PLEA NOTES

note **2**

Passive and Low Energy Architecture International
DESIGN TOOLS AND TECHNIQUES

THERMAL INSULATION

András Zőld and Steven Szokolay

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THERMAL INSULATION

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Department of Architecture, The University of Queensland
Brisbane 4072

András Zöld is professor of Building Physics at the Technical University of Budapest (Hungary), chairing the Department of Building Energetics. He is author of numerous books on energy conservation, energy economics in buildings and he serves on both national and international standards committees.

Steven V. Szokolay was Director of the Architectural Science Unit and later Head of Department of Architecture at the University of Queensland—now retired. He has a dozen books and over a hundred research papers to his credit. He is a consultant to various UN bodies and served on numerous government committees. He is currently President of PLEA.

The manuscript of this publication has been refereed by
John Martin Evans, Director, Research Centre for Habitat and Energy, University of Buenos Aires.
and
Dr. Nick Baker, Director, The Martin Centre, Department of Architecture
The University of Cambridge

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PREFACE

The Directorate of PLEA (Passive and Low Energy Architecture) International recognised the lack of inexpensive but authoritative texts on various topics relating to sustainability, to the design of buildings for passive environmental control. In response to this need it was decided to produce and publish a series of **PLEA Notes**, under the overall title: **Design Tools and Techniques**.

The first in the series: **Solar geometry** has been published last year and the present **Thermal insulation** is Note 2 in the series. Note 3, on **Thermal comfort** is in preparation and it is likely to be published later this year.

Further titles in preparation are:

- Radiative and evaporative cooling
- Control of open spaces
- Energy issues in sketch design
- Daylighting.

Any suggestions for further topics to be covered, offers of contribution, as well as comments and criticisms would be welcome and should be addressed to me, as series editor, at
P O Box 851, Kenmore, 4069, Australia
fax No: 61 7 3378 1051 or
e-mail: S.Szokolay@mailbox.uq.edu.au.

These **Notes** are available at the same address.

Steven V. Szokolay
January 1997

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CONTEXT

Thermal insulation is one of the most important techniques in the hands of the architect for providing indoor thermal comfort with minimal energy use. Insulation can drastically reduce, in some cases almost eliminate heat flow through the building envelope. Its role is most significant in climates where the thermal problem is constant for long periods of time, such as

1) in cold climates, in heated buildings, where heat loss is to be reduced
2) in warm climates, in air conditioned buildings, where heat gain is to be minimised

In climates where cold winters alternate with hot summers, insulation may be beneficial in both seasons.

However, in climates with large diurnal variations, or in any climate where the building can satisfactorily operate 'free running', i.e. without heating or cooling, the significance of insulation is much reduced. Here several other thermal control strategies may be used.

In hot-dry climates the thermal mass of the building can be relied on to even out the large diurnal variation of temperatures. In fully cross-ventilated buildings of warm humid climates the role of insulation is reduced to practically nil, as the indoor air cannot be lower in temperature than the outdoor, so there is no temperature difference. Exceptions are all envelope elements exposed to solar radiation, particularly the roof. Here the heat flow is driven **NOT** by the outdoor-indoor air temperature difference, but by the difference between the sol-air temperature of the outer surface (which expresses the combined effect of air temperature and solar radiation) and the indoor air. For such elements insulation is advisable.

Undoubtedly, insulation is paramount from the point-of-view of energy conservation. It is in consistently cold, or consistently hot climates where buildings use the most energy for heating or air conditioning. And it is under such circumstances that thermal insulation is most effective.

The present Note deals with thermal insulation only. Future Notes will be devoted to other techniques of passive thermal control.

Some may find the present Note too theoretical, abstract and short of actual application examples. This is however quite deliberate. The authors believe that rather than presenting ready-made solutions for a large number of different problems, the principles must be clarified, as if one knows these principles, one can derive the solution for any situation. The best procedure for any situation is to check what the heat trasfer mechanism is and select the appropriate insulation accordingly.

Symbols and abbreviations

A	area	(m^2)
AH	absolute humidity, moisture cont.	(g/kg)
C	conductance	(W/m^2K)
DBT	dry bulb temperature	(°C)
E	radiant emission	(W/m^2)
F_s	shape factor	
G	global (solar) irradiance	(W/m^2)
H	heat stored	(J/K)
Hs	saturation absolute humidity	(g/kg)
L	volume flow in ventilation	(m^3/h)
P	permeance	($mg/s.m^2kPa$)
Q	heat flow rate (flux)	(W)
R	resistance	(m^2K/W)
R_{a-a}	air-to-air resistance	(m^2K/W)
R_{so}	surface resistance, outside	(m^2K/W)
R_{si}	surface resistance, inside	(m^2K/W)
R_v	vapour resistance	(N.s/g)
RH	relative humidity	(%)
S	storage quantity	
ΔS	change in storage quantity	
T	absolute temperature	(°K)
Tc	time constant	(s)
U	U-value, thermal transmittance	(W/m^2K)
U_R	resultant U-value	(W/m^2K)
W	water vapour production	(g/h)
WBT	wet bulb trremperature	(°C)

b	breadth, thickness	(m)
b*	effective thickness	(m)
c	specific heat capacity	(J/kgK)
cv	vapour concentration	(g/m^3)
h	height	(m)
h_c	convective surface conductance	(W/m^2K)
h_i	inside surface conductance	(W/m^2K)
h_o	outside surface conductance	(W/m^2K)
h_r	radiation coefficient	(W/m^2K)
k	linear heat loss coefficient	(W/mK)
l	length	(m)
$\dot{m}$	mass flow rate (e.g.vapour flux)	(g/h)
p	partial pressure of water vapour	(Pa)
p_s	saturation vapour pressure	(Pa)
q	overall heat loss coefficient	(W/K)
q_c	envelope conductance	(W/K)
q_v	ventilation conductance	(W/K)
t	temperature	(°C)
t_a	air temperature	(°C)
t_i	temperature inside	(°C)
t_o	temperature outside	(°C)
t_{rel}	relative temperature scale	-
t_{sa}	sol-air temperature	(°C)
Δt	temperature difference	(K)
w	wavelength (radiation)	(μm)

α	(alpha)	absorptance	
δ	(delta)	permeability	(mg/s.m.kPa)
ε	(epsilon)	emittance	
κ	(kappa)	correction to conductivity	
λ	(lambda)	conductivity	(W/mK)
ρ	(rho)	density	(kg/m^3)
σ	(sigma)	Stefan-Boltzmann constant	(W/m^2K^4)
τ	(tau)	transmittance	
ω	(omega)	moisture content (in solids)	(%)

Part 1 BASICS AND PRACTICALITIES

1.1 The role of insulation

A building is essentially a space surrounded by the *building envelope*: floor, walls and roof as the main elements, which may include sub-elements, such as windows, doors, etc. If the interior space is kept at a temperature different from that outdoors (by heating or cooling), heat will flow through the envelope from the warmer to the colder side.

Fig.1.1 A leaking bucket

In winter, heating is provided by some energy-using installation. This heat input must equal the heat loss, if the indoor temperature is to be maintained. The analogy of a leaking bucket (Fig.1.1) may help to visualise the process. Clearly, if the water level (the indoor temperature) is to be maintained, the water flow rate from the tap (the heat input) must be the same as the water flowing out through the holes (the heat loss through the envelope). The water level is analogous with temperature. If the sum of all leaks is greater than the flow from the tap, the water level (the indoor temperature) will drop. Conversely, when the bucket is empty (the inside is at the same temperature as the outside) and we want to fill the bucket (heat up the building), the flow from the tap (the heat input) must be greater than the leaks (the heat loss).

If energy is to be conserved, or the heating cost is to be kept down, then the heat loss through the envelope should be reduced ('leak plugging'). This is the task of thermal insulation.

In summer, if the interior is cooled by an energy-based installation (eg. mechanical cooling) then there will be an inward heat flow, ie. heat gain, which is part of the cooling load. This can also be controlled by insulation.

Before we can attempt to control such heat flows, the heat transfer processes themselves must be understood.

1.2 Thermal quantities

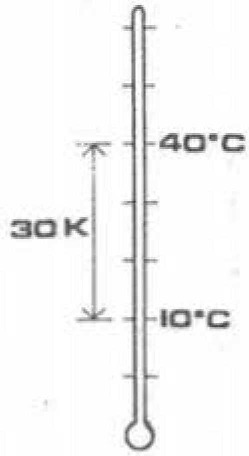


Fig.1.2 Temperature point and interval

Heat is a form of energy, appearing as molecular motion in substances or as radiation in space. It is measured in the same units as any other form of energy: the SI unit being the joule (J). The multiples kJ (kilojoule = 1000 J) and MJ (megajoule = 1 000 000 J) are often used.

Temperature can be considered as a symptom of the presence of heat in a substance; it is a measure of the thermal state of that substance. The Celsius scale takes the freezing point of water as the starting point, 0°C and the boiling point (under normal atmospheric conditions) as 100°C. The total absence of heat is the starting point of the absolute temperature or Kelvin scale. The intervals of this scale are the same as of the Celsius scale, but the starting point is the 'absolute zero', −273.15°C. In notation the following convention is adopted (Fig. 1.2):

- a particular position on the scale (t): °C
- a temperature difference or interval, regardless of its position on the scale (Δt): K

Specific heat capacity (c) of a substance expresses the relationship between heat and temperature: it is the amount of heat energy that causes unit temperature increase of a unit mass of the substance, measured in units of J/kg.K. Some typical values are:

- brick, concrete 800 – 1000 J/kg.K
- dry air 1005 J/kg.K
- water 4176 J/kg.K

For values of other materials see Data sheet 1.

1.3 Heat flow

The magnitude of heat flow can be measured two ways:

a) as **heat flow rate** (Q), or heat flux, ie. the total flow in unit time through a defined area of a body or space, in units of J/s, which is a watt (W)

b) as heat **flux density** (or density of heat flow rate), ie. the rate of heat flow through unit area of a body or space, in W/m². The multiple kW, (kilowatt) is often used for both quantities).

Heat can be transmitted by three processes:

- **conduction**, the propagation of heat within a body, ie. the spreading of molecular movement throughout an object or objects in contact
- **convection**, in a narrow sense the transfer of heat from a solid body surface to a fluid (gas or liquid) or vice-versa, but in a broader sense it may mean the transport of heat by a carrying fluid from one solid surface to another, at some distance away
- **radiation**: infrared wavelegths of the electromagnetic radiation spectrum, referred to as 'radiant heat', ie. the heat transfer between opposing surfaces, which will take place through space, even through vacuum.

All three processes occur in heat transfer through the building envelope and each can be controlled by different means.

The magnitude of conduction heat flow rate between two points of a solid (or stagnant fluid) depends on four quantities:

a) the cross-sectional area (A) through which the heat can flow, taken perpendicular to the direction of the heat flow, given in m²

b) the thickness (or 'breadth', b) of the body, ie. the length of heat flow path, given in m

c) the temperature difference between the two points (eg. two opposite surfaces of an envelope element), $\Delta t = t_o - t_i$, given in K

d) a characteristic of the material, known as **conductivity** (λ), in older literature referred to as the 'k-value', measured as the heat flow rate through unit area, with unit temperature difference, between two points unit distance apart, as W.m/m²K = **W/m.K** The value of λ varies between 0.02 W/m.K for a very good insulating material and almost 400 W/m.K for a highly conductive metal, such as copper (see Data sheet 1).

The heat flow rate (Q) is proportionate to the area, the temperature difference and the conductivity, but inversely proportionate to the thickness (b = 'breadth').

$$Q = A * \frac{\lambda}{b} * (t_o - t_i) \qquad \text{... 1.1)}$$

If both t_o and t_i are constant (or assumed to be constant) we consider *steady-state heat flow*. In real situations one or both these temperatures vary, which causes a non-steady heat flow.

A special case of this is the *periodic heat flow*, when a certain cycle (eg. the 24-hour day) repeats itself with little change. This will be mentioned in section 1.7 and discussed in detail in section 2.12-13. However, at least with lightweight structures the steady-state assumption can still be used to provide a snapshot of the momentary heat flow, or an estimate of the average heat flow over a full cycle.

Whilst conductivity is a property of the material, regardless of shape and size, **conductance** (C) is the corresponding property of a defined body, a building element, such as a slab. Its unit is W/m^2K.

The reciprocal of conductance is **resistance** (R) in m^2K/W, proportionate to the thickness and inversely proportionate to the conductivity.

$$R = \frac{b}{\lambda} \qquad \text{... 1.2)}$$

Note that the **-ity** ending implies a material property, whilst the **-ance** ending the property of a defined body, such as a slab or a wall.

