficient of the material. At current the cost of acquiring the equipment for the transient measurements is greater.

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Exterior vacuum insulation panels for buildings from the Swedish million unit program

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Abstract:
The transmission losses through the climatic envelope represent about half of the energy used for space heating, and a substantial share of the total energy use in Sweden. A reduction of the transmission losses are therefore an important part of the strive towards reducing the energy use of buildings. Vacuum insulation panels (VIPs) provide unique opportunities for slender constructions with superior thermal properties. This study proposes new solutions for improving the thermal performance of a typical wall construction from the great Swedish million unit program, from the 1970s, through the use of exterior VIPs. The proposals are based on parametric analysis of the influence of various design factors on the resulting U-value and dynamic simulations of moisture conditions. The ongoing work involves verifications through full scale measurements of thermal and hygric performance.

Keywords:
Vacuum insulation panels (VIPs), Swedish million unit program, Climatic chamber, Heat and moisture distribution, Comsol Multiphysics® computer software

1. Introduction

A house in Sweden that is to meet the passive house standards must have an insulation thickness of more than 330 mm in the external wall if traditional insulation materials are used. The heavy insulation thickness means that significant living space area may be lost and restrictions are put on architectural possibilities. In terms of refurbishing, there is often too little space available on the inside of the building and the application of external insulation may threaten the architectural values of the facades and pose problems in terms of detailing. The unique insulations properties of VIPs may, however, provide new opportunities since only a fraction of the insulation thickness is required. An account of the use of VIPs can, for instance, be found in the report of the International Energy Agency [1], Ghazi Wakili et al. [2] and Binz and Steinke [3].

1.2. Thermal bridges and Moisture conditions

The in situ performance of VIP panels depends on the properties of the panels and the manner in which they are applied. The implementation of VIPs calls for a building technology that provides an adequate protection of the VIPs, while allowing for necessary maintenance and renovation. The joints at which the panels meet give rise to thermal bridges that increase the heat loss through the building envelope. Previous work of others includes studies of thermal bridges that arise when VIPs are applied in constructions and building details [2], [4] and [5]. Our previous parametric studies show that the thermal edge loss can be compensated with an adjacent layer of thermal conductivity in the range of traditional insulation materials [6].

The implementation of a new building technology relies on a thorough analysis of the moisture performance of the construction, including an evaluation of the risk of condensation and high relative humidity. A number of studies of the moisture performance of constructions retrofitted with VIPs can, for instance, be found in the report of the International Energy Agency [1], Brunner and Simmler [7] as well as Sveipe et al. [8]. Our previous studies include transient modeling of vapor diffusion with Comsol Multiphysics® [9].

1.3. The Swedish Million Unit Program

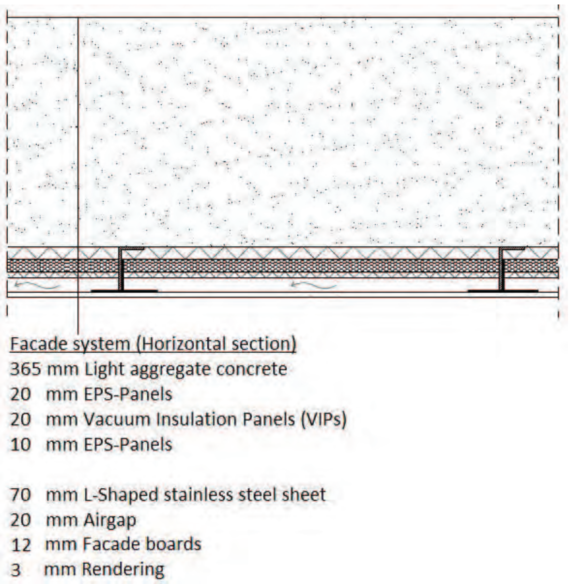
Due to its vast capacity, the Million Unit Program in Sweden must be included in the effort to reduce the energy used for heating. The Million Unit Program is a common name for about one million housing units that were built in a 10 year period around the 1970s, many of which are now in dire need of retrofitting, not at least in terms of thermal insulation. With a high degree of repeatability, it may be argued that there is much to be gained from thorough studies and development of technical solutions for refurbishment. VIPs provide an interesting alternative for the refurbishment of the million unit program. This proposal is based on a parametric analysis of the influence of various design factors on the resulting U-value and dynamic simulations of moisture conditions.

2. Full scale measurements

This study proposes new solutions for improving the thermal performance of a typical wall construction from the Swedish million unit program through the use of new mounting systems for exterior VIPs. The study contains full scale measurements that are being carried out in a climatic chamber at the department of Civil and Architectural Engineering at KTH, in which both the temperatures and moisture distribution will be monitored.

A wall construction of light aggregate concrete blocks, representative of the million unit program, was built in the climatic chamber. The wall, measuring about 12 m^2, is insulated with a VIP sandwich consisting of a 20 mm thick VIP embedded between 20 and 10 mm thick expanded polystyrene panels. The VIP sandwiches are attached to the cellblocks by the means of an adhesive, certificated for loads up to 80 KN·m^{-2} parallel to the wall.

The exterior board and rendering are attached to the wall with specially designed connections that are certificated as “passive house suitable components” by “The Passive House Institute (PHI)” in Germany. The connectors consist of an L-shaped stainless steel sheet metal fastener that connects to a T-shaped profile that carries the board on which the rendering is applied. As shown in fig. 1 the façade is ventilated by the means of an air gap between the board and the insulation.



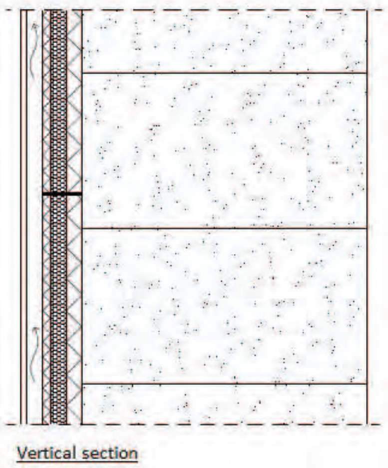


Fig. 1: Horizontal section of the wall construction at the top as well as the vertical section at below.

Two different technical solutions are applied at the 3 mm wide joints at which the panels meet. In both cases the gap is filled with a traditional insulation material but in one case the gap is also covered with a 10 mm thick EPS in order to reduce the thermal bridge. Two different types of adhesives are applied, an industrial glues and an adhesive tape with a durability of approximately 50 years.

Moisture sensors are placed at all the boundaries at which the different layers of the construction meet, both at the center of the VIPs as well as at the joints at which the panels meet. The moisture sensors were modified in order to reduce the size. The sensors are injected into a polymethylmetacrylate pipe in dimensions of 5 and 40 mm, respectively as the diameter and length of the pipe. A number of temperature sensors of type K, copper constantan thermocouple, are also installed at the same depths and locations as the moisture sensors.

A 3-dimension simulation was carried out through the use of 3D FEM simulations software (Comsol Multiphysics®) in order to illustrate the effects of the retrofitting on the heat fluxes through the construction and the moisture. The thermal properties of all materials are obtained through independent laboratory measurements. The thermal transmissivity of the VIPs is studied through steady state measurement with a hot plate apparatus while the Transient Plane Source (TPS) method (TPS 2500S-ISO/DIS 22007-2.2) is used for other building materials. The proposed technical solution will also be assessed with an IR-camera.

5. Result and discussions

The 3D Comsol simulations shows promising results of a significant reduction of thermal losses after retrofitting as well as a major lower risk in term of moisture accumulation at the VIPS joint. The data collection of this in situ measurement is currently under progress and expects to go on for a period of one year. A comparative study of the results of heat and moisture distribution across the wall, before and after retrofitting, will then be published.

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Effect of blow-off rate on the envelope material and vacuum insulation panel

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Abstract:
When envelope bags are packaged in a vacuum chamber, the envelope bags always retain bloating appearance. When gas is injected into a vacuum chamber, the pressure in the vacuum chamber suddenly becomes larger than in vacuum insulation panel (VIP). At the same time, the upper envelope film will be pressed on the surface of the core material as quickly as possible. If there were some vertically oriented fiber on the surface of the core material, the film would be punctured or destroyed by one end of the fiber. The objective of this paper is to investigate the effect of the pressed speed which is controlled by the blow-off rate on the envelope film. The adopted method was to pre-put metal needles on the surface of the core material, and then the blow-off rate was adjusted. After packaging, the VIP properties were examined. The inner pressures of the VIPs prepared by different blow-off rates were tested for a long time to evaluate the damage degree. The results indicated that the best blow-off rate was 1 atm/275 s.

Keywords:
Vacuum insulation panel (VIP), blow-off rate, glass fiber core, inner pressure.

1. Introduction

Vacuum insulation panel (VIP) is fabricated by evacuating micro-porous core material encapsulated in a laminate envelope, normally in a depressurization chamber. The core material supports the VIP mechanically where as the laminate envelope is supposed to be air and water tight to maintain the inner pressure [1, 2]. Especially pertaining to VIPs with glass fiber core material, fiber architecture will not only affect the thermal conductivity coefficient but also may have an effect on the laminate film. Especially for fiber of a particular diameter oriented vertically or perpendicularly to the laminate film. Envelope puncture or defects cannot be tolerated in VIPs as it would lead to sporadic deterioration. In this paper, the effect of blow-off rate on VIP has been investigated. Blow-off speed referred to here is the speed at which a core material bagged in an envelope is compressed to inner VIP pressure of < 1 Pa. Further, the correlation of VIP inner pressure with varying blow-off time has been discussed.

2. Experimental

The experimental set up is as shown in Fig.1.

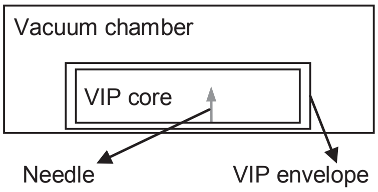

Fig.1 Experiment set-up.

The manufacturing process of glass fiber core material has been reported elsewhere [3]. A needle of diameter and length of 60 μm and 10 mm respectively was put in the glass fiber core material (see Fig.1). The envelope was an Al-laminate type composed of 50 ~ 55μm low density polyethylene (LDPE)/7 μm, aluminium foil (Al)/12 μm, polyethylene terephthalate (PET, coated with 100~300 nm, aluminium)/15 μm, polyamine (PA), laminated under heat and pressure using polyurethane (PU) glue. In all, ten VIP samples were evacuated at blow-off time ranging 20-320 s. The inner pressure was measured with an instrument that operates on similar principle to the Pirani thermal conductivity vacuum gauge (CVM-211, InstruTech, Inc,) [1].

3. Results and discussion

After the evacuation process, the thickness of VIP decreased by about 25~32%. The physical appearances of VIPs with blow-off time are listed in Table 1. At fast blow-off time ranging 20-240 s, visible pinholes were noticed. Photographic images were taken in a dark room to visualize the pinholes, shown in Fig.2. In addition, leakage was obvious as the above VIPs inflated when in atmospheric pressure.

Table 1: Blow-off time and description of VIP.

Blow-off time (s)	Appearance of VIP
20	Damaged and leakage
40	Damaged and leakage
80	Damaged and leakage
160	Damaged and leakage
240	Damaged and leakage
260	Damaged, but no leakage
270	Damaged, but no leakage
275	Damaged, but no leakage
280	Not damaged
320	Not damaged

At blow-off time ranging 260-275 s, the VIP envelope was damaged but no leakage could be determined from the appearances. Contrary, blow-off times of 280 s and 320 s showed no visual evidence of damages.

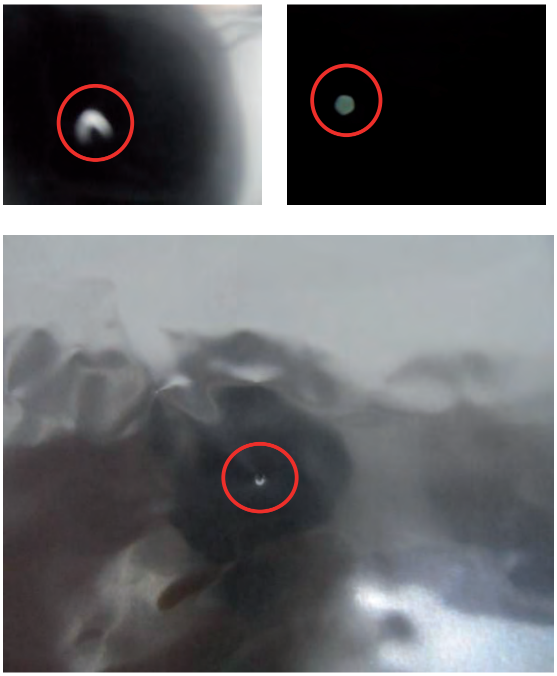

Fig.2 Photographic images showing damaged envelope, in red colored O highlight.

The inner pressure with time was measured and represented in Fig.3. It indicated that the inner pressure would increase when the blow-off rate was above 1 atm/275s. The increase of the inner pressure illustrated that the envelope film had been destroyed.

4. Conclusions and outlook

(1) The effect of blow-off rate on the envelope material and vacuum insulation panel were relatively dramatic.
(2) When the blow-off rate was quick, the envelope film would be destroyed which would lead to the increase of the inner pressure of the vacuum insulation panel. Even if the envelope film commonly had not been obviously destroyed by the glass fibers, micro-cracks could have been produced.
(3) According to the current experiments, the blow-off rate must be below 1 atm/275 s.

Acknowledgements

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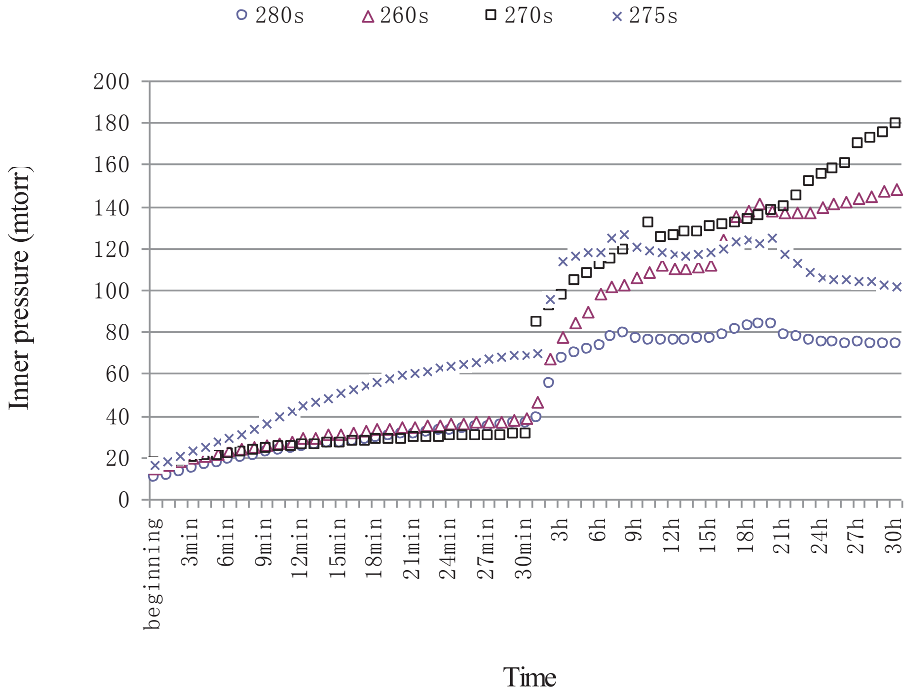

Fig.3 Inner pressure with blow-off time.

Effect of rotating speed on the diameter and distribution of ultrafine glass fiber

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Abstract: The effect of rotating speed on the diameter and distribution of ultrafine glass fiber has been studied by scanning electron microscopy (SEM) and vertical optical microscope (VOM). With the increase of rotating speed from 1800 rpm to 2800 rpm, the mean fiber diameter decreased from 7.2 µm to 3.2 µm, and the geometric standard deviation of the normal distribution curve also decreased from 3.84 to 1.32, indicating the distribution of glass wool become more uniformity. The relationship between mean fiber diameter and rotating speed is fitted by the equation $d=a\omega^{1.6}$. The results show that the rotating speed has a direct and pronounced effect on the fiber diameter and distribution.

Keywords: Ultrafine glass fiber, CSB process, Rotating speed, Fiber diameter

1. Introduction

Glass fiber has been widely used for thermal insulation in VIP materials [1-4], or reinforcing fibers in composite materials [5,6] The fiber diameter and diameter uniformity of glass wool have an important impact on the thermal insulation properties of finished products (panel, felt and pipe). The smaller the glass fiber and the more uniform the fiber distribution, the better the performance of thermal insulation. Hence, it is necessary to decrease the fiber diameter and improve the distribution of glass fiber.

In this paper, ultrafine glass wool was fabricated by CSB process with different rotating speed of centrifugal pan from 1800 rpm to 2800 rpm. The fiber diameter and distribution have been studied by using scanning electron microscopy (SEM) and vertical optical microscope (VOM).

2. Experimental Details

The ultrafine glass wool was fabricated by CSB process in Suzhou VIP New Material Company. Fig.1 is the schematic diagram of CSB process.

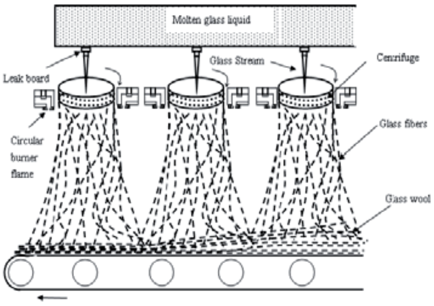

Fig.1Schematic diagram of CSB process

In order to study the effect of rotating speed on the fiber diameter and distribution, other parameters were fixed in this experiment. The rotating speed varied from 1800 to 2800 rpm. The fiber diameter and distribution of glass wool were observed by SEM (JEOL JSM-6360) and VOM (XJL-03). The SEM samples were coated with thin gold. The fiber diameter of glass wool was measured in accordance with the standard procedure of GB/T 7690.5. The histogram of the fiber diameter and the normal distribution curve of the glass wool were derived according to the data observed by VOM. 75 points (fibers) were observed for each sample.

3. Results and Discussion

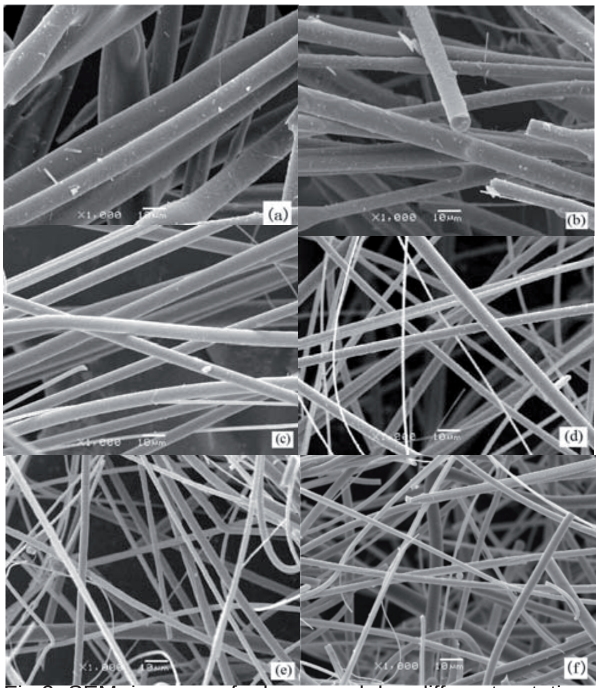

Fig.2 SEM images of glass wool by different rotating speed: (a) 1800 rpm; (b) 2000 rpm; (c) 2200 rpm; (d)2400 rpm; (e) 2600 rpm; (f) 2800 rpm.

Fig.2 is the SEM images of glass wool prepared by different rotating speed from 1800 rpm to 2800 rpm. The surface topography of fibers become smooth and the fibers become uniform when ω=2200 rpm, as shown in Fig.2(c), which indicated that ω=2200 is a key point. Some short fibers are seen in Fig.2(f), which indicated that the rotating speed was too fast and the centrifugal force was too strong.

According to the results observed by VOM, the histogram and the normal distribution curve of the glass fiber are plotted in Fig.3. The mean fiber diameter and geometric standard deviation of normal distribute curve vs. rotating speed is shown in Table 1. With the increase of rotating speed from 1800 rpm to 2800 rpm, the mean fiber diameter and the geometric standard deviation decreased from 7.2 to 3.2 μm, and 3.84 to 1.32, respectively. Therefore, the rotating speed has a direct effect on the fiber diameter and distribution.

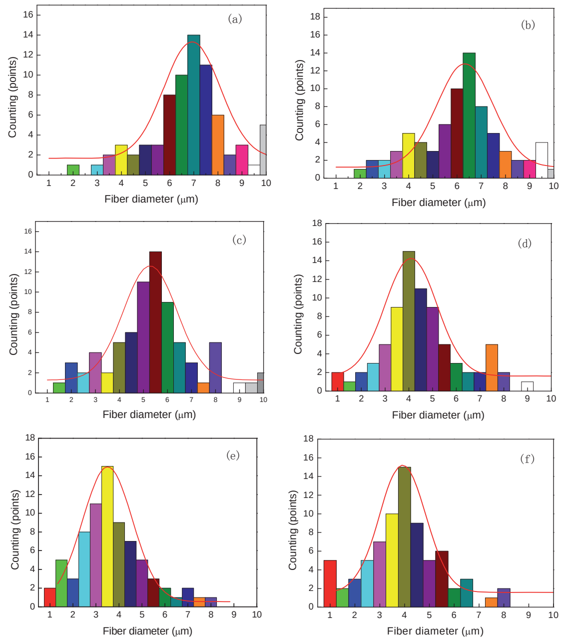

Fig.3 The histogram and normal distribution curve of glass wool: (a) 1800rpm; (b) 2000rpm; (c) 2200rpm; (d) 2400rpm; (e) 2600rpm; (f) 2800 rpm.

Table 1 the mean fiber diameter and geometric standard deviation vs. rotating speed

Rotating speed (rpm)	Mean fiber diameter (μm)	Standard deviation
1800	7.2	3.84
2000	6.0	3.42
2200	4.8	2.87
2400	3.9	1.86
2600	3.5	1.63
2800	3.2	1.32

The mean fiber diameter of fluid obtained by CSB process is mainly controlled by the centrifugal stage. The mean fiber diameter for centrifugal atomisation obeys the following equation [10]:

$$d = \frac{K}{\omega}\sqrt{\frac{\sigma Q}{\rho D}}$$

where d is the mean fiber diameter, K is a constant, ω is the rotating speed, σ is the surface tension of fluid, Q is the flow rate of fluid, ρ is the density of fluid, D is the disk diameter of centrifugal pan.

According to the data of Table 1, the relationship between mean fiber diameter and rotating speed is fitted by the equation $d=a\omega^{1.6}$, as shown in Fig.4.

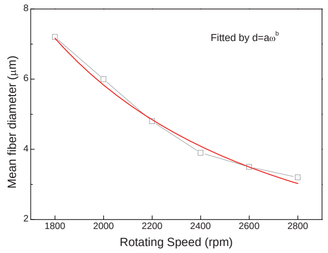

Fig.4 Mean fiber diameter vs. rotating speed

4. Conclusions

The results show the rotating speed has a direct and pronounced effect on the fiber diameter and distribution. The higher the rotating speed, the smaller the mean fiber diameter, and the higher the uniformity distribution of fiber diameter. The optimum rotating speed is about 2600 rpm.

Acknowledgement

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Glass Wool Core Material Produced by Dry process

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Abstract:
Vacuum insulation panel (VIP) is a high performance thermal insulation material composed of an evacuated core material encapsulated in an envelope and supplemented with a desiccant. Glass wool core material can be produced by one of two technologies, namely wet process and dry process. The uniformity of glass wool greatly affects the thermal insulation performance of VIP. This article mainly investigates the dry process of making glass wool core material and presents a new method to coalesce it. By adding swing cylinders under glass wool ultracentrifuges, glass wool was regularly distributed in the forming chamber and led to high uniformity of core material. The weight deviation of glass wool core material was less than 5%. The thermal conductivity of glass wool core material with different processes was contrasted, and it was demonstrated that the uniform glass wool core material can obtain a stable thermal conductivity.

Keywords:
Vacuum insulation panel (VIP), dry process, core material, swing cylinders.

1. Introduction

Heating, ventilating and air conditioning of buildings are the biggest contributor to global energy consumption, as they account for up to 45% of total energy consumption worldwide [1-3]. It is important to reduce the energy loss in buildings, and thermal insulation of buildings is thus a key element to improve the energy utilization efficiency [4]. Vacuum insulation panels are super insulation materials which have a much lower thermal conductivity. Foams, powders, mixture of foams and fibers are used for the VIP core material [5]. In this paper, the production and homogenizing processes of glass wool core material have been studied. Glass wool core material can be produced by dry process. The glass wool core material is fabricated by centrifugal-spinneret-blow (CSB) process, then collected, compression molded followed by cutting [6]. The uniformity of glass wool core material greatly affects the thermal insulation performance of VIP. This article mainly investigates the dry process of making glass wool core material and presents a new method to coalesce it.

2. Dry forming process

The glass wool core material was fabricated by CSB as shown in Fig.1. The primary glass fibers are formed through pores on a pan's surrounding wall by making use of centrifugal force. These primary fibers are immediately affected by air current jetted from ring-form combustion nozzles arranged concentrically with the centrifugal pan, and then further splitted and stretched into secondary fibers, namely, glass wool [7].

The swing cylinders are under ultracentrifuges. The glass wool passes though the swing cylinders when the trajectory of the swing cylinders are similar to a simple pendulum movement. Glass wool falls onto the conveyor belt by the guidance of the swing cylinders. The plane of the swing cylinders movement is perpendicular to the direction of the conveyor belt movement.

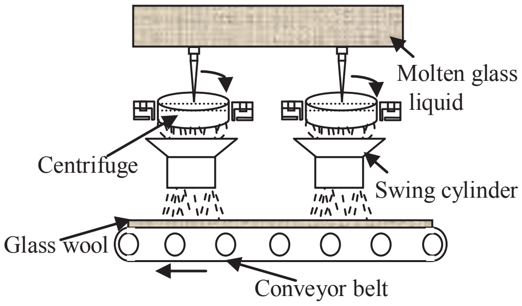

Fig.1 Schematic diagram of CSB process.

3. Experiment

The sample is pure glass wool with no resin, and the fiber diameter varies from 3 μm to 6 μm, approximately. In order to quantify the uniformity of material, coefficient of variation (CV) is calculated by the weight of samples. CV reflecting the uneven rate of fiber material is defined by:

$$CV = \frac{\sigma}{X} \times 100\% \tag{1}$$

where σ is expressed by:

$$\sigma = \sqrt{\frac{\sum_{i-1}^{n} (\Delta X)^2}{n-1}}, \text{ where } \left(\Delta X = x_i - \bar{x}\right) \tag{2}$$

where σ is mean square error of sample, $\overline{x}$ is arithmetic mean of the sample and ΔX is the mean deviation.

The thermal conductivities for glass wool core material and VIPs were determined by heat flow meter thermal conductivity instrumentation (Netzsch HFM 436). The parameters were: difference in temperature of 27.5°C between the upper and lower heat sinks and mean temperature of 25°C.

4. Results and discussion

The glass wool core material was produced by free float type (FFT) and guidance with swing cylinder (GSC), and the uniformity of glass wool is expressed by CV. The CV of FFT and GSC are compared in Fig.2. According to the curves, the greater the density is, the smaller the value of CV. With the same density, the curve culminating from FFT is always above GSC's. The CV of GSC gradually tends to 5%, and FFT's is 8%. The CV gradually tends to a constant value, and the uniformity of glass wool produced by GSC is superior to FFT's.

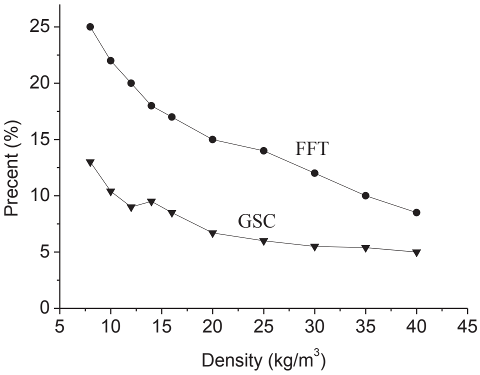

Fig.2 The CV of free float type and guidance with swing cylinder.

In the FFT, the glass wool float freely, and the distribution of fiber is random. In some part of core material, there is little glass wool leading to obvious through pores or blind pores. Under the guidance of swing cylinders, the trajectory of glass wool is sine or cosine curve. Glass wool is evenly distributed to every corner. Even if the density of core material is small, under the guidance of swing cylinders, a uniform core material also will be obtained.