In a multilayer construction (eg. a wall of n layers), the heat will flow through the layers in sequence, thus the resistances of these layers are 'in series', therefore additive.

$$R = \sum_{1}^{n} R = R_1 + R_2 + \ldots. R_n \qquad \text{... 1.3)}$$

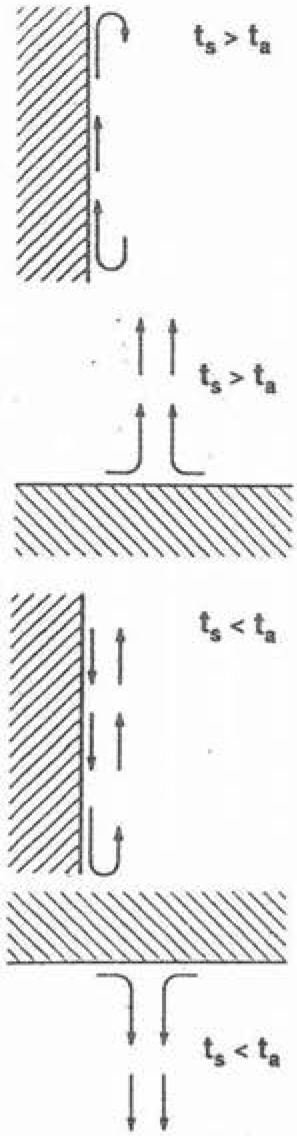


Fig.1.3 Surface conductance is increased by air flow

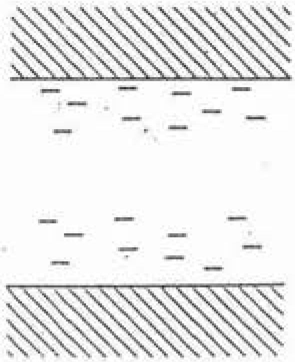


Fig.1.4 and reduced if the air is still

1.4 Surface conductance and resistance

Whilst conductance is a measure of heat transfer through an element from surface-to surface, the surface itself also offers a resistance to heat flow. These surface resistances are denoted R_{si} or R_{so}, for inside and outside surfaces respectively. The reciprocal of surface resistance is the surface conductance (h), so $R_{si} = \frac{1}{h_i}$ and $R_{so} = \frac{1}{h_o}$ Surface conductance is a lumped parameter, including radiant and convective components: $h = h_r + h_c$ In the US the terms *film coefficient* or *film conductance* (denoted f) are often used with the same meaning as surface conductance.

The magnitude of surface resistance depends on the position of the surface, on the direction of heat flow and on air movement (Figs. 1.3 and 1.4). The last can be natural, due to temperature difference, or forced, eg. due to wind. Standard values are given in Data sheet 2.

1.5 Cavities

Within a material layer heat is propagated by conduction. If the building element includes a cavity or air space, the heat transfer through this is more complex: mainly by convection and radiation, only to a minor extent by conduction.

In cavities more than a few millimetres thick, convection currents will develop and substantially increase the heat transfer (Fig.1.5). The resistance of a cavity will depend primarily on its position (vertical in a wall, horizontal in a roof) and the direction of heat flow. The width of the cavity will make very little difference beyond about 25 mm. The radiant heat transfer may be significant from the warmer to the cooler surface facing the cavity: normally about 2/3 of the total heat flux. It occurs even if the cavity is evacuated, as radiation travels also through vacuum. Radiant transfer will depend on surface qualities: emittance and absorptance of the two surfaces. In practice it is sufficient to employ a cavity resistance (R_c) value which combines convective and radiant components, but distinguishing cavities between ordinary building materials and with low emittance surfaces (eg. aluminium foil). Cavity resistance values are given in Data sheet 2.

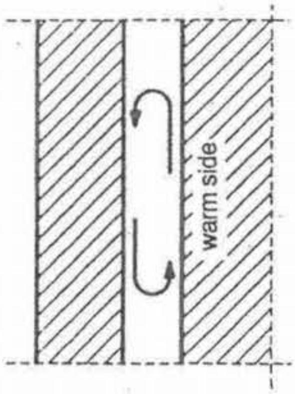


Fig.1.5 Convection air current in cavity

1.6 Transmittance: U-value

Heat transmission through an envelope element takes place from the air inside the building to the air outside (or vice-versa). The *air-to-air resistance* (R_{a-a}) will be the sum of the resistance of the element itself and the two surface resistances. The reciprocal of this air-to-air resistance is the *transmittance*, or *U-value*. The unit of measurement is the same as for conductance (W/m²K), the difference being that conductance is taken from surface to surface, whilst the U-value from air to air (Fig.1.6).

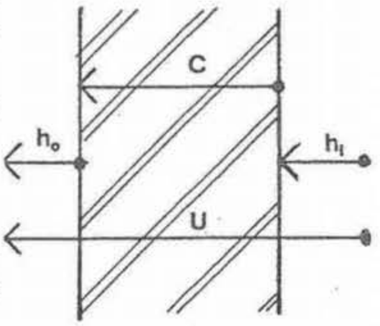


Fig.1.6 Conductance and transmittance

$$R_{a-a} = R_{si} + \sum R + (R_c)....+R_{so} \quad ... 1.4)$$

$$U = \frac{1}{R_{a-a}} \quad ... 1.5)$$

The transmission heat flow is proportionate to the U-value, the area (A) of the element, perpendicular to the direction of heat flow and the difference between the outdoor and indoor temperatures

$$Q = A*U*(t_o - t_i) \quad ... 1.6)$$

The convention here adopted is that always the t_i is subtracted from the t_o, as in winter this gives a negative difference, a negative Q, indicating heat loss. A positive Q indicates heat gain, eg. in air conditioning load calculations.

Air has a very low conductivity, as long as it is still. The best insulators are structures which encapsulate air with as little material as possible. Insulation is provided by the air, the material is there in the form of bubbles, or fibres only to keep the air still.

1.7 Insulating materials

If the definition of `insulation' is the control of heat flow, then three forms of insulation can be distinguished:
reflective, resistive and capacitive insulation.

Reflective insulation, as mentioned above, can be employed where the dominant heat transfer mechanism is radiation. The only practical reflective insulating material is aluminium foil, which has a low absorptance and low emittance (approx. 0.02 - 0.05). It can be used on its own, but more frequently laminated with building paper, either single or double-sided, or even to a plasterboard (resulting in a `foil-backed' plasterboard. To be effective, it must face a cavity or air space. Various multiple-foil insulating products are on the market (eg. `space-age batts').

Resistive insulation materials are often referred to as `bulk insulation': most products are available in this category. In fact all building materials have some resistance to heat flow. Metals are good conductors of heat, so they offer very little resistance. The resistance of a thin metal sheet is negligible: its air-to-air resistance will be the sum of the two surface resistances: $R_{a-a} = R_{so} + R_{si}$

Conceptually it may be useful to distinguish

a) insulation, single-function materials, which can only be used in conjunction with others and serve no other purpose but to reduce the heat flow
b) insulating, multi-purpose materials, which can stand up on their own, can even be load-bearing, but have reasonable insulating qualities.

In the first category there are two major types: fibrous materials and foams. Examples of fibrous insulation materials are:

- mineral wools
- glass fibre batts and quilts

but also some organic fibres (some are rarely used today):

- eel grass
- kapok
- cellulose fibre (often produced from recycled paper, used as loose fill)

Foams are mostly expanded plastic materials:

- expanded polystyrene (EPS)
- extruded polystyrene (eg. 'Styrofoam')
- polyurethane
- urea-formaldehyde (falling into disrepute for its ill-effects on health)

Most of these are available as rigid, or semi-rigid slabs of various densities and some can be foamed in situ (eg. injected into cavities). There are also some inorganic loose fill insulation materials:

- exfoliated vermiculite
- perlite.

These may be used as lightweight aggregates in concrete (in lieu of gravel or crushed stone), to form various types of lightweight concrete, which is a multi-purpose insulating material.

Lightweight concretes can also be formed with some foaming (aerating) agent. A popular example of this is the

- AAC (autoclaved aerated concrete), marketed under different trade names, such as 'Thermalite' or 'Hebel blocks'.

Other multi-purpose insulating materials include various slabs or panels made of organic materials, such as

- strawboard (eg. 'Stramit')
- reed-board
- wood-wool slab (eg. 'Heraklit')
- wood- (or cane-) fibre softboards (eg. 'Caneite')

Capacitive insulation is most often discussed as 'thermal capacity' or 'thermal mass', as a totally separate topic. It is very different. Resistive and reflective insulation has an instantaneous effect, but capacitive insulation also affects the timing of heat flow: it has a delaying effect.
This difference can be best illustrated by the comparison of

a) a 10 mm polystyrene slab ($U = 2.17 \text{ W/m}^2\text{K}$) and
b) a 400 mm dense concrete slab (also $U = 2.17 \text{ W/m}^2\text{K}$)

Under steady-state conditions there will be no difference in heat flow through the two slabs. A significant difference will however occur if these slabs are exposed to a periodically changing set of conditions.

Fig.1.7 shows the variation of heat flow rate over 24 hours at the inside face of the two slabs, exposed to the same external temperature variation, whilst the indoor is kept constant. The daily mean heat flow is the same, but the two sinusoidal curves differ in two ways:

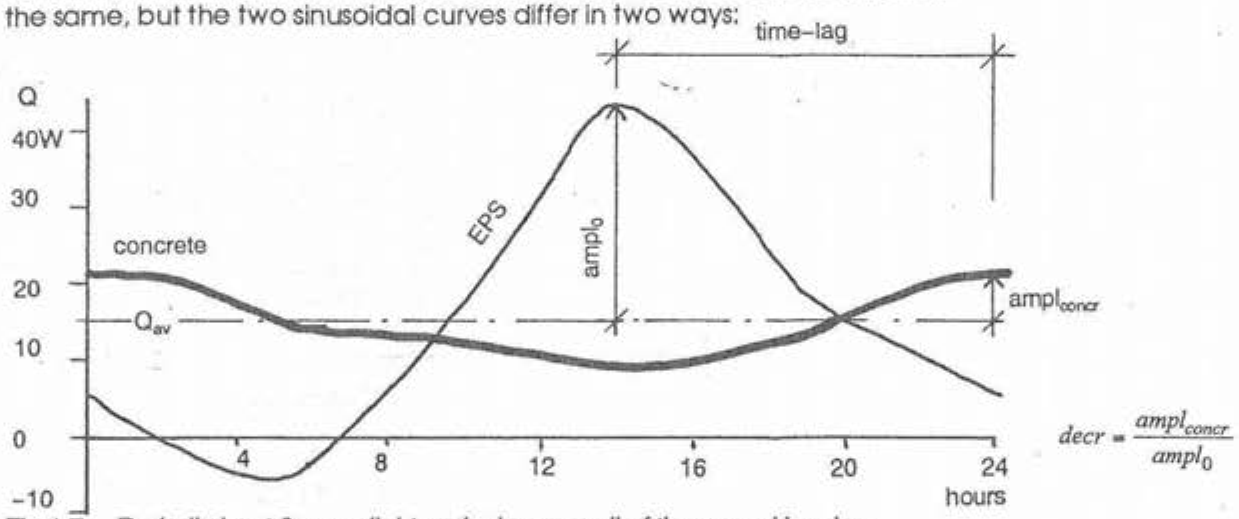


Fig.1.7 Periodic heat flow : a light and a heavy wall of the same U-value

1. the heavy slab's heat flow is delayed: the term **time-lag** is defined as the difference (in hours) between the peaks of the two curves
2. the amplitude (mean-to-peak) of the heavy slab's curve is reduced well below that of the lightweight one's; the ratio of the two amplitudes is the **decrement factor** (or amplitude decrement).

The capacitance effect will be further discussed in section 2.13-14.

1.8 Envelope conductance

A room or a building can be characterised by its *envelope conductance* (q_c). This is the sum of the products of the areas and the U-values of all envelope elements of the room or building. Note that the word 'conductance' is used here with a meaning different to the above: dimensionally this is $W/m^2K * m^2 =$ **W/K.**

$$q_c = \sum (A*U) \qquad \text{... 1.7)}$$

The sum of this and the *ventilation conductance* (q_v, which has the same dimension) is the *overall heat loss coefficient* (sometimes referred to as the specific heat loss rate of the building): $q = q_c + q_v$.

Ventilation is not the subject of this Note, suffice it to say that $q_v = 1200*vr$ or $q_v = 0.33*V*N$

where 1200 J/m^3K or 0.33 Wh/m^3K is the specific heat of air

vr = ventilation rate in m^3/s

N = number of air changes per hour

V = volume of room or building in m^3

1.9 Temperature gradient

The temperature distribution in the cross-section of a building element is important from several points of view (eg. thermal comfort, fabric protection, condensation prediction). Temperatures of the indoor and outdoor air are given. The heat flow is inversely proportionate to the resistance. Under steady state conditions the heat flux is the same at any plane of the cross section (or through any layer).

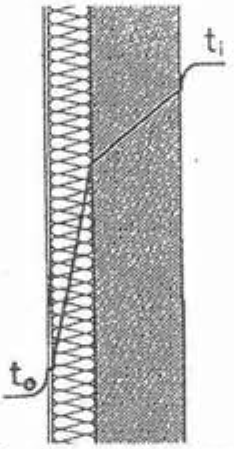


Fig.1.8 Temperature gradient: wall with external insulation

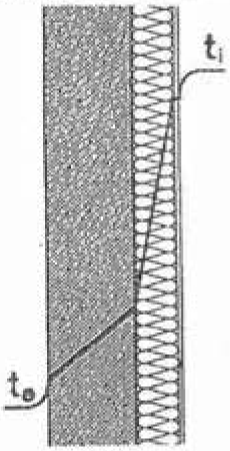


Fig.1.9 same, but internal insulation

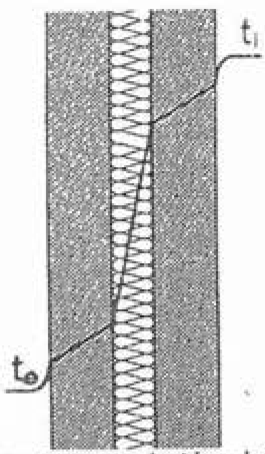


Fig.1.10 same, but insulation between two solid layers

At any point of the heat flow path, without storage capacity, the arriving flow must equal the leaving flow. The ratio of temperature drop in each layer to the resistance of that layer is the same as the ratio of the air-to-air temperature difference to the air-to-air resistance.

$$Q = \frac{t_o - t_i}{R} = \frac{t_o - t_4}{R_{so}} = \frac{t_4 - t_3}{R_3} = \frac{t_3 - t_2}{R_2} = \frac{t_2 - t_1}{R_1} = \frac{t_1 - t_i}{R_{si}} \qquad \text{... 1.8)}$$

Figs.1.8 - 1.10 show the temperature gradient in various walls. The small arcs at t_i and t_o show the effect of surface resistances. The gradient is steeper in an insulating layer and flatter in a more conductive material.