The thermal conductivity of VIPs was measured, and the results are graphically illustrated in Fig.3. One can observe that the mean thermal conductivity of VIPs with FFT and GSC are 3.5 mW/(m·K) and 2.6 mW/(m·K), respectively. The measured values fluctuate along a straight line, and deviation of FFT is larger than GSC's. In the testing process, the internal vacuum degree of VIPs is 0.1 Pa, and the thickness of VIPs is 10 mm.

VIPs with GSC have a flat surface, and the thickness is approximately 10 mm. However, the appearance of VIPs with the core material produced by FFT shows sags and crests, and the surface of such VIPs have obvious grooves. In different parts of VIPs, the thickness is variable, and the average insulation thickness is less than 10 mm in theory. The thermal conductivity is proportional to the insulation thickness. According to theoretical calculations, the thermal conductivity of FFT is smaller than GSC's; however, the result of experimental measurements is opposite to theoretical calculations. In the testing process small amounts of gas are stored in grooves and the thermal conductivity of gas are larger than VIP. In the whole measurement, gases in the grooves cause the thermal conductivity to be larger than the theoretical calculations. The larger the groove volume is, the larger the thermal conductivity is. The number of grooves on the surface is variable, and resulting thermal conductivity changes a lot. This is why the deviation of FFT is larger than GSC's in Fig.2.

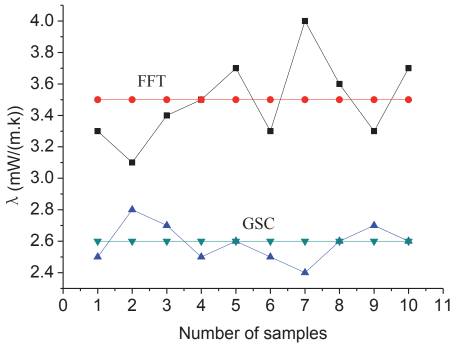

Fig.3 Thermal conductivity of VIPs with different processing.

5. Conclusions and outlook

In this paper, the glass wool core material is prepared by dry process using centrifugal-spinneret-blow process. Swing cylinders are used to unite core material, and the trajectory of glass wool is sine or cosine curve. The mode motion of glass wool is both free float type (FFT) and guidance with swing cylinder (GSC), and coefficient of variation (CV) is used to characterize evenness of glass wool core material. Compared to FFT, GSC uses swing cylinders under glass wool ultracentrifuges; glass wool distributes regularly on forming chamber and leads to highly uniform core material. The core material with sags and crests surface will affect VIPs thermal conductivity. GSC can improve the surface roughness, and obtain stable coefficient of thermal conductivity.

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Development of novel opaque and transparent barrier films for VIP-encapsulation Part-I: Concept

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Abstract:
Novel high barrier films for the encapsulation of vacuum insulation panels are developed in order to improve their thermal insulation performance and to extend their lifetimes. These barrier materials contain several inorganic and hybrid polymeric layers which significantly reduce the gas and water vapor transmission rates of the polymeric substrate film. Their barrier properties can be explained by the interaction between the materials of the different layers.

Keywords:
Vacuum insulation panels, Barrier films, Inorganic layer, Hybrid polymer, Permeation.

1. Introduction

Vacuum insulation panels (VIPs) can meet the demand for durable, efficient and sustainable thermal insulation materials. Their low thermal conductivities are caused by evacuation of nano-porous filling materials, e.g. polymer foams, precipitated or fumed silica and aerogels [1]. In order to hinder the ingress of oxygen, nitrogen and water vapor and therefore to maintain their thermal insulation performance for sufficiently long time, VIPs are encapsulated with high barrier films [1]. Maximum values for oxygen permeability (at 23°C) and water vapor transmission rate (at 23°C, 85%→0% r.h.) as allowed for such films are 10^{-3} $cm^3 \cdot m^{-2} \cdot d^{-1} \cdot bar^{-1}$ and 10^{-3} $g \cdot m^{-2} \cdot d^{-1}$, respectively [2].

2. Structure and barrier performance of VIP encapsulation

Aluminum films are not suited for VIP encapsulation since their large heat conductivity would cause a thermal bridge effect [1]. Therefore polymeric films are used which are coated with barrier layers to reduce their high gas and water vapor transmission rates [3].
Significant barrier improvement of polymeric films can be obtained by vacuum deposition of metallic or transparent oxide layers, e.g. Al, AlO_x or SiO_x, in nanoscopic thickness scale [3]. Barrier films currently used for VIP encapsulation are produced by lamination of up to three metallized polyethylene terephthalate (PET) films together with a polyethylene (PE) film for sealing [1].
However, novel films with better barrier performance are required to reach better insulation properties, longer lifetimes and lower prices of VIPs [2]. Basis of their development is a systematic approach to reduce the permeation of substances through inorganic barrier layers. Defects with a size of 100 nm to some micrometers are the reason for their limited barrier properties. They are caused by surface roughness, particles or mechanical stress [3].
Consequently, the barrier performance of an inorganic layer can be improved by closing these defects. In principle, this can be either done by extending the deposition process resulting in a larger layer thickness or by filling them with another material.
Numerical simulation shows how permeation through inorganic layers on polymeric substrates can be reduced due to filled defects [4]. On the other hand, a barrier improvement via an increase of the layer thickness is only possible up to a certain degree due to limited coverage of the defects and the increase of stress within the layers [5, 6].
As a consequence, hybrid polymeric layers (ORMOCER®) [7] are applied on top of the inorganic layers from the liquid phase. A synergistic effect of both layers improves the barrier performance by up to one order of magnitude. This effect is explained to be caused by filling the defects with ORMOCER® [7] due to its low viscosity.
Moreover, on top of the ORMOCER® layer a second inorganic layer may be deposited. In contrast to the case of two adjacent inorganic layers, such an intermediate polymeric or hybrid polymeric layer interrupts the growth of defects [3, 8] and reduces mechanical stresses in the layer structure [8].
Therefore the defects of the inorganic layers are decoupled resulting in a prolongation of permeation paths (Fig 1). At least in the case of very thin intermediate layers this tortuous path effect explains the low permeation rates measured for these structures [3, 4]. It is also assumed that decoupled defects additionally increase the time lag of permeation [9, 10]. Consequently, the measured low values might correspond to the state of transient permeation.
As an alternative, barrier structures can be made which consist of two polymeric substrates, both coated with an inorganic and an ORMOCER® layer and laminated with their coated surfaces facing together. Permeation rates measured for them are also believed to be influenced by a long time lag.

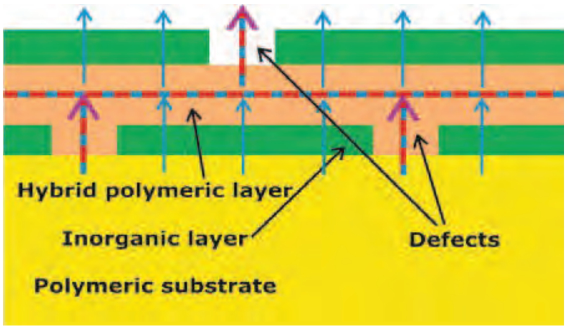

Fig 1: Model for the permeation of oxygen (red) through larger defects and of water vapor (blue) additionally through nanodefects within barrier structures [9].

However, in addition to the considered larger defects also subnano- and nanoscale defects of inorganic layers may contribute to the permeation or even dominate it [3]. Examples are permeation through SiO_x layers [11] as well as water vapor permeation through aluminum layers [5] (Fig 1). The clarification of the barrier mechanisms in these cases is a field of current research.

3. Conclusions and outlook

It was shown how multi-laminate films currently used for VIP encapsulation can be replaced by novel film materials which provide better barrier performance and possibly contain a lower amount of substrate polymers. To reach this aim, gas and water vapor permeabilities of inorganic barrier layers are further reduced by applying additional inorganic and hybrid polymeric layers on top of them.
However, the necessary liquid phase process requires a high dimensional stability of the polymeric substrate under thermal and mechanical load. Otherwise the inorganic layers would be damaged and therefore lose their barrier properties during processing [12]. Further preferable substrate properties are a low surface roughness to obtain a high quality inorganic layer on them [3] and a low price.
Due to its thermomechanical behavior and smooth surface, PET Melinex 401 has proven to be well suited for this application [12]. However, also substrate films with rougher surface can be used if they are pre-coated with an ORMOCER® layer. This layer has a very smooth surface and therefore provides excellent conditions for the deposition of an inorganic layer on top of it [13].
The novel barrier structures consist of inorganic and hybrid polymeric materials in direct contact. Therefore an adaption of material properties like surface tension [14] might be necessary to obtain sufficient adhesion strength between them.

Acknowledgements

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Vacuum insulated panels to fit perfectly the special requirements by refurbishments

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Abstract:
As a specialist for flat roofs, we are frequently called when it comes to water damage due to leakage. Often it comes up to a total refurbishment where the available space plays a key role in the choice of a possible solution. High performance insulation materials and components offer space-saving solutions in this respect. Vacuum insulation offered many advantages and improved substantially the energetic impact of the refurbishment of this terrace. The use of standard formats and thickness helped to be quite competitive, keeping at a maximum the space available and in this case a very comfortable access to the inside.
Nevertheless, it is important to follow the application guidelines and the suggested buildup to avoid damages while placing the panels and in order to ensure long term the insulation value.

Keywords:
Vacuum insulation panels, insulation value.

1. Starting point

Refurbishment to be initiated because of water leakage at the terrace doorsill and at the connection to the central drainage.

Starting Buildup:

Construction Material	Thickness [cm]	λ [W/mK]
Internal plaster	1.0	0.700
Reinforced concrete1% Steel 12	22.0	2.300
Bituminized Board 1 layer	0.3	1.000
Cork: Panels, Sheets	5.0	0.047
Bituminized Board 2 layer	0.7	1.000

In addition
- gravel,
- pavement-slab
- rectangular flower pots along the edges

Calculated U-Value: 0.74 [W/m²K]

Additional Challenges:
- 4 stakes
- Drainpipe from roof
- Terrace discharge (central drainage)
- Limited height of buildup
- Missing emergency overflow

2. Refurbishment proposal:

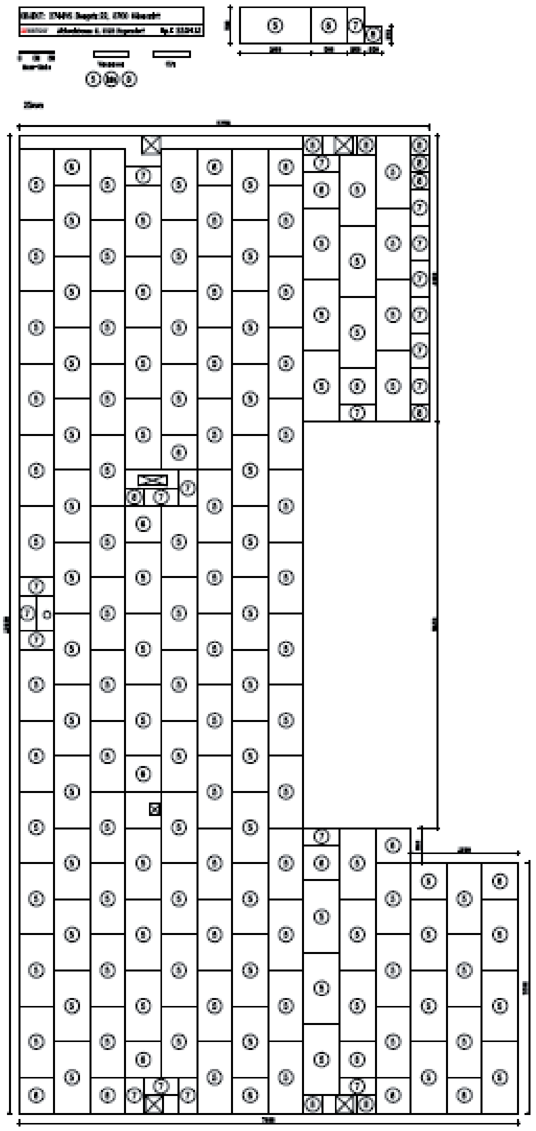
Total new build up:

Construction Material	Thickness [cm]	λ [W/mK]
Internal plaster	1.0	0.700
Reinforced concrete1% Steel 12	22.0	2.300
Bituminized Board 1 layer	0.4	1.000
Protection layer	0.3	0.140
VIP 2x20mm	4.0	0.007
Protection layer	0.3	0.140
Bituminized Board 2 layer	0.7	1.000

In addition

- gravel,
- cleaned pavement-slab

New calculated U-Value: 0.17 [W/m²K]



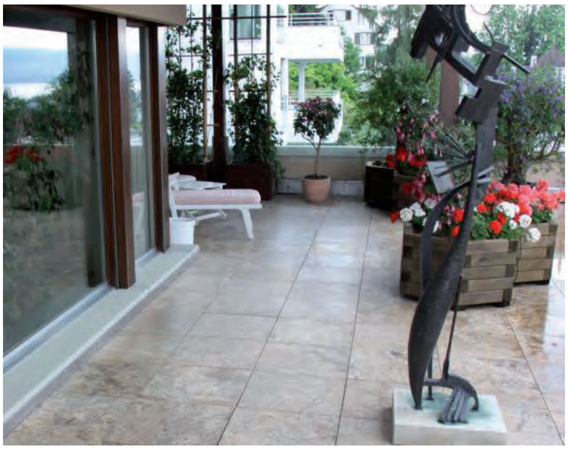
Vacuum insulation needs to be precisely thought out and detailed right from the initial planning phase and a layout plan drawn up. The wide range of modular sizes and standard formats of Vacuum Insulation Panels available on the market allow simplifying the planning and avoid custom-made elements.

Final execution:

- 2 emergency overflows have been added
- 2 layers of insulation panels

Double-layered, offset installation of the VIP insulation panels help to reduce increased thermal flow across any possible gaps in the joint area between the panels.

Terrace discharge (central drainage) had to be completely redesigned and positioned.
Entering edge to the inside leaving area could also be kept as the original.



3. Conclusions

With correct planning and careful deployment, VIP Panels provide very good thermal insulation values with a slim construction.
The wide range of modular sizes and standard formats allowed to be competitive if you take into account the space needed and the increase of the insulation value.

Nanostructured Composites of Silica Aerogels with Hydroxy Terminated Poly(dimethylsiloxane) as Core Materials for Transparent Vacuum Insulation Panels

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Abstract:
Due to their extremely low thermal conductivity, silica aerogels are one of the most promising nanostructured materials as filler materials in transparent vacuum insulation panels. However, their brittle structure complicates their processing and handling as monolithic, crack-free materials. Reinforcing aerogels with polymers results in enhanced mechanical properties that would allow for practical utilization and handling. In this study, hydroxyl-terminated poly(dimethylsiloxane) (PDMS(OH)) - silica aerogel composites were developed with a novel supercritical deposition technique. The chemical composition of the composites was analyzed by ATR-FTIR. The pore structure characteristics were studied with N_2 adsorption by BET technique. The thermal conductivities were determined to evaluate the thermal insulation performance. It was demonstrated that the supercritical deposition of PDMS(OH) with CO_2 results in chemical attachment of the polymer on to the silica aerogel surface which results in transparent polymer – silica aerogel nanocomposites which can be employed for transparent VIPs.

Keywords:
Vacuum insulation panels, silica aerogels, supercritical deposition, aerogel composites, PDMS(OH).

1. Introduction

Effective thermal insulation is a key issue for reduction of energy consumption rates in buildings. Vacuum Insulation Panels (VIPs) are emerging as an excellent solution as these materials have typical thermal conductivity values of 5 to 10 mW/mK depending on the vacuum level inside and the type of core insulation material. VIPs are prepared by placing a core insulation material in an ultra high barrier film and subsequently evacuating air from the inside of the panel to increase the thermal insulation properties. Among different insulation materials that can be used as core materials in VIPs, inorganic-organic composites with high insulation properties emerge as potential candidates.

Silica aerogels appear to be one of the most attractive inorganic components for such composite materials. Silica aerogels are nanostructured materials that have been attracting considerable attention due to their unique and intriguing properties such as low density, monolithic structure, transparency, high surface area, high porosity and low thermal conductivity [1]. Their structural properties combined with their low thermal conductivity made these materials very promising for insulation purposes. However, the fragility of silica aerogels can be stated as one of the major challenges in this area. Hence, there have been various attempts for the improvement of the mechanical characteristics, the majority of which comprises the preparation of silica aerogel composites with various polymers.

In this study, a novel reactive supercritical deposition technique was employed to develop composites of silica aerogels with hydroxyl-terminated poly(dimethylsiloxane) (PDMS(OH)).

2. Experimental Methodology

Silica aerogels were synthesized by a two-step sol-gel procedure using TEOS as the silica precursor. Water, ethanol, HCl and NH_4OH were utilized as solvent, co-solvent, acid catalyst and base catalyst, respectively. After the gelation is achieved solvent exchange with pure ethanol was performed. The gels were dried with $scCO_2$ at 313.2 K and 9 MPa. Monolithic, crack-free and transparent silica aerogel samples were obtained. After synthesizing the silica aerogels the supercritical deposition of PDMS(OH) (M_n=2750) was performed. Figure 1 displays the schematic of the experimental setup that was employed for the deposition experiments. The deposition experiments were performed at 323.2 K. Initially, a certain amount of polymer was placed into the vessel together with the silica aerogel sample. Liquid CO_2 was pumped into the vessel and the polymer was dissolved in CO_2 which resulted in a single phase binary mixture. The silica aerogel samples were exposed to the single phase mixture for certain durations. As the final step of the deposition, extraction with pure CO_2 was performed to remove the excess amount of polymer remaining in the vessel.

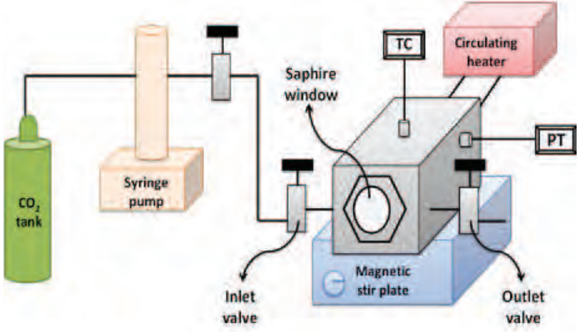

Fig 1: Experimental setup (TC: Thermocouple, PT: Pressure Transducer).

3. Results and discussions

Cylindrical silica aerogel samples with 2.5 cm diameter and 1 cm height were deposited with initial PDMS(OH) concentration of 4 g/L by varying exposure duration. The loaded polymer amount increased with increasing deposition time. 17 %wt. and 50 %wt. polymer contents were obtained for 36 h and 96 h of deposition times, respectively. Fig 2 shows that although the transparency of the silica aerogels decrease with increasing PDMS(OH) amount, transparent samples can be obtained for low polymer contents.

Fig 2: Silica aerogel samples with 17 %wt. (top) and 50 %wt. (bottom) PDMS(OH) content.

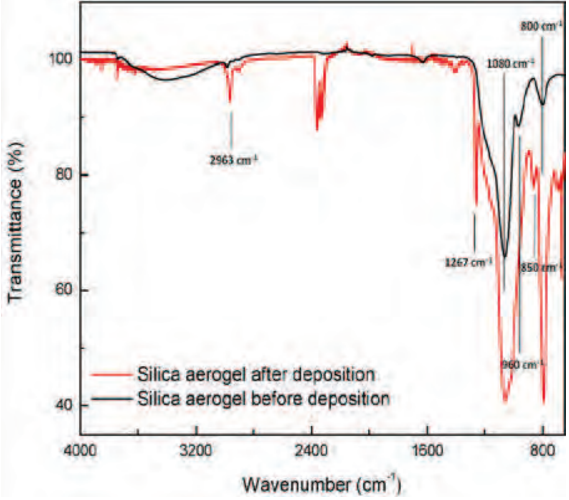

Fig 3: ATR-FTIR spectra of silica aerogel samples before and after the deposition.

The reaction of PDMS(OH) with the surface –OH groups of the silica aerogel was verified with the ATR-FTIR measurements. The peaks that are specific to PDMS(OH) are marked in the spectra displayed in Fig 3. The peak at 2963 cm^{-1} and 1267 cm^{-1} represents the C-H and Si-C stretching vibrations of the methyl side groups of the polymer backbone, respectively. The peak at 850 cm^{-1} was attributed to Si-O-Si bonds that were formed due to the co-polymerization reaction between the Si-OH groups of the aerogel and Si-OH end groups of PDMS(OH) [2] which proves the reaction between the polymer and silica aerogel.

The thermal conductivity measurements for 6x6 cm square aerogel samples were performed with a guarded hot plate device at EMPA. According to the results listed in Table 1, it was concluded that the 3 %wt. of polymer content does not affect the thermal conductivity although the density is increased significantly.

Table 1: Thermal conductivity measurements of silica aerogel samples performed at EMPA

	Density (g/cm^3)	Measured effective thermal conductivity (mW/m·K)
Silica Aerogel 1	0.183	21.4
PDMS(OH)-Silica Aerogel Composite	0.244	21.9

4. Conclusions and outlook

Silica-PDMS(OH) composite aerogels were developed by employing a novel reactive supercritical deposition technique. The technique is composed of the dissolution of PDMS(OH) in supercritical CO_2 that and the exposure of the silica aerogel samples to the single phase binary mixture. During the course of the deposition the polymer molecules are reacted with the surface –OH groups of the aerogel samples. The surface reaction was revealed by specific peaks appeared at ATR-FTIR spectrum. It was shown that high polymer uptakes can be attained depending on the deposition conditions. The deposited samples retained their monolithic structure. In addition the transparency of the aerogels can be preserved at low polymer loadings. The thermal conductivity measurements revealed that the amount of polymer content does not affect the λ values significantly, although the density is significantly increased. The monolithic structure and transparency together with low thermal conductivity are the three crucial features for VIP applications which are retained in the PDMS(OH)-silica aerogel composites that were developed with the supercritical deposition technique.

Acknowledgements

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Study of heat sealing of polymer-metal multilayers used for vacuum insulation panels

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Abstract:
Polymer-metal multilayers have been widely used for decades in packaging industry, and more recently for vacuum insulation panels (VIPs) for building applications. For mechanical and barrier properties, the seal could represent a weak zone. The aim of this paper is to investigate the heat sealing properties of multilayer films composed of one sealant layer and one or three polyethylene terephtalate (PET) layers coated or not with aluminum. Two sealant materials have been studied: polyethylene (PE) and polypropylene (PP). The quality of seal was quantified by peeling test and the failure modes were observed during these tests.

In order to optimize the set of heat sealing parameters, several mechanical and morphological parameters were optimized and compared to failure mechanism evidenced during peeling tests. The influence of sealing temperature and dwell time were first studied for sole sealant material (PE or PP). Then the influence of additive layers was estimated using multilayer. A comparison between the simple film and the multilayer and a study of influence of sealant material were performed in terms of range of optimal heat sealing parameters and mechanical behavior of seals.

Keywords:
Vacuum insulation panels (VIPs), Sealing, Mechanical properties.

1. Introduction

Polymer-metal multilayers have been widely used for decades in packaging industry and more recently in building, as the envelope of vacuum insulation panels (VIPs). The use of multilayer structures enables to have good level of barrier to gas, combined with sufficient mechanical properties. In both cases the seal corresponds to the weakest zone. Even if the optimization of the heat sealing parameters of single layer films have been the subject of many investigations [1, 2], the heat sealing of multilayer has been less studied [3, 4]. Thus the aim of this study is to investigate the heat sealing properties of multilayer films, and to compare them to that of a single layer.

2. Experimental

Materials . The multilayer films are composed of one polyethylene (PE) or polypropylene (PP) layer and one (Complex 1-1) or three (Complex 3-1) polyethylene terephtalate coated or not with aluminum [5]. The low density polyethylene (LDPE) or polypropylene (PP) were employed as the sealing material: a control film was sealed and characterized for comparison.

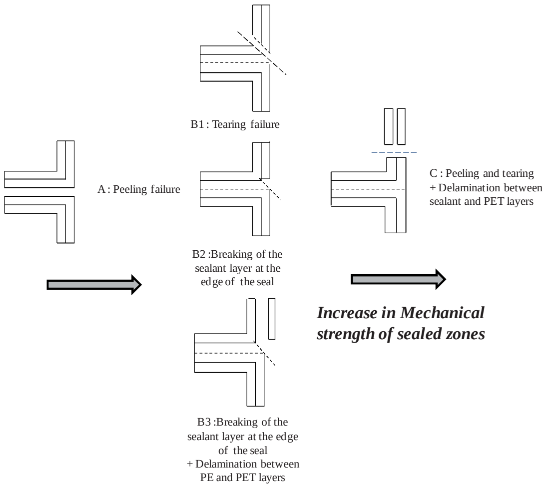

Figure 1. Schematic illustration of failure modes observed in multilayer films

Methods . Heat-seals were performed in the laboratory using Medsealer 460 MSID (K) heat sealer (Francopack). The pressure was fixed at 240 kPa and different experimental conditions were tested, varying dwell times: from 1 to 90 s and sealing temperatures from 110 to 180℃ for multilayers with PE sealant layer and from 180 to 220℃ for multilayers with PP sealant layer. Strips 25 mm wide were used for T-peel test at 90°. The samples were peeled at room temperature in an Instron mechanical testing machine, using a 2kN load cell. The constant rate of loading 100 mm.min^{-1} was chosen and the force F (N) and displacement (mm) were recorded during the test. In this report, the raw data show the force divided by the width (F/W) as a function of the displacement. The maximum force (F_{max}) divided by the nominal width (W) and the thickness (e) of the film is commonly employed to quantify the quality of the seals and defined as apparent seal strength SS. In addition, the failure modes of each test were carefully examined, Fig. 1.

3. Results and Discussion

As shown previously in the literature [1, 2] with monolith films, the most influencing heat-sealing parameter is the temperature. This remains true for multilayer films. In addition the sole observation of failure modes enables to estimate the set of parameters to optimize the mechanical strength of the seal. In fact, the "peeling and tearing mode" (C-mode in Fig. 1) corresponds to the maximal seal strength of the seal [6]. This is further confirmed by the effect of temperature or dwell time on the seal strength.

Even if the study of multilayer sealing presents some similarities with one of simple film: the range of optimal heat sealing parameters, which was included within that of LDPE film, some differences were evidenced, Fig.2. A reduction of the optimal time-temperature range was observed for multilayer with LDPE layer. The latter shrunk a lot with increasing the number of PET layers, and even vanished with PP as sealing layer. In this case no C mode could be observed, even with a large number of samples in the vicinity of the optimal temperature as revealed by DSC experiments. A real advantage for using multilayer was however evidenced in this study. The stiff PET layer, compared to flexible PE or PP sealant layer, improves the mechanical behavior of the structure, and significantly enlarged the maximal strength.

4. Conclusions

In this study, a method of optimization of heat sealing parameters was developed based on the observation of failure modes after peeling tests.

This work has allowed highlighting the interest of multilayer for sealing: an overlap of the range the optimal heat sealing parameters with the one of the sole sealant material and a more elevated mechanical strength of seal in the case of multilayer.

It would now be interesting to study other sealant materials in multilayer and more particularly the influence of the number, the nature (in chemical and mechanical terms) of the different layers of the multilayer.

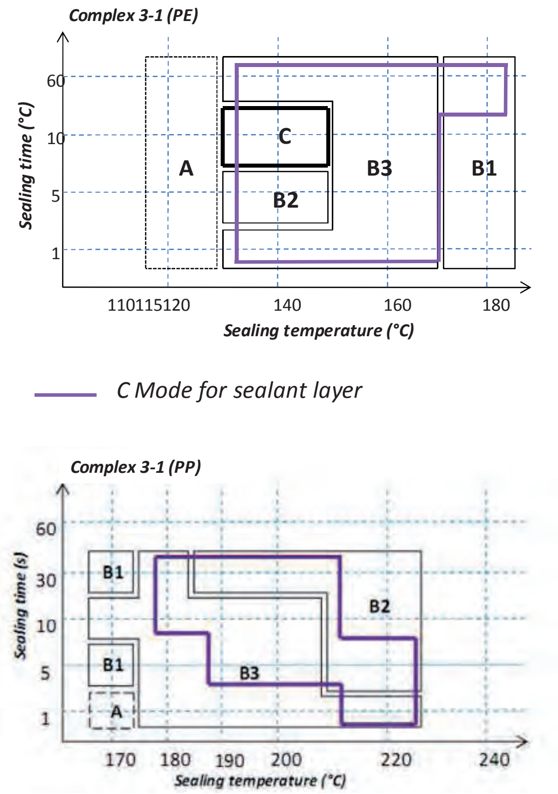

Figure 2. Range of optimal heat sealing parameters for two sealant layers (PE and PP) and for two multilayers "Complex 3-1"

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Hydric behaviour of silica for VIP and ageing

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Abstract:
Nanostructured silica powders are mainly used in the formulation of the Vacuum Insulation Panel (VIP) cores, especially the pyrogenic types. Previous studies indicated on silica ageing induced by the direct exposure to coupled humid atmosphere and temperature. This mechanism is characterized by a modification of the physical and microstructural properties of the silicas: increase of surface hydrophily and decrease of the specific surface area as well. New recent ageing tests demonstrate that this silica ageing phenomenon occurs also inside VIPs. As these properties impact directly on the core material performances, these results lead to the necessity to include this parameter in the VIPs ageing simulations. Furthermore, as the water adsorption capacity of the silica is determined by sorption isotherm measurement, a second consequence of this ageing phenomenon is the necessity to select suitable characterization method, in particular between gravimetric and volumetric ones.