1.10 Transmittance calculations

Example 1 U-value of a multilayer wall

A wall of four layers has the these characteristics, starting from the inside:

No	Material	b m	λ W/mK
1	Plaster	0.015	0.50
2	Brick	0.30	0.62
3	Expanded polystyrene	0.05	0.035
4	Rendering	0.01	0.60

The λ values are obtained from Data sheet 1 and the resistances from Data sheet 2. Calculate the transmittance.

The component resistances are:

Inner surface:	R_{si}		= 0.12
1st layer	R_1	$= \frac{0.015}{0.50}$	= 0.03
2nd layer	R_2	$= \frac{0.30}{0.62}$	= 0.484
3rd layer	R_3	$= \frac{0.05}{0.035}$	= 1.4286
4th layer	R_4	$= \frac{0.01}{0.60}$	= 0.017
outer surface	R_{so}		= 0.06
Air - to - air resistance	R_{a-a}		= 2.14 (rounded)

The transmittance: U - value $\frac{1}{2.14}$ = 0.467

Example 2 Temperature gradient

Continue the previous example and establish the temperature gradient, when t_i = 20°C and t_o = 0°C. The temperature drop in each layer is proportionate to its resistance. The ratio of these temperature drops and the total indoor-outdoor temperature difference is the same as that of the resistance of the layer and the air-to-air resistance. The resistance ratios (R_n/R_{a-a}) are the following:

Inner surface	$\frac{0.12}{2.14}$	= 0.056
1st layer	$\frac{0.03}{2.14}$	= 0.014
2nd layer	$\frac{0.484}{2.14}$	= 0.226
3rd layer	$\frac{1.4826}{2.14}$	= 0.668
4th layer	$\frac{0.017}{2.14}$	= 0.008
External surface	$\frac{0.06}{2.14}$	= 0.028

(these ratios must add up to 1)

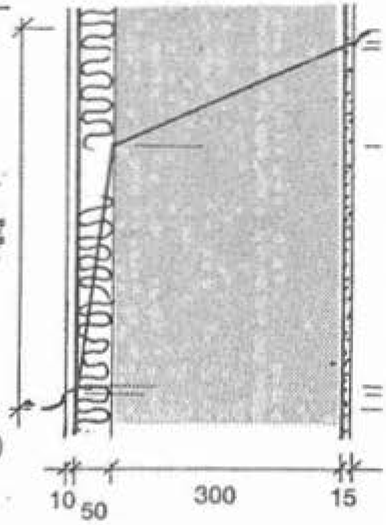


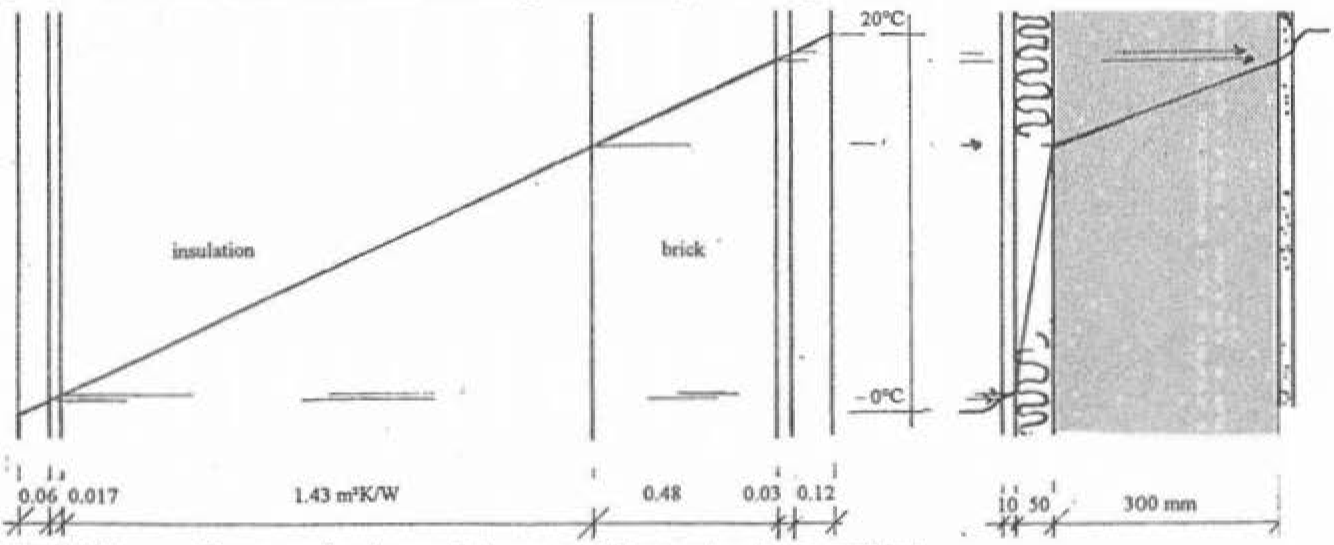
Fig.1.11 Temperature gradie
constructed by resistance rati

For each layer the temperature drop will be the above ratio times the air-to-air temperature difference ($t_o - t_i$), which in this case is 0 - 20 = -20K

	Δt	t
		ti = 20.0°C
-20 * 0.056 =	-1.12 =	18.88
-20 * 0.014 =	-0.28 =	18.6
-20 * 0.226 =	-4.52 =	14.08
-20 * 0.668 =	-13.36 =	0.72
-20 * 0.008 =	-0.16 =	0.56
-20 * 0.028 =	-0.56 =	0

see Fig. 1.11.

Temperature gradient can also be constructed by drawing a cross-section of the element to a scale of resistences (Fig.11/a). In the above example the air-to-air resistance is 2.14 m²K/W. To fit the size of space available take this to equal 107 mm, ie. a scale of 1 m²K/W = 50 mm. Set up an arbitrary vertical temperature scale (eg. using the same as above, 20 K = 50 mm or 1 K = 2.5 mm), mark the inside and outside air temperatures and connect these by a straight line. The intersection point of this line with the layer boundarues can then be projected across to a physical section of the element and will give the temperature gradient.



Fig,1.11/a Cross section to a resistance scale for constructing a gradient

Example 3 U-value to limit inner surface temperature

An existing solid brick wall has the following data:

No	Material	b m	λ W/m K
1	Plaster	0.01	0.5
2	Brick	0.38	0.84
3	Rendering	0.015	0.6

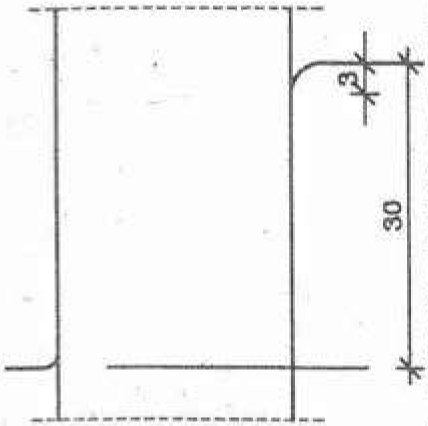


Fig.1.12 Maximum inner surface temperature stipulated

The order is given from the inside. Temperatures: $t_i = 20°C$, $t_o = -10°C$.

The inner surface temperature should not drop below 17°C, to avoid a lowering of the MRT (mean radiant temperature) and to prevent surface or capillary condensation. Define the necessary added thermal insulation so that the inner surface temperature should not be less than 17°C at design conditions.
The maximum permissible temperature difference between the indoor air and inner surface is 20-17 = 3K, 10% of the total outdoor - indoor temperature difference. Thus the inner surface resistance, 0.12 m²K/W Fig.1.12.) should not be more than 10% of the total air - to - air resistance of the insulated construction. Therefore the minimum air - to - air resistance must be 10 * 0.12 = 1.2 m²K/W

Resistances of the existing wall layers are:

Inner surface	R_{si}	= 0.12
Plaster	$R_1 = \frac{0.01}{0.5}$	= 0.02
Brick	$R_2 = \frac{0.38}{0.84}$	= 0.452
Plaster	$R_3 = \frac{0.015}{0.6}$	= 0.025
External surface	R_{so}	= 0.06
Air - to - air resistance	R_{a-a}	= 0.677

To have the required value, 1.2 - 0.677 = 0.523 resistance must be added. Thus for the additional thermal insulation the ratio

$\frac{b_{ins}}{\lambda_{ins}} = 0.523$ must be achieved.

If expanded polystyrene is applied as in ex. 1, the λ value is 0.035, thus
$b_{ins} =$ 0.035 * 0.523 = 0.018 m (18 mm)

Insulation materials are produced in discrete thicknesses, therefore the calculated thickness should be rounded up to the next thickness available and the calculation repeated with this.

Example 4 Insulation to satisfy a requirement

Assume that a given regulation limits the U value of building elements and the maximum for exposed walls is U_{max} = 0.5 W/m²K. The intended construction is: 250 mm brick (plastered) + thermal insulation + 120 mm brick. What is the necessary thickness of the insulation?

The given construction from the inside is:

No	Material	b m	λ W/m K	
1	Plaster	0.01	0.50	
2	Brick	0.25	0.62	(inner skin)
3	Insulation	?		
4	Brick	0.12	0.84	(outer skin)

The necessary air – to – air resistance will be

$$R_{min} = \frac{1}{U_{max}} = \frac{1}{0.5} = 2.0$$

Resistances of the surfaces and of the given layers:

Inner surface	R_{si}	= 0.12
1st layer	$R_1 = \frac{0.01}{0.5}$	= 0.02
2nd layer	$R_2 = \frac{0.25}{0.62}$	= 0.403
4th layer	$R_4 = \frac{0.12}{0.84}$	= 0.143
External surface	R_{so}	= 0.06
Total	R_{a-a}	= 0.746

To achieve or exceed the above value, 2.0 – 0.746 = 1.254 m^2K/W resistance is to be added. The λ value of a mineral wool (150 kg/m^3 density) is 0.044. With this the minimum thickness will have to be

$b_{min} = 0.044 * 1.254 = 0.055$ m

The discrete thicknesses available are 20, 40, 60, 80, 100 mm, the next higher value, 60 mm is to be chosen, thus

$$R_3 = \frac{0.06}{0.044} = 1.36$$

With this, the new air-to-air resistance will be 1.36 + 0.746 = 2.106

and the U value: $\frac{1}{2.106} = 0.475$ W/m^2K

which is less than the limiting value of 0.5, therefore O.K.

Example 5 Locating a point of a specified temperature

Calculate the temperature distribution of the previous wall and determine the plane of 0°C temperature if $t_i = 20$°C and $t_o = -10$°C.

The ratios of component resistances to the air-to-air resistance are:

Inner surface	$\frac{0.12}{2.106}$ =	0.057
1st layer	$\frac{0.02}{2.106}$ =	0.0095
2nd layer	$\frac{0.403}{2.106}$ =	0.191
3rd layer	$\frac{1.36}{2.106}$ =	0.646
4th layer	$\frac{0.143}{2.106}$ =	0.068
Outer surface	$\frac{0.06}{2.106}$ =	0.0285

These will also be the ratios of the temperature drops and the total $(t_o - t_i)$ temperature difference, in this case (−10°C−20°C =−30K). Temperature drops and values on the surfaces or at the contact planes of adjoining layers are to be calculated step by step in the following way:

		Δt	t
	Indoor air		20.0
	0.057∗−30 =	−1.71	
	Inner surface		18.29
1st layer	0.0095∗−30 =	−0.285	
	boundary		18.00
2nd layer	0.191∗−30 =	−5.73	
	boundary		12.27
3rd layer	0.646∗−30 =	−19.38	
	boundary		−7.10
4th layer	0.068∗−30 =	−2.04	
	External surface		−9.14
	0.0285∗−30 =	−0.855	
	Outdoor air		−10.0

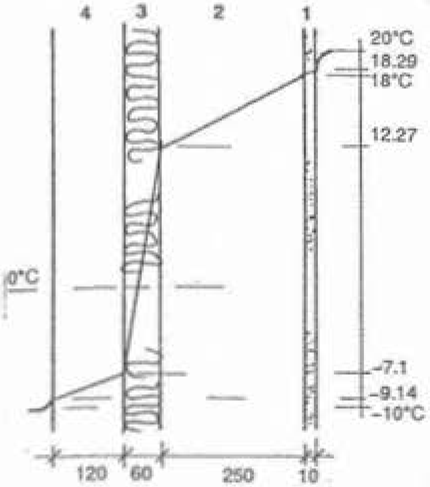


Fig.1.13 Temperature gradient

It can be seen, that the plane of 0°C will be within the 3rd layer. Its position can be pinpointed from the Fig. 1.13, or calculated in the following way:

The resistance of the 3rd layer is $R_3 = 1.36$

Temperature drop in the 3rd layer is $\Delta t_3 = 19.38$

The temperature on the inner surface of the 3 rd layer is $t = 12.27$

Temperature drop between this plane and the plane of 0°C is

$\Delta t = 12.27 - 0 = 12.2$

The ratio of the above two values is: $\frac{12.27}{19.38} = 0.633$

meaning that 63.3% of the total temperature drop is within the 3rd layer. The ratio of the resistance (also of the thickness, in this case 60 mm, as the layer is homogeneous) being the same as that of the temperature drops, the distance of the plane of 0°C from the inner surface of the 3rd layer is

$0.060 * 0.633 = 0.0328$ m, ie. 38 mm

Example 6 U-value of a composite wall

Fig.1.14 shows a framed wall, with 50 x 100 mm hardwood studs at 600 mm centres, 20 mm timber (pine) boarding externally and 10 mm plasterboard internally. The resistance at the stud will differ from that through the hollow part, so both must be calculated and the area-weighted average must be found. The surface resistance are the same, so these can be added after the averaging.

		b	λ		R	
Hollow part:	plasterboard	10	0.16	$\frac{0.01}{0.16}$ =	0.0625	
	cavity				0.35	
	boarding	20	0.13	$\frac{0.02}{0.13}$ =	0.1538	0.5663
at stud	plasterboard	as above			0.0625	
	hardwood	100	0.15	$\frac{0.1}{0.15}$ =	0.6667	
	boarding	as above			0.1538	0.8830

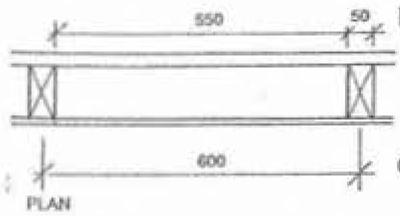


Fig.1.14 Composite wall: average U-value

In a 600 mm panel 550 mm is hollow and 50 mm is the stud, so the weighted average resistance will be

$$\frac{0.5663 * 550 + 0.883 * 50}{600} = 0.593$$

plus	R_{si}	= 0.12
	R_{so}	= 0.06
	R	= 0.77 ∴ U = 1.29 W/m²K

1.11 Roofs and exposed floors

Heat losses through flat roofs and floors exposed to outside air (eg. a house built on stilts, where the under-floor space is completely open) are calculated the same way as walls, using the appropriate U-values, such as those given in Data sheet 5.

Heat losses through pitched roofs are usually calculated taking the horizontal projected area, and the U-values are given as a function of roof pitch. In calculating such a U-value, the resistance of any sloping layer is corrected for the increased developed area, as shown below in Example 7.

Insulating products are increasingly designated by their R-value (rather than by their thickness). If the U-value of a basic construction is known, the result of added insulation can readily be calculated, as demonstrated by Example 8.

Example 7 U-value of a pitched roof

A ceiling/roof combination consists of the layers listed in the following calculation (Fig.1.15):

		b	λ		R
	R_{si}			0.1	
1 horizontal	plasterboard	13	0.16	0.0813	
2	cavity (roof space)			0.17	0.3513
3 sloping (30°)	bituminous felt	3	0.5	0.0015	
4	tiles	10	0.84	0.0119	
	R_{so}			0.04	
				0.0534	
	cos 30° = 0.866	0.0534 * 0.866 =			0.0462
					0.3975

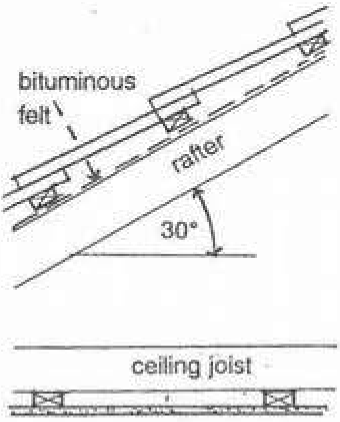


Fig.1.15 A pitched roof

therefore $U = \frac{1}{0.3975} = 2.51$ W/m²K

The sloping area is larger than its horizontal projection, transmits more heat, thus its resistance is reduced by the cosine of the pitch angle.

Note: it is suggested that in such calculations in the intermediate steps as many decimals should be retained as the calculator can handle and only the final result is rounded. It is usual to have 3-decimal precision for conductivity but only 2 decimals for U-value.

Example 8 Modifying U-values for added insulation

In Example 7 the U-value of a simple basic roof construction has been calculated. Modify this U-value for insulation added on top of the ceiling, of R 1.5, R 2 and R 2.5

Basic U = 2.51 $\therefore$ R = $\frac{1}{2.51}$ = 0.398

for + R 1.5 0.398 + 1.5 = 1.898 $\therefore$ U = $\frac{1}{1.898}$ = 0.53 W/m²K

for + R 2 0.398 + 2 = 2.398 $\therefore$ U = $\frac{1}{2.398}$ = 0.42 W/m²K

for + R 2.5 0.398 + 2.5 = 2.898 $\therefore$ U = $\frac{1}{2.898}$ = 0.35 W/m²K

1.12 Slabs on ground and basements

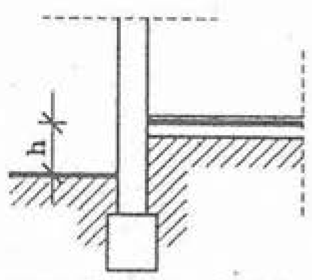


Fig.1.16 Definition of relative height (h) for ground losses

The BRE/CIBSE system in the UK gives U-values as a function of floor size for both slab-on-ground and suspended floors. The European system is thought to give more reliable results and it is now adopted in several international standards, therefore it will also be presented here. This system employs linear heat transfer coefficients, taken for the perimeter of the building. Informative data are given in Data sheet 6, with the term 'relative height' explained in Fig.1.16 (this is the level difference between the floor and the adjacent ground, negative, if the floor is below ground level). These coefficients will have to be multiplied by the perimeter length of the building.

Linear heat transfer coefficients for earth sheltered (bermed) walls and the explanation of the data are also given in Data sheet 6 and Fig.1.17 respectively. These are also linear coefficients for the stated depth of basement or earth bermed wall. Losses through the adjacent floor must be calculated separately, as above.

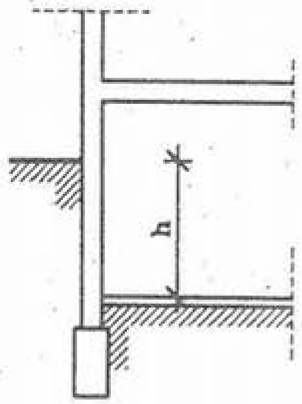


Fig.1.17 Definition of height (h) for earth sheltered walls

Example 9 Calculation of ground losses

Consider a slab-on ground floor, the level of which is 0.7 m above the adjoining ground. It consists of the following layers:

No	Material	b m	λ W/mK	R m²K/W
1	Carpet			0.150
2	Concrete	0.05	1.20	0.042
3	Polystyrene	0.03	0.035	0.857
4	Waterproof membrane			
5	Concrete	0.10	1.40	0.071
6	Gravel	0.25		

As far as the thermal resistance of the floor slab is concerned, layers below the insulation can be neglected, that of the polystyrene and the layers above if are to be taken in account:

R = 0.150 + 0.042 + 0.857 = 1.05 m²K/W (thus U = 0.95 W/m²K)

From Data sheet 6, column headed 1.05-1.5 (resistance) and the line labelled +0.45 to +1.00 the linear heat loss coefficient is
k = 1.30

If the thickness of thermal insulation is doubled, then
$R = 1.05 + 0.857 = 1.91$ (thus $U = 0.52\ W/m^2K$)
and the linear coefficient is found in the seventh column:
$k = 1.15$
Note that the linear heat transfer coefficients are not proportionate to the resistance of the thermal insulation.

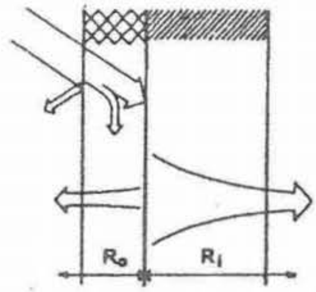


Fig.1.18 Heat flows in a wall with transparent insulation

1.13 Transparent insulation

A promising new technique is the use of transparent insulation materials on external walls and, recently, on their own as a translucent envelope element. The most obvious application is to install transparent insulation on the outer side of massive walls. Due to the good optical transmittance of the insulation (and of the "surface finishing", which in most cases is glass) a major part of incident radiation reaches and is absorbed by the outer surface of the massive wall. The ratio of heat fluxes from this plane towards the room and the environment depends on the ratio of thermal resistances between the absorbing surface and environment, and between the absorbing surface and indoor space. The usual thickness of the massive wall provides an appropriate time lag: a good complement to instantaneous direct gains (see Fig 1.18).

Although generally this system is considered as a "collecting storage wall", separate analysis may be reasonable taking into account that transparent insulation materials combine the properties of good optical transmittance and high thermal resistance, thus they exhibit both 'defensive' and 'interactive or solar' properties.

The transparent insulation itself can be (Fig.1.19):

a) a series of plastic films, parallel with the absorbing surface
b) a honeycomb structure, perpendicular to the absorbing surface
c) scattering structures (foam, bubbles)
d) quasi-homogeneous materials (aerogel, glass fibres)

Besides the above application transparent insulation materials can be used in combination with glazing, partly to replace conventional windows, partly to create well-insulated translucent building elements where daylight requirements take priority over visual contact.

In summer the protection of transparent insulation is necessary both to ensure thermal comfort and to protect the fabric. An effective and reliable solution is the use of thermochromatic (or photochromatic) glazing as the outer surface.

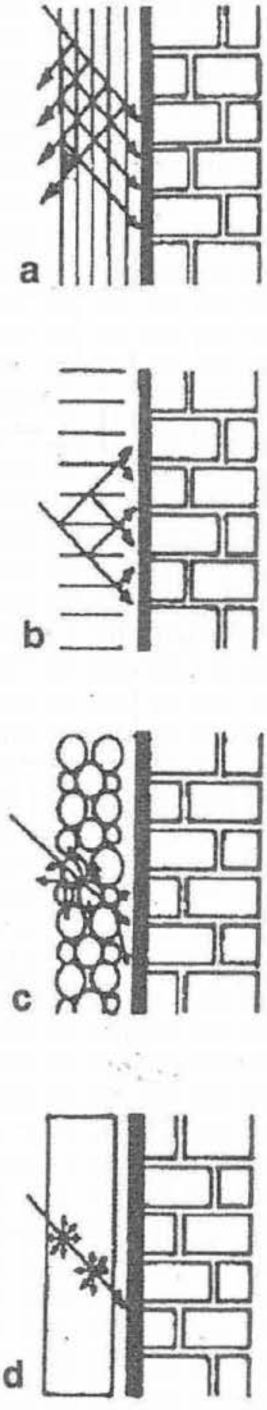


Fig.1.19 Four structures of transparent insulation

1.14 Practicalities : Where to put the insulation?

The geometry of the building is an important determinant of fabric losses. In multistorey buildings the importance of the roof and lowest floor slabs is relatively less than of the exposed walls. However, in single-storey buildings the roof represents a relatively high proportion of the envelope area and so is the lowest floor slab, although, with a strongly indented plan the exposed walls may still prevail. Besides their area, the U-value of the envelope elements determine their relative weight within the fabric losses. Usually roofs are better insulated than the walls. Thermal insulation of the lowest floor slab is frequently missed.

In tall buildings the facade area represents the largest part of the total envelope. However, the relative importance of exposed walls depends also on the glazing ratio. The smaller, or the more compact the building is (in three dimensional terms) the more important the complete insulation.

With larger buildings it is sufficient to concentrate on the most effective measures. A considerable part of fabric losses is due to *thermal bridge* effects (refer to Sections 2.5–6). For a given construction these losses depend on the length of edges and joints. The *specific length* of thermal bridges, i. e. the length/area ratio is higher if

- the layout and form of the building is not compact (outer corners, edges), see Fig.1.20;
- the glazed area is divided into small units (the perimeter of windows), see Fig.1.21;
- there are balconies or other projections on the facades which act as 'cooling fins'
- partitions are closely spaced (T-form joints with the envelope elements).

The latter two cases are typical in some multistorey buildings.

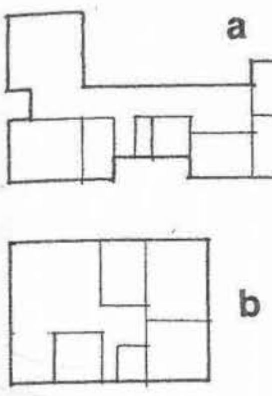


Fig.1.20 Spread out and compact plans: both 120 m² area
perimeter: a) 78 m, b) 44.4
wall surface: a) 187 m², b) 106
No.of corners: a) 16, b) 4

Depending on the construction and the specific length of thermal bridges these losses are **15 - 50%** of the transmission losses calculated on one dimensional basis. These facts prove that, while applying added insulation, not only the modified *U* values, but also the thermal bridge effect must be taken into account. Depending on the order of the layers, or the position of the added thermal insulation there are different solutions resulting in the same *U* value. Some solutions can decrease the thermal bridge losses quite considerably, others have practically no effect on them.