Keywords:
Vacuum insulation panels (VIPs), Core, Hydric behavior, Ageing

1. Introduction

For two ageing studies, pure silica powders and commercial VIPs containing core material, composed of 90 mass percent of a fumed silica powder, were exposed to various humid atmospheres for long times. Hydrous properties and specific surface area of the porous materials were measured.

2. Ageing studies

Study 1 : pure silicas ageing in climatic chambers[1]
Pure silica powders samples were stored in various humid atmospheres generated in climatic chambers. Various parameters were assessed such as:

- Mass of samples after stabilization at 20°C-44%RH,
- **A_{BET}** : specific surface area by N_2 adsorption,
- **ψ_{H2O}** : total (Chemically and physically [2]) adsorbed vapor water surface concentration by TGA analysis,
- VOC identifications and concentrations by combination of ^{1}H, ^{13}C, ^{29}Si MNR techniques and carbon mass concentration measurement.

Study 2 : Commercial VIPs ageing
Three commercial VIP references having the same core material were exposed to high temperature and high humidity atmospheres for more than one year. The mass of core material is composed of 90% fumed silica (noted as FSx) + 5% PET fibers + 5% SiC. PET fibers and Sic have negligible and stable vapor adsorption capacities compared to FS_x.
The VIPs weight variation was noted. Water vapor uptake capacity at 25°C of the core materials and of the fumed silica itself was measured by volumetric adsorption method achieved by an automatic very accurate apparatus (BELSORP AQUA3, BelJapan) after degassing between 140°C and 150°C in vacuum.

3. Results and discussions

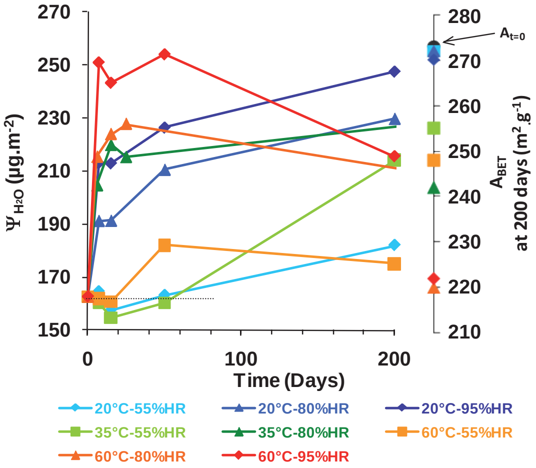

Fig 1: Surface concentration of chemically and physically adsorbed water vapor (ψ_{H2O}) of fumed silica HDK T30 as function of the ageing time – Specific surface area (A_{BET}) at 200 days.

Fig 1 presents the evolution of **ψ_{H2O}** and **A_{BET}** of a fumed silica (HDK T30) established from Study 1. This study brings out that an evolution of the microstructure and hydrophilic behavior of silica powders is effective when exposed to humid atmospheres. The main tendency is as follows: higher the humidity and higher the temperature, higher is the increase of the water adsorption surface capacity and higher is the reduction of the specific surface area. Furthermore, a non expected result was acquired thanks to this study: those ageing tendencies may strongly be modulated by a VOC adsorption. Thus, in Fig 1, the decreases of water concentrations observed for several conditions are due to hydrophobic VOC generated by the climatic chambers themselves.

Table 1: Mass humidity τ , Specific surface area A_{BET} and VIP mass variations measured in Stud.2 (FS$_x$ mass humidity measurements are presented for comparison)

Material	Treatment	A_{BET} (m^2/g)	τ (25°C-50%RH)	VIP mass variation
VIP-1 Core	70°C-90%RH 540 days	134	2.24%	+5.0%
VIP-2 Core	70°C-90%RH 400 days	155	2.41%	+5.3%
VIP-3 Core	50°C-90%RH 540 days	142	2.23%	+5.0%
FS$_x$	Initial state	200	0.94%	-
FS$_x$	23°C-80%RH 30 days	170	2.89%	-

Table 1 and Fig 2 present Study 2 results. Another observation is no inside vacuum loss was noted on the VIPs. Thus, the VIPs mass uptakes associated to the fact that water vapor adsorption of core materials are closed to aged FSx demonstrate that the same evolution of silica powder occurs inside VIPs as well (i.e. increase of surface hydrophily and decrease of specific area).

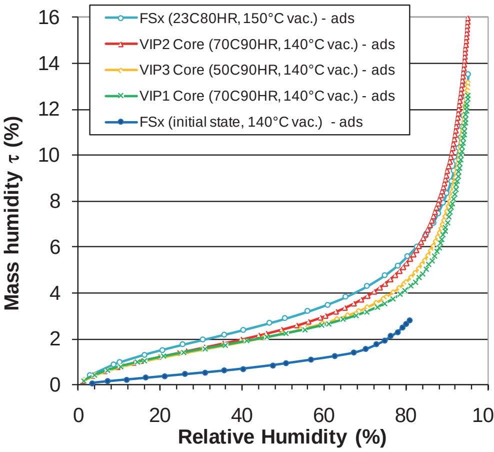

Fig 2 : Water vapor adsorption isotherms at 25°C of aged VIP cores and of pure FS$_x$ silica measured by volumetric adsorption method.

All of these results demonstrate that the determination of hygroscopic sorption properties, using desiccators with salt solution or climatic chambers, as required by the NF EN ISO 12571[3] standard, is not adapted for silica powders and silica powders based core materials. Indeed, the application of the standard may induce a modification of the silica during the test itself, altering its hydrous properties in its initial state. Due to their short time execution (about 3 days for complete adsorption and desorption curves) volumetric adsorption method driven by automatic systems allows to assess the effective vapor sorption isotherm of silica powders in a given moment. The comparison of vapor sorption isotherms measured by both methods in Fig. 2 exhibits this fact.

In addition to the previous observation, the idea consisting in estimating the VIPs internal vapor pressure by measuring the VIP mass variations and linking it to a non aged core material vapor isotherm is also not applicable. As illustrated in Fig. 3, for a same mass humidity τ, the corresponding vapor pressure changes with the evolution of the hydrophilic behavior of the silica powders during their ageing.

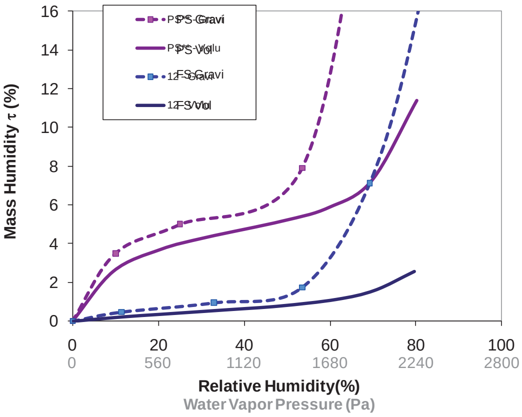

Fig 3: Comparison of water vapor adsorption isotherms measured by volumetric and gravimetric methods on a fumed silica (FS) and a precipitated silica (PS).

4. Conclusions and outlook

The necessity to select suitable characterization method, in particular between gravimetric and volumetric ones, for measuring the water adsorption capacity of silica powders has to be considered. In addition, the hydrophilic behavior of the core materials during VIP ageing has to be considered as well for the prediction of its long-term performances.

Acknowledgements

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The Ageing Effects of Vacuum Insulation Panels (VIPs) on the Long Term Thermal Performance of a Building Envelope with the use of Dynamic Simulation Tools

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Abstract:
This paper presents a computational approach investigating the effect of the gradual decrease of VIPs' thermal resistance, on the total insulation efficiency of a 99.6 m^2 one-storey apartment. An in-house developed code, named VIPMODE, which takes into account dynamic temperature and moisture variations at the boundary surfaces of the VIP was utilized, in order to predict the gradual increase of the panel's thermal conductivity. VIPMODE code was validated against experimental data obtained from the literature and was subsequently integrated with the TRNSYS platform, in order to perform the building full scale simulations. Results, presented in this paper, indicate the significant impact of climatic conditions as well as the effect of the dimensions of the panels on the insulation performance of the envelope during its life cycle.

Keywords:
Vacuum insulation panels, Ageing, Modeling, TRNSYS

1. Introduction

A major issue concerning the long term application of VIPs in buildings is the deterioration of thermal resistance due to gradual increase with time of the initially low internal pressure and moisture content of the panel [1]. As a result, thermal performance of an envelope insulated with VIPs is expected to be gradually reduced. The latter, affects significantly the heating and cooling loads of a building.

Many studies have addressed the ageing issue with the use of heat and mass transfer models [2]. In this work, an in-house code named "VIPMODE" was developed in order to define the ageing of a VIP panel, taking into account dynamic temperature and moisture boundary conditions at the surfaces of the panel. Predictions were compared with experimental data revealing the good accuracy of the code. Moreover, VIPMODE was coupled with the TRNSYS platform in order to simulate the thermal performance of a one-storey building. The study focuses on the effect of VIP ageing, under different climate conditions and type of VIP panels, on the annual heating and cooling demands. Simulations for 50 year periods are discussed.

2. VIP Modeling

The ageing effect of VIP due to thermal resistance degradation is modeled according to the well-known equation [2]:

$$\lambda_{eq} = \lambda_c + \lambda_s + \lambda_g + \lambda_r \qquad \text{(Eq. 1)}$$

Where λ_{eq} is the equivalent thermal conductivity, λ_c is gas convection, λ_s is solid conduction, λ_g *is the* gas conduction and λ_r is the contribution of radiation to the total thermal conductivity. Eq. 1 takes into account temperature, moisture and pressure dependences (λ_s, λ_g) inside the material, as well as radiation inside its pores (λ_r).

In order to study the ageing effect of a VIP panel, an in-house code, named VIPMODE, was developed, based on Eq. 1. VIPMODE code allows the calculation of pressure and mass increase inside the VIP panel taking into account dynamic temperature and humidity conditions on its surfaces. Separation of the gas transmission rate through the surface from the perimeter of the panel allows the simulation of panels with different sizes.

3. Dynamic Building Simulation

In order to quantify the effect of different climatic conditions and VIP sizes on the ageing phenomenon and consequently on the heating and cooling demand of a building, the VIPMODE code was coupled with the commercial software TRNSYS, version 17.0 [3]. For the dynamic interconnection between the two codes, TRNSYS calculates and provides temperature and humidity boundary conditions as input to VIPMODE code, while VIPMODE defines and provides the variation of VIP thermal conductivity to TRNSYS.

4. Materials, building geometry and test cases

The VIP panels investigated in this work consist of fumed silica core with three metalized-film layer membranes. The density is assumed to be equal to 170kg/m3. The area and perimeter related transmission characteristics of the assumed VIP panels are tabulated in Table 1 (WVTRA, ATRA:

water vapor and air transmission rates related to the area of the panel, WVTRL and ATRL the same rates related to the perimeter)

$WVTR_A$ [g/(m^{2}d)]	$WVTR_L$ [g/(m^{2}d)]	ATR_A [cm^3/(m^{2}d)]	ATR_L [cm^3/(m^{2}d)]
0.0022	0.00044	0.032	0.0033

Table 1: Area and perimeter related transmission characteristics of VIP panel (23°C, 50% RH, 1bar)

The simulated apartment (Figure 1) with a floor area of 99,6m², is assumed to be a "middle" floor of a multi-storey building; thus allowing the utilization of adiabatic boundary conditions on the upper and lower boundaries, and focusing on the insulating properties of the external walls. The wall assembly is depicted on Figure 1.

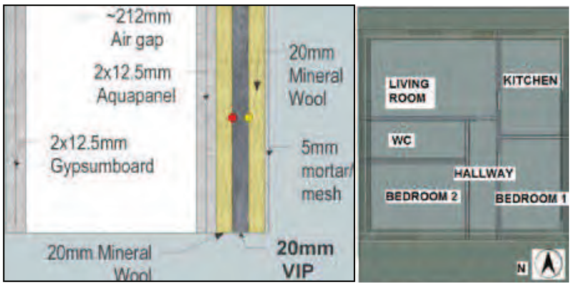

Fig. 1: Wall assembly for the TRNSYS model (left) and room arrangement of the apartment (right)

Parametric studies were performed for three climatic zones corresponding to three European cities (Athens, Zurich and Stockholm). Regarding the VIP panels, two different sizes were examined (100×60×1cm^3 and 100×60×2cm^3). In total, six different test cases were examined.

5. Results and Discussion

The most important findings of the study are summarized in Figures 2 and 3. The worst scenario regarding the deterioration of the thermal resistance of the panel is in Athens where thermal conductivity at 20°C ($\lambda_{eq,20}$) after 50years reaches a value of approximately 16mW/mK. Consequently, annual heat demand in Athens increases up to more than 3 times its initial value; while in Zürich and Stockholm the corresponding increase ranges from 1.4 to 1.5.

The effect of different panel thickness is depicted in Fig.3. An increase of the thickness by a factor of 2 seems to improve the final values of thermal resistance up to 3 times, as total pressure and moisture accumulation per kg of panel is significantly reduced.

6. Conclusions and outlook

The study of VIPs with the use of dynamic simulation algorithms is a valuable tool providing insight of the behavior of the panels with different characteristics under various climatic conditions during their service life. Findings of the current paper suggest that climate conditions and panel size, amongst other, can be a major factor affecting the lifetime of VIP's and are critical issues that need to be addressed during the design of insulation systems for building envelops.

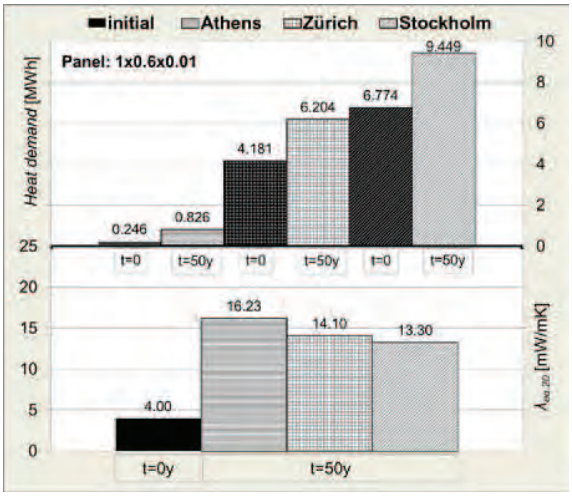

Fig. 2: thermal conductivity and Heat demand at the beginning and at the end of a buildings service life (t=50y).

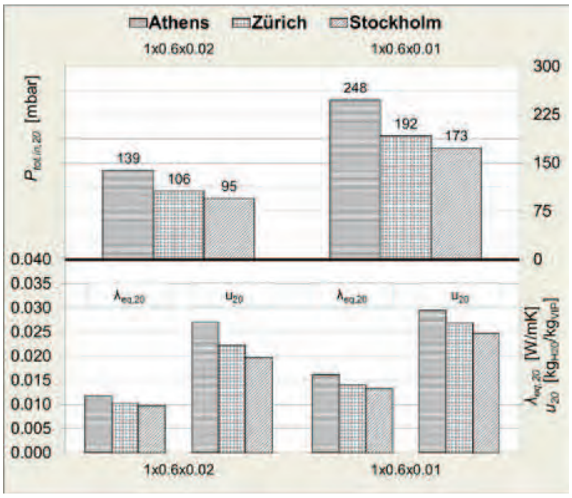

Fig. 3: thermal conductivity, moisture accumulation and panel pressure for 2 panel sizes and 3 climatic regions

Acknowledgements

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Field application and long-term thermal performance of vacuum insulation panels (VIPs) in Canadian arctic climate

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Abstract:

Vacuum insulation panels (VIPs) have thermal resistance values up to 10 times or more than those of conventional thermal insulation materials. In Canada, known for its predominantly extreme cold climate, the potential to apply VIPs in the building construction industry is estimated to be enormous, particularly with the introduction of the new 2011 National Energy Code of Canada for Buildings (NECB 2011) that aims to achieve 25% less energy use in buildings than the energy code requirements set in 1997. VIPs can play a major role in Canadian buildings to meet the new requirements of the NECB 2011. However, lack of long-term performance credentials and various constructability issues are perceived to be the major barriers for mass application of VIPs in the Canadian construction industry.

This paper presents the thermal performance monitoring observations of a VIP retrofitted wall system in Yukon, located in Northern Canada, known for its sub-arctic weather.

Keywords:
Vacuum insulation panels, Arctic climate, Retrofit, Long-term performance.

1. Introduction

The territory of Yukon, located in Northern Canada, is known for its sub-arctic weather, and because of its climate, thermal insulation plays a very important role in building envelope construction in this region [1]. Use of high performance, lightweight and thin vacuum Insulation Panels (VIPs) in northern buildings is potentially an attractive option for the construction industry because of its high insulation value per unit of thickness, and low material volume [2]. Regional stakeholders[1] and researchers collaborated to retrofit a portion of the exterior of an institutional building in Yukon with VIPs. This paper summarizes the construction details of the instrumented VIP retrofitted wall system and critical analysis of selected thermal performance data from winter months.

2. Work plan

The overall work plan of this project can be classified under three major tasks:

Task 1: Laboratory characterization of thermal performance of VIPs.
Task 2: Construction and instrumentation of VIP retrofitted wall.
Task 3: In-situ thermal performance assessment of VIPs.

3. Thermal performance of VIPs

The dimensions of VIPs used were 560 mm (length) x 460 mm (width) x 12 mm (thickness). The thermal characteristic of one VIP specimen was examined before field installation and the R-value per in. of VIP was found to be nominally 42.5.

4. Construction and instrumentation

The cross-section of the VIP retrofitted wall is shown in Figure 1 below. The wall selected for retrofitting was approximately 8.3 m (27 ft.) wide and 3.7 m (12 ft.) high. It was comprised of 38 x140 mm (2x6) wood studs with fibreglass batt insulation and a concrete block exterior, with a nominal total insulation value of RSI 3.5 (R-20). The retrofit insulation goal for this was based on previous studies which showed that the economic wall insulation level in northern locations is in the order of RSI 8.8 - 10.5 (R-50 to R-60). The retrofit increased the nominal R-value from 20 to about 50, with R-21 coming from the VIPs.

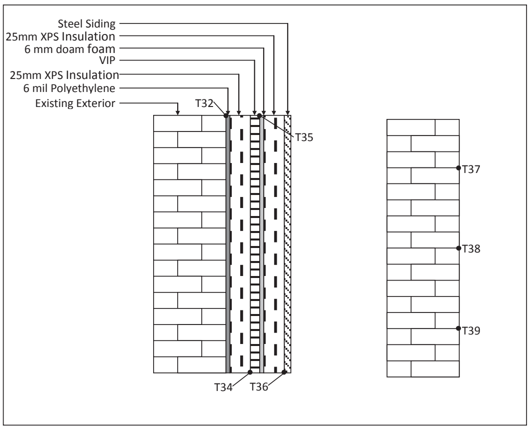

Fig 1: VIP retrofitted wall cross-section with instrumentation (T: Thermocouple)

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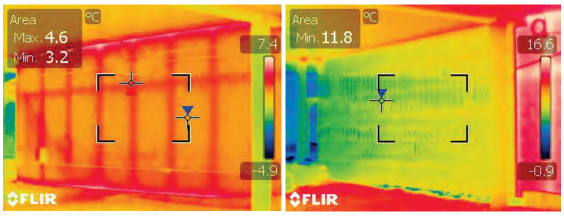
[1] Yukon Technology Innovation Centre, Yukon Housing Corporation, Energy Solutions Centre

Temperature sensors (Figure 1) were placed to assess the effectiveness of thermal insulation by measuring the temperature on the existing wall surface, on the exterior of the first polystyrene layer, on the exterior surface of the VIPs, and on the exterior surface of the second polystyrene layer.
Thermal (infrared) images of the original and VIP retrofitted wall were also taken at the construction site.

5. Results and discussions

Thermal image of the wall was taken at the site before and after the exterior insulation retrofit (Figure 2). Although the ambient temperature is higher than it was when the first infrared image was taken before adding insulation, it is clear nonetheless the area with the greatest heat loss is over the 50 mm x 75 mm (2" x 3") support members which are not covered with VIPs.



(a) Pre retrofit (b) Post retrofit

Fig 2: Infrared Image of the wall

In order to examine the performance of the VIP within the wall assembly, the temperature difference across each of the three exterior insulation layers was monitored and then expressed as percentage (Table 1) to total temperature drop across the exterior insulation. The results in Table 1 show that the temperature difference across the VIP is 70% of the total temperature difference. Each of the dates shows approximately the same results.

Table 1: Percentage temperature difference (selected dates)

Date	% Delta T		
	1st XPS (interior)	VIP	2nd XPS (Exterior)
20-Dec-11 (0:00 to 6:00)	14%	70%	17%
20-Jan-12 (0:00 to 6:00)	13%	70%	17%
20-Feb-12 (0:00 to 6:00)	14%	70%	17%
20-Mar-12 (0:00 to 6:00)	13%	69%	18%
14-Apr-12 (0:00 to 6:00)	13%	69%	17%
Average	**13%**	**69%**	**17%**

This table also shows no significant changes over time in the relative performance of the VIP. That is, the percentage of the temperature difference across the VIP has not changed significantly from December 2011 to April 2012. A graph (Figure 3) showing percentage of the temperature difference across each of the three insulation layers using hourly averages for the entire time period also reaffirms this observation.

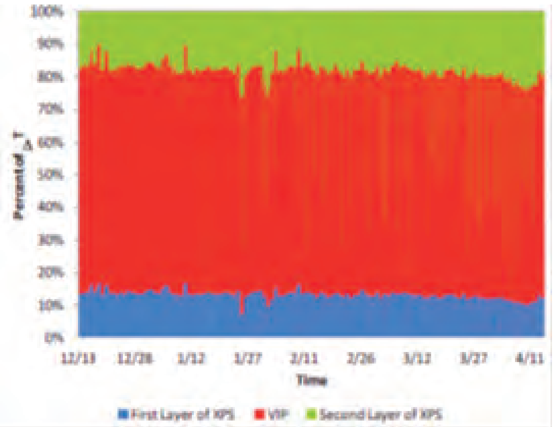


Fig 3: Percentage temperature difference (entire time period)

6. Conclusions and outlook

The results from the first winter field monitoring of the VIP retrofitted wall assembly, constructed in the sub-arctic climate of Yukon (Canada), clearly indicate that there were no significant changes over time, apart from the initial aging indicated in laboratory tests, in the relative in-situ performance of the VIP during the time period from December 2011 to April 2012. This will be examined further in future to determine if there are any reductions in the R value of the VIP over extended time period.

Acknowledgements

The authors are very appreciative of the support of Panasonic Canada Inc. for supplying the vacuum insulation panels used in this pilot project. Authors would also like to thank Yukon Housing Corporation for allowing one of their buildings to be used for this pilot project, and for providing monitoring equipment. The financial help and technical contributions provided by Yukon College are also highly appreciated.

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Experimental Pathways for Achieving Superinsulation through Nano Insulation Materials

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Abstract:
A key strategy in order to achieve energy-efficient buildings is the development of high performance thermal building insulation materials and solutions, also often denoted as superinsulation. One possible and promising way to reach these advanced insulation materials is to exploit the Knudsen effect, where the gas thermal conductivity is reduced as the pore diameter in a material is decreased below the mean free path of the gas molecules, i.e. in the nanometer range. These nano insulation materials (NIM) utilizing the Knudsen effect, and also addressing radiation and solid state thermal conduction aspects, may be made by miscellaneous production techniques. This work summarizes and investigates various experimental pathways for achieving superinsulation through nano insulation materials. Among the different pathways explored, are various techniques to make hollow silica nanospheres (HSNS), e.g. by using selected sacrificial template methods.

Keywords:
Superinsulation, nano insulation material, NIM, silica, hollow, nanosphere.

1. Introduction

In the years to come energy-efficient buildings will increase in demand. In that respect high performance thermal building insulation materials and solutions will play an important role, where one possible and promising way to tailor-make superinsulation is to exploit the Knudsen effect by decreasing the gas thermal conductivity by decreasing the pore diameter in a material below the mean free path of the gas molecules, i.e. in the nanometer range. Hence, the objective of the work reported herein is to summarize and explore various experimental pathways for achieving superinsulation through nano insulation materials (NIM) [1-5]. Special focus is given on hollow silica nanospheres (HSNS) being manufactured by utilizing selected sacrificial template methods.

2. Experimental Pathways

The first experimental attempts were carried out along three paths, namely membrane foaming, gas release and templating. The idea of membrane foaming is to produce foams with nanoscale bubbles, followed by condensation and hydrolysis within the bubble walls to obtain a silica nanofoam, where a gas is pressed through a membrane to obtain bubbles with controlled size. As no surfactant was found that could stabilize nanofoams long enough, this path has so far been abandoned. The gas release method requires simultaneous formation of nanosized gas bubbles throughout the reaction system, followed by hydrolysis and condensation to form a solid at the bubble perimeter, where the bubble formation could be achieved by either evaporation or decomposition of a component in the system. This method is similar to a process described by Grader et al. [6], where crystals were heated to produce foams with closed cell structures. Due to various experimental difficulties the gas release approach has at the moment been terminated. Utilizing the templating process, a nanoscale structure in the form of a nanoemulsion or polymer gel is prepared, followed by hydrolysis and condensation to form a solid. Our starting point was based on the work by Du et al. [7], who used the method to prepare antireflection coatings, and the work by Wan and Yu [8]. For further details it is referred to our initial experimental work [5]. In the following results from utilizing the template method forming HSNS will be presented.

3. Hollow Silica Nanospheres

Currently, our NIM research is mainly focused on various attempts to tailor-make HSNS by manufacturing and applying different sacrificial templates, synthesis procedures, parameter variations, and inner diameters and shell thicknesses of the nanospheres. It should be noted that the future NIMs may not necessarily be based on HSNS, nevertheless the investigations on the HSNS represent a possible stepping-stone towards the ultimate goal of achieving high performance thermal insulation materials. The sacrificial template approach has been described in earlier studies [9-12], where e.g. polyacrylic acid (PAA) and polystyrene (PS) have been utilized as template materials, see Fig.1 for an example of a scanning electron microscope (SEM) image of manufactured spherical PS templates. The templates were hence coated with small silica particles, where an example is depicted in Fig.2 applying a PS template. By removal of the templates, HSNS are formed, see e.g. Fig.3. Other examples are shown in Fig.4, depicting a SEM image and a transmission electron microscope (TEM) image of HSNS with and without PS templates, respectively (different HSNS manufacturing). Powder samples of the HSNS have measured thermal conductivity values typically in the range 20-90 mW/(mK), though some uncertainties in the Hot Disk apparatus measurement method have to be further clarified.

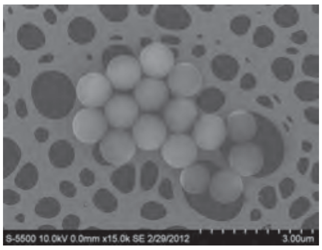

Fig.1: SEM image of spherical PS templates.

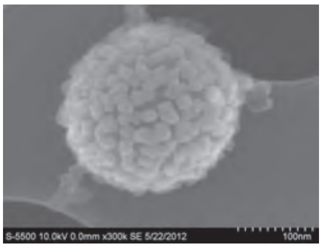

Fig.2: SEM image of small silica particles coated around a spherical PS template.

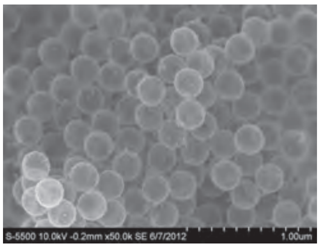

Fig.3: SEM image of HSNS after removal of PS.

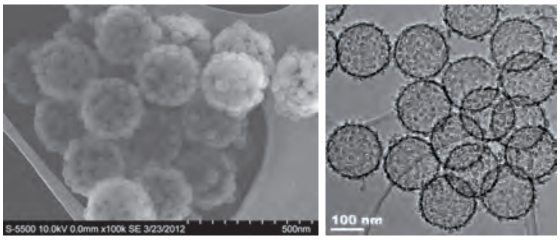

Fig.4: SEM and TEM images of different HSNS with (left) and without (right) PS templates.