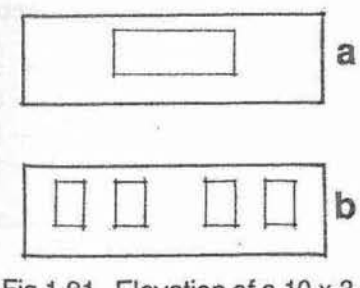


Fig.1.21 Elevation of a 10 x 3 m wall, with 10 m² window
a) one 4x1.5 m, perimeter: 11 m
b) four 1x1.5 m, perimeter: 20 m

In selecting the most appropriate solution, several constraints should be considered from both architectural and constructional points of view. Besides the building geometry, the application of added insulation is influenced by many other pragmatic factors. There are considerable differences in the investment costs of insulation added to walls, roofs, pitched roofs or attics. Adding an insulation layer to walls may be accompanied by the extra costs of surface finishing or vapour barriers.

In flat roofs thermal insulation of better mechanical properties is required, one that is not affected by moisture. Such materials tend to be more expensive. With other, already multilayer constructions the improvement of insulation may not result in any extra costs.

Added insulation can be most easily applied in attics, on top of the ceiling, where usually neither new surface finishing, nor a vapour barrier would be necessary. The insulation can be installed with simple "dry" technology and fixed mechanically, without expensive scaffolding or disturbance to the occupants. The thickness of the insulation is not limited and there are usually no significant mechanical, climatic or moisture effects. Similarly, there would not be too much problem with the added insulation of floors over basements but due to the small temperature difference this insulation is less effective.

Thermal insulation added to flat roofs requires complex reconstruction of the roof system, additional layers (vapour barrier, waterproof membrane, etc.) The thickness of the thermal insulation is not limited but the material must not be vulnerable to moisture and climatic effects.

Outside insulation of walls requires scaffolding and (on existing buildings) new surface finishing. The thickness of the thermal insulation layer can be limited and either the material must be able to withstand mechanical and some moisture effects or a more expensive construction with ventilated air gap has to be installed. However, as it will be shown, *external insulation is thermally more effective.*

As far as inside insulation is concerned, different techniques can be applied (in existing buildings with more or less disturbance of the users during the execution). New surface finishing and usually a vapour barrier are necessary. The thickness of the thermal insulation can vary widely. The new internal surface should be able to resist mechanical effects and allow the fixing of pictures and other objects, accept plugs for the fixing of shelves or small pieces of furniture.

In a few special cases existing air gaps of cavity walls can be filled with insulation, if moisture penetration can be prevented by other means.

1.14.1 Flat roofs

The problem of added ('retrofit') thermal insulation of flat roofs cannot be separated from the problem of waterproofing. The following options exist:

- to keep the traditional layer-order (on existing buildings by re-building the roof from the load bearing construction.
- on existing buildings to keep the traditional layer order by placing an added thermal insulation layer and a new waterproof membrane on its top,
- to apply an *inverted roof membrane assembly* by placing an added thermal insulation on the roof with mechanical fixing.

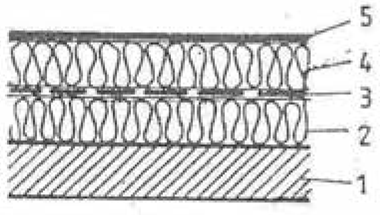


Fig.1.22 Added insulation + waterproof membrane on a flat roof
1: slab, 2: original insulation,
3: existing membrane perforated
4: new insulation, 5: new membrane

The first retrofit option is the most expensive and because of the risk of rain penetration it can be applied only if the building is not occupied during the process of reconstruction.

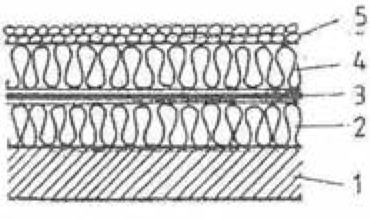


Fig.1.23 Added insulation to create an inverted roof
1: slab, 2: original insulation
3: original membrane
4: new insulation, 5: gravel

The second option is to be preferred if the original waterproof membrane would need repairs or change, thus the motivation or one of the motivations is the replacement of that membrane. A wide range of materials can be used. Depressurisation, ie. the release of vapour pressure should be checked carefully and for this purpose the original membrane may have to be perforated (Fig.1.22).

The third version is to be applied if the waterproof membrane is in good condition. The thermal insulation **must be extruded** polystyrene, which is fixed (against negative wind pressure) by gravel or stepping stones (Fig.1.23). The added thermal resistance is not limited, the usual value being $R = 0.5 - 1.0$ m²K/W.

1.14.2 Pitched roofs and attics

There are two options: if the attic is heated (or the ceiling follows the roof slope), the added thermal insulation should be located along the pitched roof, between the rafters or below them. The internal surface finishing can be plaster on lath, gypsum board or timber panelling. A vapour barrier below the thermal insulation and ventilated air gap are advisable in order to prevent interstitial condensation (refer to Section 3.3) and some form of sarking, eg. a foil or bituminous felt over it, as a precaution against any moisture that may have penetrated the tiles (Fig.1.24).

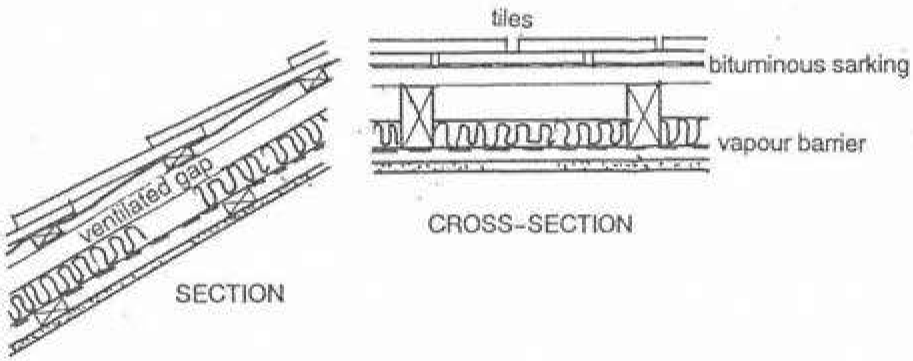


Fig.1.24 Insulation of a pitched roof with coupled ceiling

Special care has to be taken of the correct insulation of any garrets and dormer windows, in order to avoid leaving thermal bridges. (These are often indicated by local melting of any snow cover.) If the attic is not heated and there is no significant mechanical load, the added insulation is to be located horizontally on top of the ceiling. The area of this is less than that of the pitched roof.

In both versions attention should be paid to fire protection requirements.

1.14.3 Floors

Ground losses represent a considerable part of the total, especially in single storey buildings of a small floor area and indented plan form. Thermal insulation should cover the whole floor area.

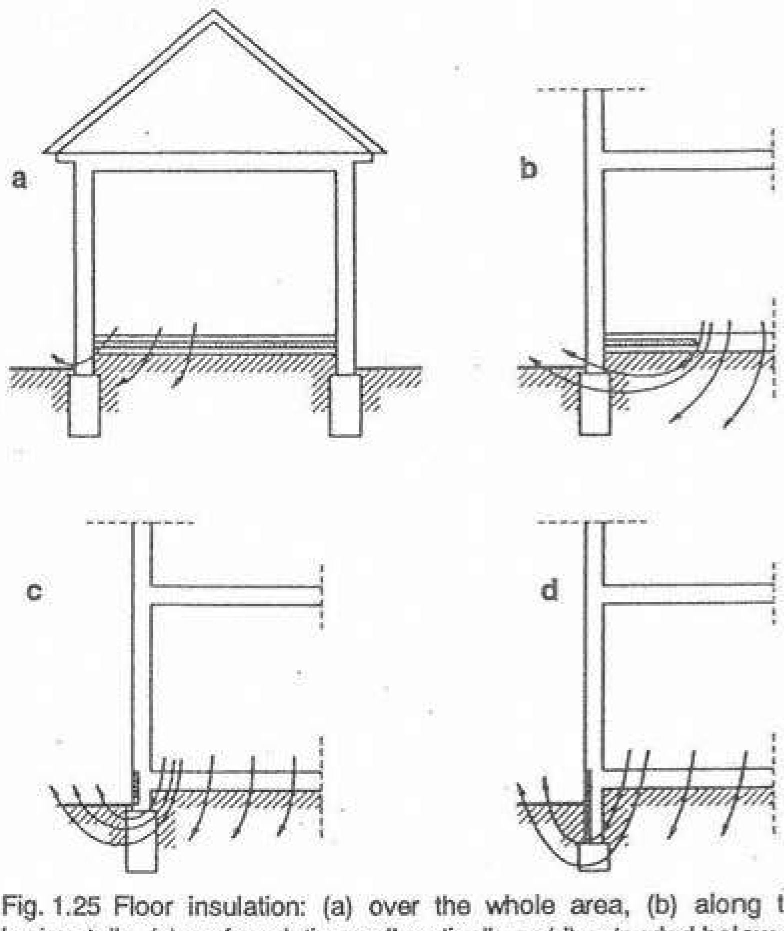


Fig. 1.25 Floor insulation: (a) over the whole area, (b) along the perimeter, horizontally, (c) on foundation wall vertically or (d) extended below ground level.

On a large and compact floor this solution would be quite expensive, but it is not necessary, as ground losses are concentrated along the edges of the building, it is sufficient to insulate the perimeter of the building (in a width of 1 – 2 m). This perimeter insulation can be located vertically, partly on the foundation wall, partly embedded in the ground, as shown in Fig.1.25.

The material of the vertically located insulation must be hard and water-proof; extruded polystyrene foam is appropriate. A continuous barrier up to the top of the footing is necessary.

1.14.4 Walls : External insulation

From many points-of-view external thermal insulation is the most effective option. Different versions are possible such as:

- insulating plaster (its thickness is maximum 60 mm, with a usual λ value of 0.09 – 0.14 W/m.K),
- "Thermal skin" (added insulation plus thin reinforced rendering)
- added insulation outside a ventilated air gap and external protective skin (Fig. 1.26).

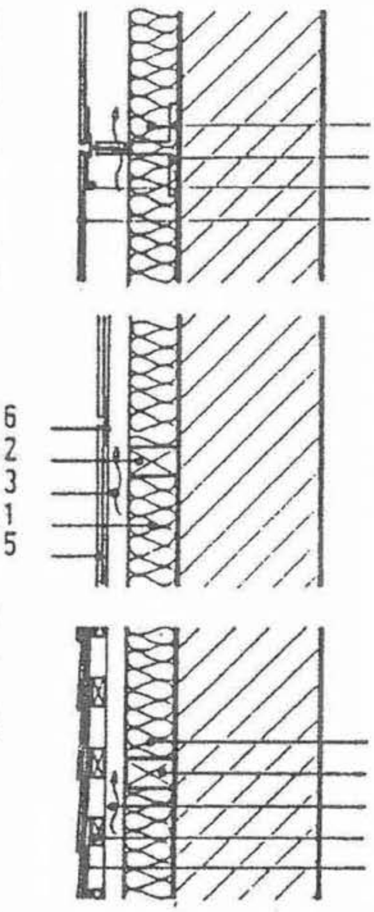


Fig.1.26 Alternatives for add external insulation+vented air 1: insulation, 2 & 4: battens, 3: counter-battens, 5: tile-ha or fib.cement sheet, 6: sealin 7: metal support, 8: fixings

External insulation is usually accompanied by a new surface finish, which may itself cause some thermal effects, eg. admission/exclusion of moisture or its response to solar radiation.

Waterproofing of exposed walls.

Due to the several forms of precipitation, primarily the driving rain effect, wetting of the exposed walls has to be taken into account. Different phenomena are involved, namely water penetration to the inner surface through cracks and joints (of panels or masonry blocks to each other or to windows), or into the construction, moisture absorption of the wall material itself.

Water, penetrating to the inner surface through cracks or by moisture conduction can cause fabric damage (corrosion, erosion, mould growth), as well as indoor air quality problems (mites, living on the mould and spreading in the indoor air).

Due to increased moisture content the conductivity of the wall material increases, resulting in extra transmission heat losses and lower inner surface temperature. Lighter bricks and older hygroscopic plasters are particularly sensitive to this effect. Along cracks and joints filled with water this effect is stronger and the joint itself becomes a thermal bridge or the existing thermal bridge effect is increased

There is another heat loss effect: the absorbed water will be evaporated during drier intervals within the heating season, causing an evaporative heat loss.

The consequences of fabric damages are not easy to allow for in heat loss calculations. The relationship of conductivity and moisture content is known (or at least can be measured in the laboratory) but the moisture content itself depends on the time of the exposure, the driving rain index, and the length of the dry periods between the exposures. Tests carried out on a normal plastered brick wall specimen in climate chambers under simulated exposure have shown, that the effect of increased conductivity *and* the evaporative losses can be expressed as a notional increase of the *U* value by 0.1 – 0.2 W/m²K, depending on the density of the material.

Moisture penetration can be prevented by waterproof surface finishing which can be applied by itself or together with the added external thermal insulation (this is the so called "thermal skin" system). The expected thermal effect is the prevention of the wetting, thus avoiding the above notional increment of the *U* value.

Waterproof plastering is usually reinforced in order to prevent any cracks, which may occur due to thermal movement. Cracks would be especially dangerous here, as any water penetrating could not evaporate through the waterproof plaster (as it would through a normal one).

Waterproof plastering has a considerable resistance to vapour diffusion, it could increase the risk of interstitial condensation (refer to Section 3.5). This problem can be eliminated if a ventilated air gap of min. 40 mm width is provided between the thermal insulation and the outer skin. This is also the appropriate solution if the wall cannot be dried before applying the new surface finishing.