4. Conclusions

Hollow silica nanospheres have been manufactured, which thus represent a possible foundation for the development of the future nano insulation materials.

Acknowledgements

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Experimental and Theoretical Study of Vacuum Pressure in Evacuated Windows Used in Energy Efficient Buildings

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Abstract:
Vacuum glazing (VG) is a highly insulating window typically used in energy-efficient buildings. It consists of two or more glass panes hermetically sealed together around their periphery enclosing a vacuum gap. Arrays of tiny support pillars maintain the separation of the panes under atmospheric pressure [1]. This paper reports a detailed experimental study of the internal pressure of vacuum glazing using a newly developed optical system which, unlike the conventional method of measuring vacuum pressure by drilling a hole in the glazing and using the physical connection of a vacuum gauge [2, 3], enables the measurement of the internal pressure without affecting the integrity of the glazing. Samples of indium sealed vacuum glazing incorporating a getter were fabricated. The experimentally and theoretically determined internal pressures of the glazing were in good agreement.

Keywords:
Vacuum glazing, support pillars, polarized light.

1. Introduction

Due to atmospheric pressure a high level of stress exists across a vacuum glazing especially in the vicinity of the support pillars; a schematic diagram of vacuum glazing is shown in Fig 1. Since the stress in the glass panes can change the orientation of the polarization of polarized light, 3-D glasses can reveal such an effect [4]. Based on this principle a system has been designed and calibrated to measure the pressure inside vacuum glazing. The system is a vacuum chamber with two ports; one port is connected to a vacuum pump and the other port is connected to a vacuum gauge. The box has four aluminium and two glass walls as shown in Fig 2.

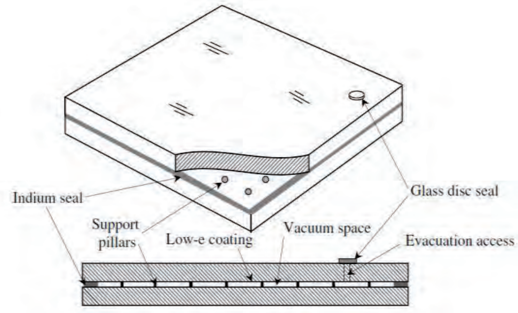

Fig 1: A schematic diagram of indium based vacuum glazing.

2. Optical Measurement Method of the Internal Pressure

Vacuum glazing is placed inside the box and polarized light is directed at the glazing. The light is observed through a 3-D polarized lens after passing through the box as schematically shown in Fig 3. By evacuating the vacuum chamber the pressure difference between the internal space within the vacuum glazing and the vacuum chamber reduces and consequently the stress pattern across the glazing reduces When the two pressures equalize, the stress around the pillars disappears, therefore the pressure on the gauge connected to the vacuum chamber is equal to the pressure inside the vacuum glazing. Using this technique the internal pressure of vacuum glazing samples was measured and the results are presented in Table 1.

Fig 2: Vacuum chamber.

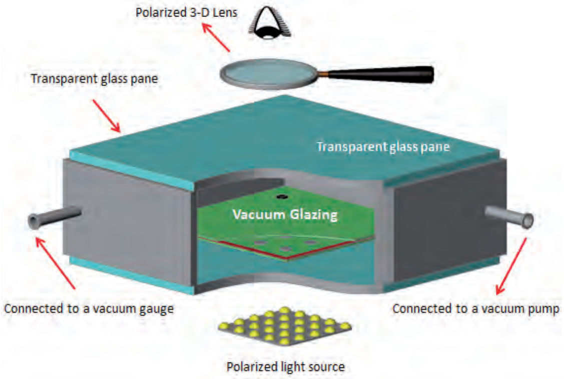

Fig 3: A schematic diagram of vacuum chamber.

3. Fabrication and Characterization of VG

Vacuum glazing samples were fabricated with an indium seal using an ultrasonic soldering technique [6]. The vacuum glazing comprised two K-glass panes, 0.4 m × 0.4 m with low-e coatings (emittance of 0.16) on one side of each pane. Arrays of stainless steel support pillars were spaced at 25 mm intervals on a regular square grid. The pillars had a diameter of 0.4 mm and a height of 0.15 mm. Getters were positioned in one of the samples and after completing the fabrication process, the getters (St707 Pill/4-2/50) were activated at 250℃ using an induction heater. Thermal performance of the samples were characterized experimentally using a guarded hot box calorimeter [5] and their internal pressure were calculated using the Equation below [5]; the results are presented in Table 1.

$$C = 0.8P + 4\varepsilon_{effective}\sigma T_{average}^{3} + 2k_{glass}\, a/\lambda^{2} \quad (1)$$

Where

$$\varepsilon_{effective} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \quad (2)$$

P = internal pressure of VG expressed in Pascals
σ = Stefan Boltzmann constant
$T_{average}$ = average temperature of glazing expressed in Kelvin
A = pillar diameter
λ = pillar separation
K_{glass} = glass thermal conductivity and
$\varepsilon_{effective}$ = effective emittance given by:
ε_1 and ε_2 = emittance

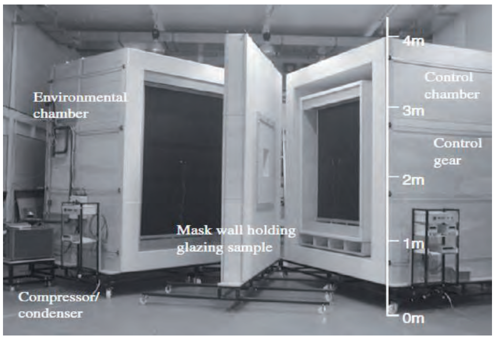

Fig 4: Hot box calorimeter.

Table 1: Results from the hot box calorimeter and the vacuum chamber for vacuum glazing

Sample	Glass surface temperature (°C)		Thermal conductance $(Wm^{-2}K^{-1})$
	Cold side	Warm side	
1	1.4	12.26	3.51
2	0.79	13.41	2.99

Sample	Internal pressure ($\times 10^{-2} mbr$)	
	Calculated	Measured by new system
1	3.8	1.9 – 2.5
2	3.19	1.3 – 2.7

4. Discussion and conclusions

A study of internal pressure of vacuum glazing can provide valuable information about the insulation properties of the glazing. The internal pressure has a direct influence on both the stress profile across vacuum glazing and thermal performance. In this project the relationship between these factors has been studied using a system which enables an evaluation of the internal pressure of vacuum glazing. The thermal performance of vacuum glazing samples has been evaluated using the hot box calorimeter and their internal pressure has been calculated. The results from both methods are in good agreement. The optical measurement of the internal pressure eliminates the need for the physical connection of a vacuum gauge and perforating the glazing. The system may also be used to study the internal pressure of vacuum insulation panels.

Acknowledgements

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Vacuum Insulation Panels (VIPs) Encased in Stainless Steel Envelopes

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Abstract:

A Vacuum Insulation Panel's (VIP's) envelope has a significant impact on its overall thermal performance and where it can be used. Many VIPs are enclosed in a metalized polymer film, or a laminate of polymer and aluminum foil. The polymer film is fragile and limits the VIP to applications where the temperature is below 165 °C. A method of sealing a fumed silica core inside a 51 μm thick stainless steel envelope that can be of any size or shape has been developed. The stainless steel foil has considerably higher puncture resistance than polymer film envelopes and a maximum use temperature exceeding 500 °C. VIPs with a straight edge at their perimeter which translates to a crossover size of 0.8 m have been fabricated. Crossover size occurs when the heat flow through the area of a square VIP's core equals the heat flow around the perimeter. We have an extended edge design that reduces heat flow at its edge by a factor of five. This heat-flow reduction has been confirmed by finite element modeling. Thermal comparator measurements indicate that a 2.5 cm thick VIP with a straight edge achieves a center of panel R value of 6 $m^2 \cdot K/W$.

Keywords:
Vacuum insulation panels, stainless steel envelopes, edge loss minimization.

1. Introduction

In order to utilize VIPs for retrofitting buildings, they need to be cost effective and durable. A stainless steel envelope greatly increases the puncture resistance and is strong enough to be mounted directly on a building's envelope. The stainless steel edge losses can be minimized with a simple extended edge design.

2. Hermetically Sealed Stainless Steel Envelopes

The stainless steel foil is sheared to size, and then clamped between two rings and a punch is hydraulically pressed into the foil, forming a 1.3 cm deep cavity. This stretch process forms the foil so that it remains flat where it will be welded. After a 1.3 cm thick fumed silica layer is placed into each cavity, the assembly is placed in the fixture and evacuated to less than 1.3 Pa through a port in the foil. Inert gas flows below and above the foil in order to prevent the stainless steel from oxidizing during welding. The fixture is shown in Figure 1, and the weld lines of 0.05 mm thick foil are in Figure 2.

3. Minimizing Edge Losses

The thermal edge losses of a panel decrease the effective R value of the insulation. These losses are proportional to the thermal conductivity of the edge material times its thickness. Aluminum and stainless steel have thermal conductivities of 240 and 16 W/(m·K), respectively. The product of $\lambda_{Al} \cdot t_{Al}$ is twice the value of $\lambda_{SS} \cdot t_{SS}$ with 7.6 μm and 51 μm thick films, and the product of $\lambda_{Al} \cdot t_{Al}$ is one tenth the value of $\lambda_{SS} \cdot t_{SS}$ when the total aluminum thickness is 0.3 μm.

A 2.54 cm thick fumed silica core can have an R value of ~9.7 $m^2 \cdot K/W$.[1] Increasing the heat-flow path along the edge reduces the edge losses, and the edge geometry under consideration is shown in Figure 3. The edge losses are from heat flowing through the stainless steel with thickness t_{SS}. The two halves of the VIP have a small transverse jog in both transverse directions to facilitate 100% coverage of a building envelope's surface. The cost of this performance improvement is the extra manufacturing complexity and stainless steel foil required for the indicated jog.

Thermal modeling of the heat flow is challenging because of the large difference between the VIP and stainless steel thickness, t_{VIP} and t_{SS} respectively. The model we developed[2] uses 0.00262 and 16 W/(m·K) for the VIP core (λ_{core}) and stainless steel (λ_{SS}) thermal conductivities, and assumes a thermal short along the hot and cold surfaces of the VIP. A 170x170 node array is used to model a jog surrounded on each side by half the panel's width. The model is schematically indicated in Figure 4. The red resistors are for the stainless steel edge and are thermal shorts compared to the black resistors for the VIP core. Enhanced heat flow regions are indicated

and are adjacent to the thermal shorts. The thermal contact resistance between the panels and between the stainless steel and core is neglected. The reduction in heat flow never reaches the value for a VIP without edges, even with a 30 cm jog.
The model assumes that commercially available stainless steel foil is limited to 1.2m width. The separation between edges, W_{VIP}, is decreased by the thickness of the VIP, t_{VIP}, and the length of the jog. As the jog becomes longer the edges of the VIP get closer together. The width of the weld lines are neglected.

Fig 1: Laser setup for 25 cm samples. Red tube is for Argon gas (flows below & above stainless steel foil). Clear tube is for vacuum.

Fig 2: Laser welded stainless steel, weld width is ~0.5 mm.

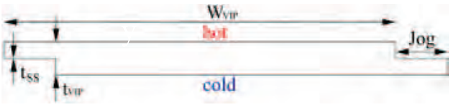

Fig 3: A VIP with width W_{VIP} and thickness t_{VIP}, can minimize thermal edge losses with the indicated Jog.

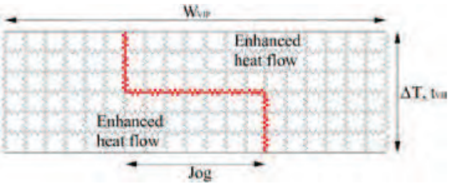

Fig 4: The numerical model lumps all of the thermal resistance between the nodes into a discrete resistance, and then solves a set of simultaneous equations to determine the heat flow within each loop.

4. Results and discussions

A VIP in a stainless steel envelope with a straight edge was placed on a thermal comparator and a center of panel R value was recorded as 6 $m^2 \cdot K/W$.
A VIP edge with a jog was designed to reduce thermal losses. As indicated in Figure 5, the R value for a panel reaches a maximum of 8.6 $m^2 \cdot K/W$ with a ~20 cm jog. This is 89% of ideal fumed silica VIP without edges, and is equivalent to a straight edge that is 10 μm thick. The model assumes a maximum width of 1.2 m for commercially available stainless steel, and increasing the jog's length reduces edge losses but places the VIP's edges closer together.

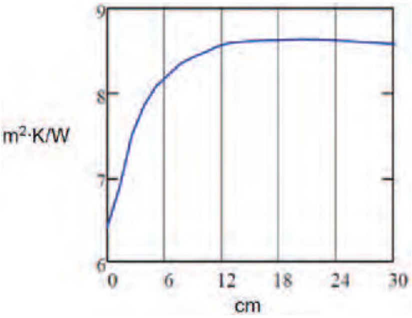

Fig 5: The effective R value vs. jog distance in cm for a VIP with a fumed silica core that is 2.5 cm thick.

5. Conclusions and outlook

A method of evacuating VIPs enclosed in stainless steel through a port has been developed. This allows the VIPs to be of any dimension. Larger VIPs have lower edge losses due to their smaller ratio of perimeter to area. An edge with a jog has been designed to lower edge losses by 75% below losses associated with a straight edge.

Acknowledgements

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Model Benchmarking For Field Energy Retrofit Towards Highly Insulated Residential Wood-Frame Construction Using VIPs

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Abstract:

Field monitoring of the dynamic heat transmission characteristics of residential 2 x 6 wood-frame wall systems that had been retrofitted using Vacuum Insulation Panels (VIPs) and extruded polystyrene foam (XPS) were undertaken in 2011-2012 at the Field Exposure of Walls Facility (FEWF) of NRC-Construction, located in Ottawa. The main objective of this research was to evaluate the dynamic heat transmission characteristics of three side-by-side mid-scale (4 ft x 6 ft) wall assemblies, two of which incorporated VIPs within an XPS layers with different techniques of installation and the third assembly incorporating only XPS, in the FEWF for a one year cycle of exposure to outdoor natural weather conditions. The scope of work included the experimental design, installation of test specimens, commissioning of instrumentation, operation of the test facility, collection and monitoring of data and data analyses, and numerical modeling. A hygrothermal model, known as hygIRC-C, was benchmarked against field measured data. Results showed that the model predictions were in good agreement with the experimental data obtained from the different wall specimens. Given the fragile nature of VIPs that they could be punctured during the installation process (e.g. inadvertent use of fasteners in wall assembly) or may fail during normal operating conditions, the hygrothermal model was used to conduct parametric analyses to predict the thermal resistance (R-value) in cases where one or more VIPs are failed.