1.14.5 External surfaces: absorptance and emittance

The external surface determines the absorptance and long wave emittance of the wall. The effect of the solar radiation and long wave re-radiation can be estimated by introducing the sol-air temperature concept. A notional temperature increment is calculated, which would have the same effect on heat flow, as the radiant heat exchange (based on the average irradiance values over the heating season). It is usually a few degrees Kelvin (see section 2.11).

In a cool-temperate climatic zone, due to the lower external temperature and irradiance values, external surface absorptance influences the cumulative transmission losses by a maximum of 4 – 6 %. However, in warm-temperate climates, where both the external air temperature and irradiance values are higher, this effect can be 8 – 12 %.

Besides heat losses, heat gains in summer and deterioration of the surface finishes (thermal expansion, shrinkage) should be considered. Surface finishes highly absorbent for solar radiation (which may be desirable in winter) could have unfavourable consequences in the summer, thus should be avoided.

With regard to absorptance it should be remembered that it is not the colour of the surface alone that determines absorption and surface temperature.

Colour is an attribute of visible light, but thermal balance is influenced by the long-wave infrared re-radiation, thus by the emittance in this wavelength band as well. Surface temperature is the result of the combined effects of absorption and emission. As a consequence, a visually light surface can be quite "dark" in thermal sense and vice versa. A white painted surface is quite 'selective', it has low absorptance for solar wavelengths, but high emittance at terrestrial temperatures. Most building surfaces have a high emittance in the long infrared wavelengths.

1.14.6 Walls : cavity insulation

Cavity walls are generally used in housing of many areas in temperate rainy and windy climates.

Cavity insulation is defined and limited by the width of the existing air gap and the properties of the applicable foam (Fig.1.27). Such insulation improves the air tightness of the fabric. In comparison with external insulation a difference is that waterproofing, although it is possible as a separate measure, is not an inherent element of the technology.

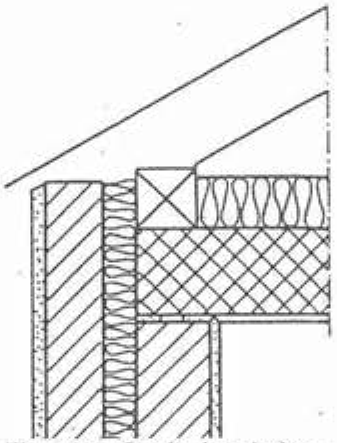


Fig.1.27 Cavity insulation: - junction with ceiling

In cavity walls the purpose of the air gap is to prevent moisture penetration to the inner skin. At one stage it was quite popular as a 'retrofit' to fill the cavity with injected foam (in situ foaming), eg. of polyurethane or urea-formaldehyde. Subsequent research showed that, although the continuous foam is a good moisture barrier, gaps and air pockets often remain around cavity ties, which will allow water penetration.

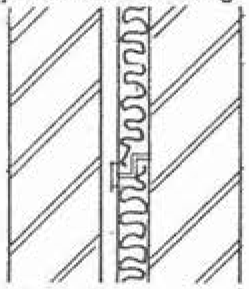


Fig.1.28 Recommended cavity-insulation with a rigid board

This 'cavity fill' practice is no longer recommended. For new work rigid insulating boards can be used (eg. extruded polystyrene) held against the outre face of the inner skin (Fig.1.28); in a normal 50 mm cavity a 38 mm board would leave a 12 mm clear cavity, which is an adequate barrier against water penetration.

1.14.7 Walls : internal insulation

Sometimes the thermal insulation cannot be located either on the external surface (the facade of an existing building may be of historic or aesthetic value, the scaffold would be to expensive or, only some of the rooms are to be separately insulated), or in the cavity (there is no cavity at all or the wall is damaged by rain penetration). In this case internal insulation is the only solution (Fig.1.29).

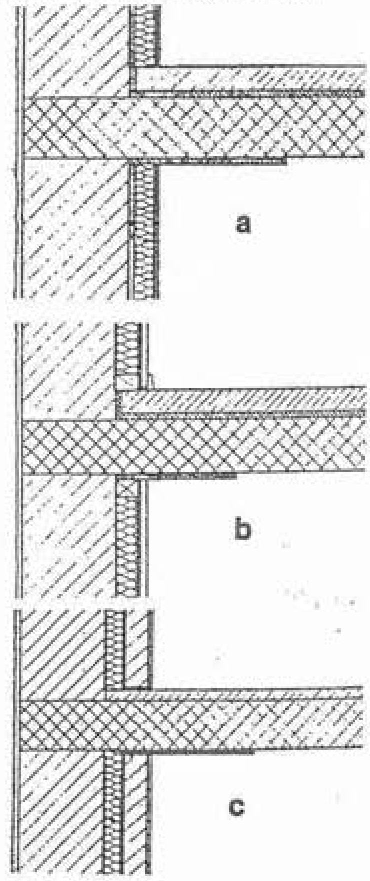


Fig.1.29 Retrofit internal thermal insulation, a) a sandwich panel: plasterboard+foam+plasterboard b) foam on wall+rigid sheet cover c) light masonry protective layer

Due to the low temperature in the load bearing layers a continuous vapour barrier has to be installed. Its best position is between two layers of insulation, where the inner layer provides enough depth for fixing plugs and electric wiring. Continuity of this vapour barrier is essential; simple overlapping is not satisfactory, welding or taping is necessary.

When inner layers or surface finishing are changed, it is advisable to take into account the thermal consequences other than reducing the heat flow. Such changes may be:

- new floor covering
- inside added thermal insulation
- suspended ceiling.

Any added layer of insulation inside decreases the active heat storage capacity of the construction beyond it. Carpets, suspended ceilings, acoustic absorbers isolate the floor slab heat storage capacity from the room, so does the inside thermal insulation (and the usual air gap of the plasterboard dry lining).

The consequences of reduced heat storage capacity are complex. The thermal mass of the load bearing layers will be isolated from the room; the thermal mass of the added layers is negligible. As a result, less free gain will

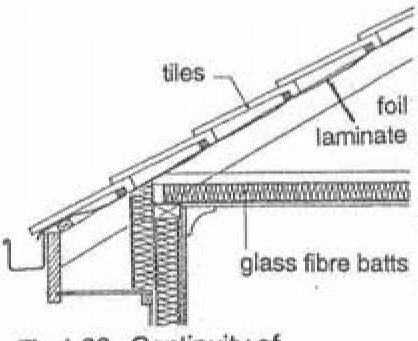


Fig.1.30 Continuity of wall and roof insulation

be utilised, larger temperature swings are expected in free running rooms in summer, night ventilation will be less effective. The other side of the coin is that energy can be saved where the heating is intermittent, provided that some temperature swings will be acceptable from the point-of-view of thermal comfort and there is no fabric damage risk due to the lower temperature and consequent higher relative humidity.

1.14.8 Some common mistakes

Not only the design and detailing of thermal insulation, but also the supervision of its installation are very important. Workmen on building sites tend to take shortcuts. In the documentation there should be sufficient detail to prevent the occurrence of such shortcuts.

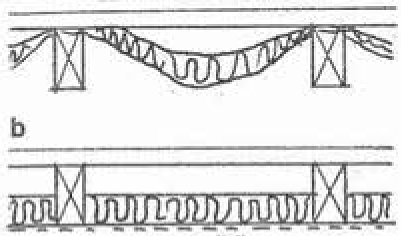


Fig.1.31 Insulation of exposed timber floor (over open space) a) incorrect, b)correct

a) Both wall and roof insulation may be satisfactory, but ***continuity*** at the junction of the two must be thought out and ensured (Fig.1.30).
b) ***Compression*** of insulation materials greatly reduces their performance and can result in local thermal bridges. This often occurs in exposed timber floors, where the insulation is draped over the floor joists and the flooring boards are nailed down through the insulation blanket (Fig.1.31). The correct solution would be to fit the insulation batts between the timber joists supporting it by a wire mesh fixed to the underside of joists (possibly with a building paper).
c) An even worse and frequent mistake is to drape the insulation over metal purlins and to fix the clips of the metal roofing to these purlins through the insulation (Fig.1.32).
d) In an attic space reflective insulation is often placed on top of the ceiling (or over some bulk insulation on the ceiling)

1.15 What does thermal insulation give ?

Thermal insulation, no doubt, decreases fabric losses, but it is an error to assume that the *only result* will be the lower thermal transmittance of the opaque building elements. To focus on the U-value can lead to serious misunderstanding, calculations may be performed out of context, which may lead to exaggerated expectations. ***The energy saving by the added thermal insulation can be as much as double or only half of the value calculated on the basis of one dimensional steady-state heat flow.*** This is due to the complex interrelations of different phenomena.

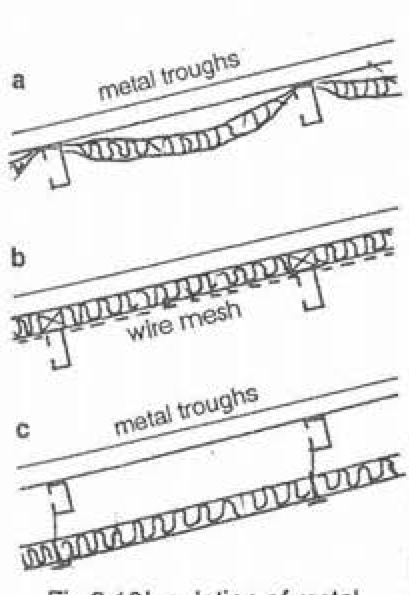


Fig.3.12Insulation of metal roof on pressed steel purlins
a: incorrect
b: battens for thermal break
c: rigid boards on T-bars, wire hangers

The added thermal insulation is more than just improved thermal resistance. If it is applied to the outer surface of exposed wall, many other parameters are influenced. Their relationships are illustrated in Fig.1.33. Continuous external insulation improves the thermal properties of joints and other thermal bridges: "linear" heat losses along the joints and thermal bridges decrease. Internal insulation does not give the same effect except at outer corners and at deeply recessed windows.

1.15.1 Thermal insulation and the necessary air change

Lower U-values *and* decreased thermal bridge effects increase the average inner surface temperature, thus also the mean radiant temperature. If the same resultant temperature is to be provided the air temperature can be lower. Besides the average, the minimum values of the inner surface temperature (around thermal bridges) also increase. As a result, a higher relative humidity of indoor air can be accepted without increasing the risk of capillary condensation and mould growth.

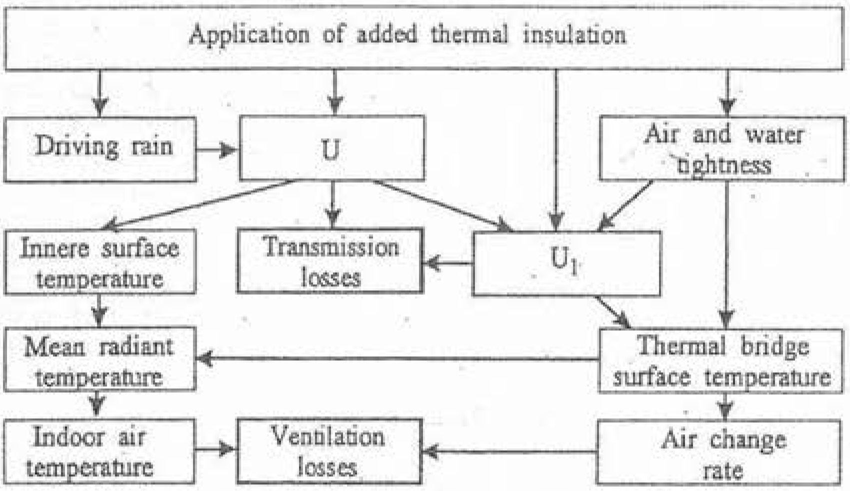


Fig. 1.33 Effects and side-effects of thermal insulation

In residential buildings the necessary air change rate is usually determined by the relative humidity of indoor air, low enough to prevent capillary condensation in the inner surface layers. The higher the acceptable relative humidity, the less the necessary air change rate. Due to such acceptable lowering of the indoor-air temperature, and decreased air change rate, ventilation heat losses are reduced.

1.15.2 Fabric protection

Temperature distribution around panel-joints is often influenced by air infiltration between the panels. External thermal insulation and outer surface finishing improve the air tightness and eliminate this side-effect.

Improving the tightness of joints, direct moisture penetration in driving-rain or air exfiltration will be reduced, possibly eliminated. The drier joint decreases the risk of the mould growth. Waterproofing properties of the outer surface finish decrease the driving rain effects: the drier construction will maintain its conductivity, heat losses by evaporation are lower.

1.16 Some conclusions

If the attenuation of one-dimensional heat flow is considered as the primary effect of insulation and the others, such as thermal bridge losses, ventilation, etc. as side effects, - if outside insulation is added - the energy saving due to side effects is of the same magnitude or even greater than that due to the primary effect.

This is why there are considerable differences between internal and external insulation of the same added resistance. These differences are greater if other, non transmission related side effects are also considered, such as waterproofing, reduced evaporative losses and moisture absorption or sol-air temperature. With external insulation the air change rate can be decreased without increasing the risk of the fabric damage. This does not apply to internal insulation. Contrary to the transmission losses this side effect is more important if the surface to volume ratio is lower. As a result, the energy saving by external insulation is about twice that achieved by internal insulation of the same added thermal resistance.

Part 2 THEORY AND REFINEMENTS

2.1 Transport phenomena in general

A generalised description of the transport processes and the balance equations might appear to be a needless academic exercise, but this generalisation gives us a broader view. It allows us to find similarities and analogies between different processes, to develop generalised algorithms, to model a specific process with another one (e.g. heat transfer with an electrical network) and – hopefully – it leads to a better understanding of the very complex, exciting and interesting system: the building.

The term `mass transfer' refers to the movement of air and moisture and includes processes such as ventilation, vapour diffusion, evaporation and condensation in building structures and in air conditioning installations. In heat and mass transfer two types of quantities are involved.

1) Potential-like quantities, which measure the *state* (temperature, pressure) of a medium (air, water, solids) *at a given point*. A difference in magnitude of these quantities between two points (e.g. inside a building and outside) provides the *driving* force for the flow of one of the second type of quantities:

2) *Flow quantities* (a substance or energy that may be transferred) eg. a kg of air or a J (joule) of heat) or measured as the rate of that flow, eg. kg/s air flow, or W (J/s) of heat flow. [*Per analogiam:* electric potential difference (volt) drives the current (amp), the flow of electricity].

The indoor space and the outside environment are separated by the building envelope. Its properties: transmittance, mass, etc. control the flow rates.

Among the above physical quantities interrelated pairs can be discovered such as temperature – heat, (air) pressure – mass (of ventilation air). Heat flow depends on temperature difference, mass flow on pressure difference. They are connected by the related properties of envelope: transmittance for heat and permeance for water vapour. The flow is described by the transport equation, which, in general terms is:

$$Q = C\,(i_1 - i_2) \qquad \text{... 2.1)}$$

$$Q = (i_1 - i_2)\,/\,R \qquad \text{... 2.2)}$$

where
- Q flow rate (or flux) of a quantity
- i the state of the medium at two points
- C coefficient of transmission (conductance, permeance)
- R resistance

C and R are reciprocal values.

This general form of the transport equation applies to any phenomenon, independently of the "content" of the process. Thus, *i* can be air pressure, vapour pressure, temperature, electric potential, Q can be mass flow of air or water vapour, heat flow, electric current. This general form is then adapted to specific processes. Sometimes the flow is a power function of the driving (state) quantity (e.g. air flow through cracks).

C itself may depend on the driving- (state-) quantity (eg. thermal conductivity may vary with temperature) or another state quantity (eg. thermal conductivity on relative humidity). The nature of the flow (eg. laminar or turbulent flow) or its direction (eg. air permeance of windows at in- and exfiltration) can also influence the transport equation. There are *cross effects* and linked processes: eg. between heat and moisture transfer. Nevertheless, the simplified general form facilitates the understanding of the fundamental processes.

2.2 Balance conditions

The building, or a part of it (a room, a part of a wall) can be considered as a thermal system - bordered by real or imaginary boundary surfaces.

Under steady state conditions, if the driving values (eg. temperature) are constant, the condition of balance is:

$$Q_{in} = Q_{out} \qquad \text{... 2.3)}$$

thus the sum of the flows (eg. heat flows) into the system is equal to the sum of the flows out of the system.

in a non steady state condition

$$Q_{in} - Q_{out} = \Delta S \qquad \text{... 2.4)}$$

thus if there is a difference in the flows (eg. heat flows in and out) this will result in a change of the stored quantity (S), e.g. of heat. This will produce a change of the state of the system (eg. more heat stored increases the temperature).

A special case - the quasi steady state condition - exists when the change is periodic in time. In this case equation (2.4) describes the momentary situation, but equation 2.3 applies to the average values for a full cycle. Thus, at a given moment a difference can exist between the flows into and out of the system, but the sum of the flows for the period of a full cycle is the same.

2.3 Design objectives and approaches

A precondition of successful design is the unambiguous identification of the objectives. With regard to energy use for thermal control (and its environmental consequences) the following results are expected:

- low heating energy consumption (zero, if reasonably achievable)
- low or zero cooling energy consumption
- reduction of the required capacity (thus the size) of the heating or cooling system

thus, as a consequence of the above:

- as long as possible free running periods of acceptable indoor thermal conditions

and, taking into account other (structural, constructional or aesthetic) aspects:

- to improve thermal comfort and living conditions
- to improve fabric preservation
- to keep existing or to add new aesthetic values.

These objectives can be achieved in different ways. With some simplification two different possibilities can be distinguished: the **defensive** and the **interactive** approaches.

The **defensive** approach involves the minimisation of the unwanted energy fluxes which would have to be compensated by the HVAC (heating, ventilation and air conditioning) systems. The main features of a defensive building are: compact form, high level of thermal insulation, air-tightness, restricted glazing ratio (sometimes with high-tech windows), effective shading devices and heat recovery. As a special case earth-sheltered houses can be mentioned.

The **interactive** (or **solar**) approach aims at maximising the desirable energy flows which reduce the task of the HVAC systems. The main features of an interactive building are: building form dictated by orientation, higher and orientation-dependent glazing ratio; some solar systems, conscious use of heat storage capacity and convective energy flows, and effective shading devices, in some cases heat recovery.

Sometimes the protagonists of solar strategy overestimate the role of the heat storage capacity and underestimate that of the thermal insulation. In reality the utilisation of the stored and released energy depends on the *time constant* of the building (see Section 2.14), which is proportionate to the ratio of the thermal mass and the envelope conductance (the overall heat loss coefficient) of the building. Thus, although the overall insulation level of a solar or interactive building is limited by the larger glazing ratio and some other solar collecting elements (eg. a greenhouse), the solar building should also be insulated as well as possible in order to improve its solar performance.

2.4 Conductivity: declared and design values

Conductivity was introduced in Section 1.3. Conductivities of building materials show a wide variation: from 0.02 W/m.K for the lightest foams, through 0.4–0.9 for different bricks, 1.5 of reinforced concrete, up to 70 for steel and over 200 for aluminium (see Data sheet 1). The trend -with a few exceptions- is that the higher the density the higher is the conductivity.

Conductivity is strongly influenced by porosity, the pores filled with stagnant air. This is the case with foams or fibrous materials. Conductivity increases if the pores are filled with water, ie. if the moisture content of the material is increased. A fibrous cement insulating board showed the following properties at different levels of moisture content:

dry	density:	136 kg/m^3	conductivity:	0.051 W/m.K
wet		272		0.144
soaked		400		0.203

If the structure of a material is such that the air spaces are interconnected (this is the case of fibrous materials or foams with an open pore structure) and the layer is in a vertical position, a thermosiphon air circulation can be generated inside this layer, by the temperature differences (see Fig.1.5). This phenomenon increases the heat transfer which can be expressed by an increased λ value.

The operational conditions in transportation, on building sites and during the life cycle of a building are such that damage of insulating materials is often inevitable. Therefore in design conservative λ values must be used, to allow for the compression, crushing, moisture and other effects reducing the insulating value of these materials. Due to such effects, eg. the λ value of a polystyrene foam between reinforced concrete layers (in a sandwich panel) may increase by 35–45% !

Published values (eg. those given in Data sheet 1) are measured in laboratory tests, and are referred to as *declared values.* Designers should be aware that these are not appropriate for calculating the transmittance (U-value). *Design* conductivity values should be used. These depend not only on the material itself, but also on the way it is used, thus allowing for any probable deterioration.

If no such *design values* are available, declared λ values should be corrected according to the equation

$$\lambda_{design} = \lambda_{declared} * (1 + \kappa_1 + \kappa_2 ...) \qquad ... 2.5)$$

where κ = correction factors (additive) from Table 2.1.

Table 2.1 Conductivity correction factors

Material		κ
Expanded polystyrene	between cast concrete layers	0.42
same	between masonry wall layers	0.10
Rockwool	between masonry wall layers	0.10
Polyurethane	in ventilated air gap	0.15
Expanded polystyrene	in ventilated air gap	0.30
same	with cement render applied	0.25

To illustrate the magnitude of such corrections, some of the examples of part 1 are re-examined:

In ***Example 1*** (p. 11) the conductivity of expanded polystyrene was taken (from Data sheet 1) as 0.035 W/m.K. This is an external insulation and cement rendering is applied directly to it (with some wire mesh): the correction factor (the last item in Table 2.1 above) is κ = 0.25
therefore the corrected *design value* will be
$\lambda = 0.035 * (1 + 0.25) = 0.0438$ W/m.K
thus the resistance of layer 3 will be $\frac{0.05}{0.0438} = 1.1416$
and the total, corrected resistance becomes 1.8526
therefore its reciprocal, the corrected U-value = 0.54 W/m²K
(as compared with the previously calculated 0.467, or some 15% increase)

Example 2: the temperature gradient of the same wall has to be recalculated (combining the two tabulations of the original example):

	R-ratio*(-20) =		Δt	t °C
Inner surface	$\frac{0.12}{1.85}$	= 0.065	-1.3	18.70
1st layer	$\frac{0.03}{1.85}$	= 0.016	-0.32	18.38
2nd layer	$\frac{0.484}{1.85}$	= 0.261	-5.22	13.16
3rd layer	$\frac{1.1416}{1.85}$	= 0.617	-12.34	0.82
4th layer	$\frac{0.017}{1.85}$	= 0.009	-0.18	0.64
External surface	$\frac{0.06}{1.85}$	= 0.032	-0.64	0

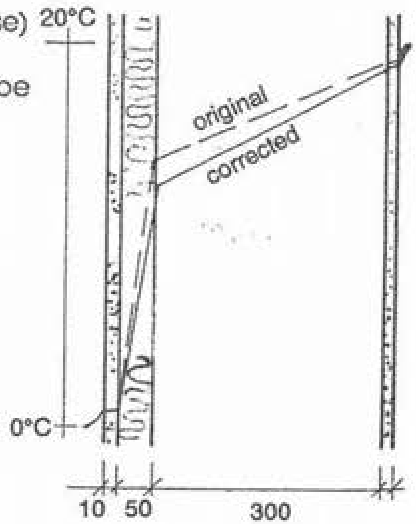


Fig.2.1 The effect of us
corrected ('design') λ val
the gradient is lowered

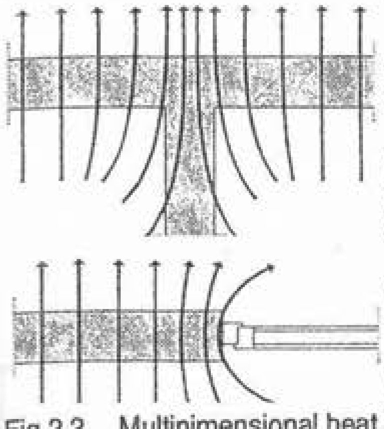


Fig.2.2 Multinimensional heat flow, due to geometry: T-junction and window reveal

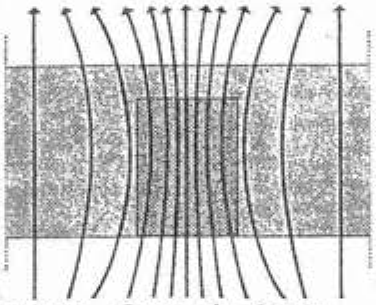


Fig.2.3 Same, due to non-homogeneous construction

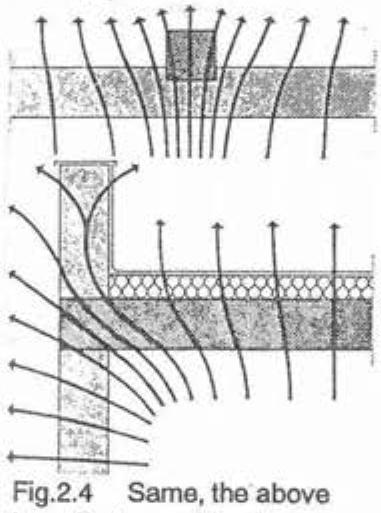


Fig.2.4 Same, the above two effects combined

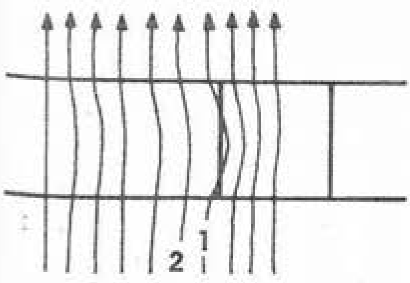


Fig.2.5 Heat flows the 'shortest' (the least resistance) path

Fig.2.1 shows the revised gradient, compared with the uncorrected original.

In *Example 3* it was found that a resistance of 0.523 m²K/W must be added to the wall construction. The conductivity of polystyrene is to be corrected same as in example 1, thus the required insulation thickness is

$b_{ins} = 0.0438 * 0.523 = 0.023$ (23 mm)
- rather than the previously calculated 18 mm

In *Example 4* (p.13) it was found that a resistance of 1.254 m²K/W must be dded to the wall. The density of mineral wool was taken as 150 kg/m³ (from Data sheet 1) giving a conductivity of 0.044 W/m.K

As this insulation will be placed between two layers of brick, the correction factor from Table 2.1 is $\kappa = 0.1$, thus
$\lambda = 0.044 * (1 + 0.1) = 0.0484$ W/m.K

therefore the minimum thickness needed is
$b_{min} = 0.0484 * 1.254 = 0.061$ m (= 61 mm)

This is just over the available 60 mm thickness, but any rounding must be upwards: the nearest larger thickness available is 80 mm and this must be used, therefore the resistance of layer 3 will be

$$R_3 = \frac{0.08}{0.0484} = 1.65$$

thus the the corrected $R_{a-a} = 0.746 + 1.65 = 2.396$
and $U = 0.417$ W/m²K

2.5 Multidimensional steady state heat flow: thermal bridges

In Part 1 the assumption was made that heat flows through an envelope element with the flow path being perpendicular to the plane of that element, ie. the phenomenon is analysed as a *one-dimensional heat flow*. This is true only for infinitely large elements with parallel plane surfaces and uniform cross-section. The results obtained with calculation techniques presented in Part 1 are approximate only.