Keywords:
Vacuum insulation panels, Modelling, Wood construction, retrofit, residential.

1. Introduction

To achieve high levels of energy performance with existing wall systems and materials, the wall systems would need to be considerably thicker and this may be less acceptable to consumers because of the loss of usable floor area, greater weight, increase in costs due to transportation, and time of construction, as well as new challenges for the structure associated with greatly increased wall thickness. To maintain reasonable envelope thickness while having high thermal performance, a promising recent innovation in building technology was investigated within the context of its application using Vacuum Insulation Panel (VIP) systems. VIPs are of interest owing to their exceptional insulating R-value, up to R-60 per inch or even higher. The VIP technology can be used in retrofitting existing homes. It can also be used in new construction such as in double stud wall wood-frame construction [1].

2. Objectives

The main objective of this paper is to describe the results derived from the use of a numerical model to evaluate the dynamic heat transmission characteristics of three side-by-side 2 x 6 wood-frame wall assemblies (4 ft x 6 ft), two of which incorporated VIPs within either an XPS Tongue and Groove (T&G) configuration or VIPs within an XPS Clip-On (C-O) configuration, and a third assembly incorporating only XPS. The three wall assemblies were installed in NRC-Construction's Field Exposure of Walls Facility (FEWF) for a one year cycle of exposure to outdoor natural weather conditions. The numerical model was benchmarked against the measured data that was obtained from field monitoring of these wall systems in period between May 2011 and May 2012. Given that the VIPs could be punctured during the installation process (e.g. inadvertent use of fasteners in wall assembly) or that some panels could fail during normal operating conditions, the numerical model was used to conduct parametric analyses to allow predicting the R-value in cases where one or more VIPs failed.

3. Model Description

The hygIRC-C model [2] simultaneously solves the highly nonlinear 2D and 3D Heat, Air and Moisture (HAM) equations that define values of heat, air and moisture transfer across the wall assembly. These equations were discretized using the Finite Element Method (FEM). Having previously benchmarked the present model to several tests undertaken in controlled laboratory conditions (e.g. see [3]), a subsequent and important step was to benchmark the present model against field measurements.

4. Retrofitted Wall description

The backup wall for all three retrofit strategies consisted of interior drywall (1/2 inch thick), polyethylene air barrier (6 mil thick), 2 x 6 wood-frame having friction-fit glass fibre batt insulation installed between vertical studs, OSB (7/16 inch thick), and Tyvek sheathing membrane. The backup wall was retrofitted by adding different configurations of external insulation. The first wall (W1) was retrofitted by adding an XPS layer (2 inch thick) between the sheathing membrane and vinyl siding. The other two walls were retrofitted with Vacuum Insulation Panels (VIPs) using two concepts as described below.

In the second retrofit concept (W2), each VIP having a nominal thickness of 15 mm (5 panels in total), was sandwiched between two XPS boards, the exterior board being 1 inch thick and the interior board 5/8 inch thick. To protect the VIP, a hollow piece of XPS of the same thickness as the VIP was cut and the VIP panel was placed inside the opening such that the VIP would be protected by the XPS surround. The assembly, consisting of the VIP and XPS surround, was placed between the exterior and interior XPS layers to form a “Tongue and Groove (T&G)” VIP “sandwich” [4].

In the third retrofit concept (W3) (see [4]), the VIP sandwich was similar to the previously described second concept VIP sandwich, but without the tongue and groove assembly. In this concept, five VIP sandwiches were assembled using clips; hence, the retrofitted wall specimen was called “Clip-On” (C-O) VIP. Vertical furring strips (16 inch o.c. and 5/8 inch thick) were attached to metal clips, which supported the C-O VIP assembly and provided the nailing surface to which the smart board was attached [5].

5. Material Properties

The measured thermal conductivity of the VIP layer, λ_{eff} (in W/(mK)), as a function of temperature, T (in $^{\circ}$C), that was used in the numerical simulation is given as:

$$\lambda_{eff} = a + b \times T, \; \mathrm{a} = 0.002054, \; \mathrm{b} = 7.03088 \times 10^{-6}. \qquad (1)$$

The above correlation of λ_{eff} is in good agreement with all measured values at different temperatures (within ±1.6%). The corresponding average R-value of the VIP sample (15 mm thick) is 7.03 m^2K/W (39.9 $ft^2hr^{o}F$/BTU).

6. Results and discussions

The benchmarking exercise is very important in gaining confidence of the model. In Figure 1 is shown one of the comparisons between the measured and predicted values of heat flux during the test period at different locations for the T&G VIP retrofit wall specimen (W3). The predicted values of heat flux were in good agreement with the measured values at the XPS–OSB interface. All R-values presented in this paper for different wall specimens are the surface-to-surface R-values. Figure 2 shows a comparison between the R-values for different wall specimens. As shown in this figure, the XPS retrofit wall assembly (W1) resulted in the lowest R-value (29.6 ft^2 hr ^{o}F/BTU); whereas the C-O VIP retrofit wall assembly (W2) resulted in the highest R-value (55.4 ft^2 hr ^{o}F/BTU).

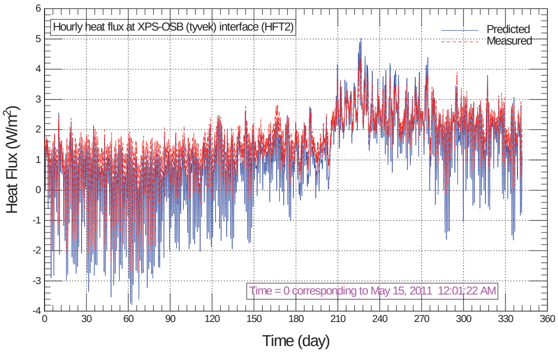

Figure 1. Comparison between predicted and measured heat fluxes at XPS-OSB interface for T&G VIP retrofit wall specimen (W3)

The R-value of the T&G VIP retrofit wall assembly, W3 (without furred-airspace) was 53.8 ft^2 hr ^{o}F/BTU, which is lower than that for W2 by 1.58 ft^2 hr ^{o}F/BTU. This means that the furred-airspace in the C-O VIP retrofit wall assembly (W2) having surface emissivity of all surfaces bounded in the airspace of 0.9 contributed to the R-value by a value of 1.58 ft^2 hr ^{o}F/BTU.

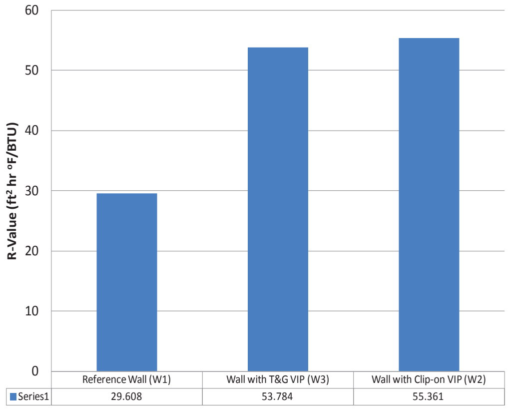

Figure 2. Comparisons between the R-values of different wall specimens

As explained in the report by Maref et al. [5], the test results of the C-O VIP retrofit wall specimen (W2) showed that one of the VIPs failed during normal operation (at time = 202 day). At time = 271 days, this VIP was subsequently replaced by a new VIP component once it became apparent that the expected thermal performance of the wall was not being achieved. The R-value of the failed VIP was measured and found the R-value reduced from 39.9 $ft^2hr^{o}F$/BTU to 3.32 $ft^2hr^{o}F$/BTU (a factor of approximately 12). Consequently, because there is always a risk of puncturing VIPs either during the installation process or over the course of its in-service use, a parametric study was conducted to predict the R-value of the wall assembly when one or more VIPs is punctured or failed by other means. Furthermore, because the VIP is more expensive than an XPS panel, this parametric analysis was conducted to determine the R-value when one or more VIPs is replaced by an XPS panel of the same dimension as that of the VIP. In these analyses, six cases were considered. These cases are shown in Figure 3a through Figure 3f for the T&G VIP wall specimen (W3). The sizes (length, height and thickness) of the VIP-1 through VIP-4 are equal. The length and thickness of the VIP-5 is similar to other VIPs, but its height is equal to half the height of other VIPs. In Figure 3f, the case-VI represents the situation when the five VIPs in Figure 3a have either failed or been replaced by a XPS layer. When one or more VIPs is replaced by a XPS layer, the temperature distributions for the different cases (i.e. case-I through case-VI) are shown in Figure 3a through Figure 3f.

It is important to indicate that when all VIPs were failed (case-VI), the R-value of the T&G VIP wall specimen (R = 30.139 ft^2 hr ^{o}F/BTU) is only 1.8% higher than that for the reference wall (XPS retrofit wall specimen, R = 29.608 ft^2 hr ^{o}F/BTU (see Table 1). Therefore, consideration must be given when handling and installing VIPs for retrofitting wall specimens to minimize the risk of puncturing the VIP. As indicated earlier, the measured thermal conductivity and R-value when the VIP was failed were 0.0257 W/(m.K) and 3.32 ft^{2}hr^{o}F/BTU, respectively. On the other hand, the R-value of an XPS layer (thermal conductivity = 0.029 W/(m.K)) of the same thickness as a VIP (15 mm thick) is 2.94 ft^{2}hr^{o}F/BTU, which is approximately equal to the R-value of a VIP when it was failed. As such, the reduction in the R-value when replacing a VIP by XPS layer is approximately the same as when the VIP has failed. For example, for the situation when the VIP is replaced by a XPS layer, Table 1 shows that the R-values are reduced by 8.3%, 25.1%, 41.8%, 58.6% and 76.2% for case-II, case-III, case-IV, case-V and case-VI, respectively, which are approximately the same as when the VIP has failed. Hence, unless the VIP panel itself can be replaced, there is no benefit in respect to thermal performance of the overall assembly if replacing it with an XPS panel.

Table 1. Comparisons between R-values for case I through case VI (see Error! Reference source not found.) of T&G VIP wall specimen (W3)

Case	**R-value of wall assembly having failed VIPs (ft^2 hr ^{o}F/BTU)**	**R-value of wall assembly having VIPs replaced by XPS (ft^2 hr ^{o}F/BTU)**	**Reduction in R-value due to failed VIPs**	**Reduction in R-value due to replacing VIP by XPS**
case-I	53.784	53.784	0%	0%
case-II	49.545	49.653	8.5%	8.3%
case-III	42.761	42.982	25.8%	25.1%
case-IV	37.641	37.923	42.9%	41.8%
case-V	33.593	33.906	60.1%	58.6%
case-VI	30.139	30.468	78.5%	76.2%

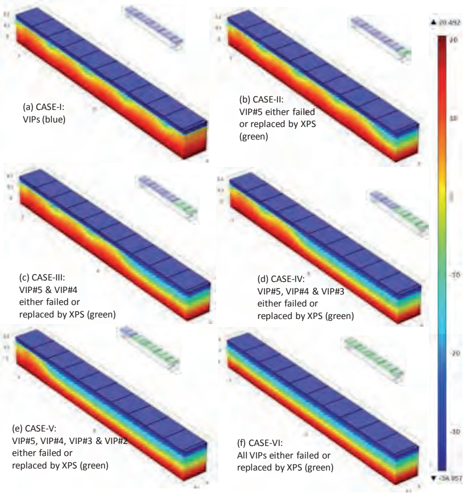

Figure 3. Temperature contours for case I through case VI of T&G VIP wall specimen (W3)

7. Conclusions

In this study, steady-state and transient numerical simulations were conducted to predict the thermal performance of residential 2 x 6 wood-frame wall specimens that were retrofitted using VIPs (W2 and W3) and extruded polystyrene foam, XPS (W1). In order to determine the R-values of different wall specimens, the steady-state numerical simulations were conducted using the same outdoor and indoor conditions as described in the standard test method using a Guarded Hot Box (GHB). Results showed that the XPS retrofit wall specimen resulted in the lowest R-value (29.6 ft^2 hr ^{o}F/BTU), whereas the C-O VIP retrofit wall specimen resulted in the highest R-value (55.4 ft^2 hr ^{o}F/BTU). The R-value of the T&G VIP retrofit wall specimen (without furred-airspace) was 53.8 ft^2 hr ^{o}F/BTU, which was lower than that for the C-O VIP retrofit wall specimen (with furred-airspace) by a margin of 1.58 ft^2 hr ^{o}F/BTU. The numerical results derived for heat flux were compared with the measured values of heat flux and the results showed that the comparison between the present model predictions and experimental data were in good agreement.

Acknowledgements

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EMPA Materials Science & Technology

IVIS 2013

About the host:

Empa is the ETH Domain's interdisciplinary research institution for materials science and technology. The ETH Domain comprises the two Federal Institutes of Technology ETH Zurich and EPF Lausanne and the four research institutes PSI, WSL, Empa and Eawag.

Previous IVIS:

7th International Vacuum Insulation Symposium, Dübendorf	2005 [1]
8th International Vacuum Insulation Symposium, Würzburg	2007 [2]
9th International Vacuum Insulation Symposium, London	2009 [3]
10th International Vacuum Insulation Symposium, Ottawa	2011 [4]

These IVIS are in continuation of VIA Symposia from 1998 to 2003 (Vacuum insulation association) and the follow-up biannual symposia of IVIS since 2005. The first Symposium in 1998 was organized by Mr. Manini from SEAS Getters and lead to the VIA (Vacuum insulation association). Additional to these, Empa has organized in 2001 a conference and workshop on High Performance Thermal Insulation Systems - Vacuum Insulated Products (VIP) [5] under the IEA ECBCS frame. A new IEA ECBCS annex on Superinsulation is in preparation. In 2012 there was a symposium organized by BBRI and Empa. The booklet related to the International Symposium Superinsulating materials Brussels, Belgium, 26 April 2012 is online at [6].

Coming IEA EBC Annex 65 "Superinsulation":

IEA ECBCS recently transformed to IEA EBC [7] and the new logo with the transformation shall represent not only small houses , but also larger buildings and community scale technologies as shown on the EBC News Issue from June 2013 [8]. This issue has by coincidence Empa's aerogel based render on its title page, and it shall be mentioned here, that a team involved in VIP projects won the "Empa – Innovationspreis 2012". The coming IEA EBC Annex 65 "Superinsulation" will cover both Aerogel Based Products and Vacuum Insulated Products (VIP).

EBC

EBC NEWS

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