In real building elements the criteria of one dimensional heat flow are often not fulfilled. Where the boundaries are other than plane parallel surfaces, or the material is not homogeneous, two or three-dimensional heat flows develop. Areas where increased, multidimensional heat flow occurs are called *thermal bridges*. These may be consequences of the geometric form (Fig.2.2), including corner effects, the combination of materials of different conductivities (Fig.2.3), or both (Fig.2.4).

Temperature distribution around thermal bridges

Heat flow will take place along the shortest path, the path of least resistance. In Fig.2.5 the resistance along flow path 1 is less than it would be along a line perpendicular to the surface, due to the higher conductivity of the column. Along flow path 2 the resistance is less, due to the bigger "cross section", not "occupied" by other flows. The heat flow density will be greater at thermal bridges, therefore the surface temperature outside increased and inside reduced.

Heat flows in the direction of the steepest temperature gradient, as water flows in the direction of the steepest slope (Fig.2.6). Thus the heat flow paths are at right angles to the isotherms (an isotherm is the locus of points of equal temperature). In Fig.2.7 the density of heat flow paths indicates an increased heat flow, whilst the isotherms show an increased outside surface temperature at the column and a reduced inner surface temperature.

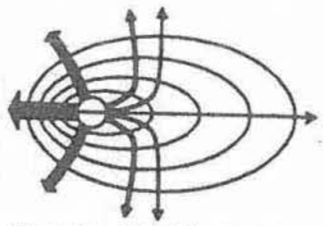


Fig.2.6 Heat flows as water flows downhill

If, as in Fig.2.8 an isulating element is inserted (here: on the outside face of the concrete column), which blocks the heat flow, the temperature in the highly conductive column will be higher than in the adjoining wall, therefore a sideways heat flow will occur, increasing the flow density near the column. The outside surface temperature over the insulating insert will be lower and next to this insert higher than of the plain wall.

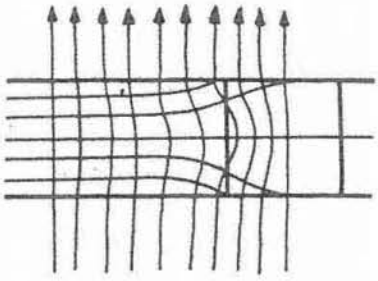


Fig.2.7 Thermal bridges: temperature distribution

As a rule of thumb, the effect of thermal bridges diminishes to negligible levels beyond a strip of a width of twice the wall thickness. If the wall thickness is 300 mm, the width of this strip is approx. 600 mm, in both directions from the edge. Viewing a usual room size facade element and marking these strips along the joints it can be seen that there is no area on this element that would be free of thermal bridge effects and of multidimensional temperature distribution (Fig.2.9).

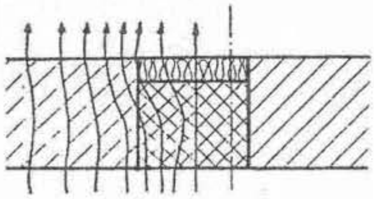


Fig.2.8 The effect of an insulating insert

2.6 Calculation method

Conceptually the calculation is based on a subdivision of the construction around the thermal bridge into small parts. (Fig.2.10). Each part is in thermal equilibrium, thus heat flows at each part from and to the neighbouring small parts are equal. The thermal conductance between these parts is proportionate to their surface area and the conductivity and is inversely proportionate to the distance between their centre-points. The temperature at the boundary is given. The number of the unknown temperatures is the same as that of the small parts, thus same as the number of equations. Now, "only" a computer and a fast algorithm are needed to solve a system of equations, consisting of some hundreds - possibly thousands - of unknown temperatures and the same number of equations. (The program ESP is known to solve up to 10 000 simulateneous differential equations.)

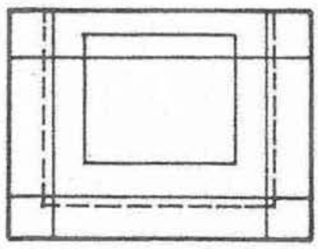


Fig.2.9 A facade element with a window: fully covered by thermal bridge strips

Practical approach

To simplify the calculation of the extra heat losses due to the thermal bridge effect, the concept of *linear heat transfer coefficient* has been introduced. This allows for the extra heat losses along a unit length of a thermal bridge, at a unit temperature difference and in a unit time.

For a given part of the building envelope, the length of different thermal bridges (edges, joints, window perimeter, etc.) has to be measured. The thermal bridge losses ("linear" losses) are

$$Q = \Sigma (l * k_l) * (t_o - t_i) \qquad [m * W/m.K * K = W] \qquad \dots 2.6)$$

where
l = length of each thermal bridge [m]
k_l = linear heat transmission coefficient of each thermal bridge [W/m.K]

Besides such linear losses, the reduced inner surface temperature is important from the point of view of fabric protection. Critical surface temperatures are given on a relative scale. The zero point of this scale is the outdoor temperature, the unit is the difference between the indoor and outdoor air temperature. Thus, at point x the temperature (t_{rel}) measured on this relative scale will be:

$$t_{rel} = \frac{t_x - t_o}{t_i - t_o} \qquad \text{...2.7)}$$

ie. t_{rel} is a fraction of the air-to-air temperature difference, taken as 1. Converting from relative temperature to the Celsius-scale:

$$t_x = t_o + t_{rel} \cdot (t_i - t_o) \qquad \text{...2.8)}$$

"Thermal bridge catalogues" are available, with thousands of generalised temperature data and linear heat loss coefficients. Some informative linear heat loss coefficient data are given in Table 2.2.

Note that the extra heat losses due to thermal bridge effects are in general 20-50% of the losses calculated on one dimensional basis.

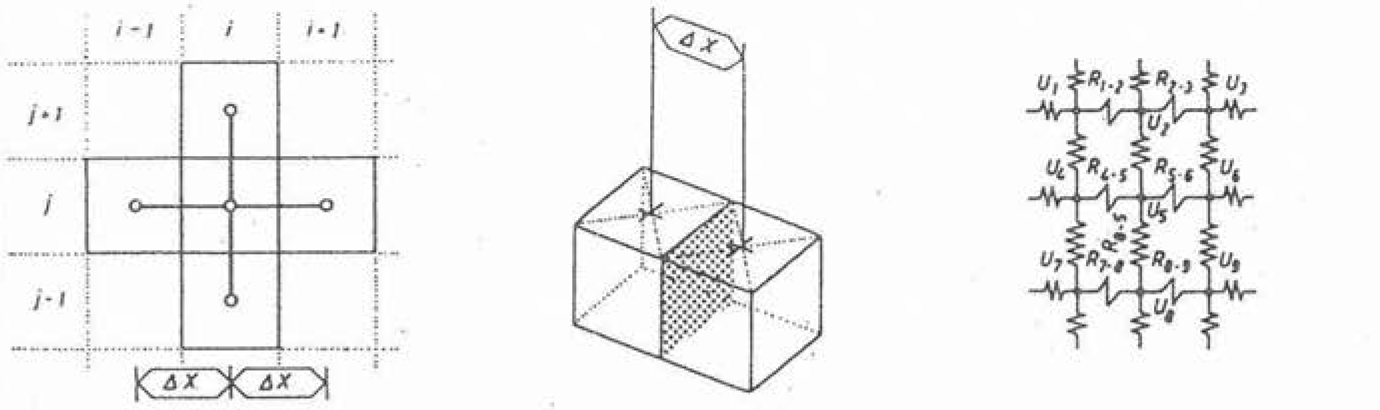


Fig.2.10 The schema of elementary parts. The resistance between them is proportionate to Δx and inversely proportionate to λ and the contact plane area. This is analogous with an electric resistance network.

Table 2.2 Linear heat loss coefficients

Description	k_l W/m.K
Window perimeter	0.15
Window perimeter if the frame is in the plane of the thermal insulation	0
Outer corner of homogeneous wall	0.10
Outer corner of wall with external insulation	0.15
External wall with internal insulation	0
Joint of homogeneous external wall and internal wall (both edges counted)	0.12
Joint of ext. wall with external insul.and internal wall (both edges counted)	0.06
Joint of homog. ext. wall and floor slab with insul.strip (booth edges counted)	0.15
Joint of ext. wall with external insulation and floor slab (both edges counted)	0.06
Parapet wall, cornice	0.20
Balconies	0.30

Note that for "T"-form joints k_l values should be applied to both the left and right side. These are of the same values, if the perpendicular construction has a symmetrical cross section, but they differ from each other for an asymmetrical cross section.

2.7 Thermal points

If thermal insulation is pierced through with elements of high conductivity (eg. steel reinforcement ties in sandwich panels), an average conductivity value should be taken into account, using an area-weighted averaging:

$$\bar{\lambda} = \frac{(A - A_s)\lambda_d + A_s\lambda_s}{A} \qquad \text{... 2.9)}$$

where

A = area of the element in question

A_s = steel area

λ_d = design conductivity value of thermal insulation

λ_s = conductivity of steel

Due to the large difference between λ_d and λ_s, lateral heat flows (parallel with the surface) can be neglected. Note that this approach - area-weighted average of λ values - ***is not applicable*** to any other form of thermal bridges

Example 10 Modify U-value for thermal points

A sandwich panel includes an 80 mm expanded polystyrene slab between two reinforced concrete layers. In 1m² elevation area there are 4 steel ties of 16 mm diameter, penetrating the polystyrene. Calculate the U value including the effect of the thermal points for the following panel, by an area-weighted averaging method:

No	Material	b m	λ W/m.K
1	Reinforced concrete	0.15	1.55
2	Expanded polystyrene	0.08	0.04
3	Reinforced concrete	0.10	1.55

The expanded polystyrene is between two layers of cast concrete, the necessary correction factor: $\kappa = 0.42$, thus the λ design value is:
$(1 + 0.42)*0.04 = 0.0568$ W/m.K

The value will be further increased by the steel ties. Their aggregate cross-sectional area per unit panel area (area fraction) is:

$$4*\frac{0.016^2\pi}{4} = 0.0008 \text{ (m}^2\text{/m}^2\text{)}$$

the weighted average conductivity is:
$0.0008*70 + 0.9992*0.0568 = 0.113$ W/m.K

With this, the resistances are:

Inner surface	R_{si}	= 0.12
1st layer	$R_1 = \frac{0.15}{1.55}$	= 0.065
2nd layer	$R_2 = \frac{0.08}{0.113}$	= 0.708
3rd layer	$R_3 = \frac{0.1}{1.55}$	= 0.065
External surface	R_{so}	= 0.04
Air-to-air resistance		= 0.998

Thus the U value $\frac{1}{0.998}$ = 1.002 W/m²K

(without allowing for the thermal points this would be 0.587)

2.8 The resultant transmittance

For a given part of the building envelope a resultant heat transmission coefficient can be calculated:

$$U_R = \frac{A*U + \Sigma(l*k_l)}{A} \qquad ...2.10)$$

The resultant U value of prefabricated elements can be measured in calorimeters of adequate size.

Example 6 Resultant U-value calculation

A facade element, at the corner of a building, shown in Fig.2.11, consists of the following layers (from the inside):

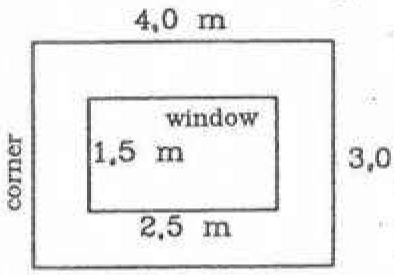


Fig.2.11 A facade element at a corner, with a window

No	Material	b m	λ W/m.K
1	Plaster	0.015	0.80
2	Light hollow Brick	0.38	0.41
3	Plaster	0.015	0.80

The resistances are:

Inner surface	R_{si}	= 0.12
1st layer	$R_1 = \frac{0.015}{0.80}$	= 0.019
2nd layer	$R_2 = \frac{0.38}{0.41}$	= 0.926
3rd layer	$R_3 = \frac{0.015}{0.80}$	= 0.019
External surface	R_{so}	= 0.04
Air-to-air resistance		= 1.12

U value $\frac{1}{1.12}$ = 0.89 W/m²K

Linear loss coefficients ($l * k_l$) (m*W/mK = W/K)

- along the window perimeter 8 * 0.15 = 1.20
- along the outer corner 3 * 0.10 = 0.30
- along the external wall–internal wall joint (one edge only) 3 * 0.12 = 0.36
- along the external wall – floor slab joint
  (one edge edge on the floor, one at the ceiling) 4 * 0.15 = 0.60

sum of the linear heat loss coefficients 2.46

area of the wall (excluding window): $A = 3 * 4 - 2.5 * 1.5 = 8.25\ m^2$

The resultant U value is:

$$U_R = \frac{8.25*0.89 + 2..46}{8.25} = 1.19\ W/m^2K$$

Add 40 mm expanded polystyrene thermal insulation outside. The added resistance (see previous examples) will be:

$$\Delta R = \frac{0.04}{0.05} = 0.8$$

Thus the improved air-to-air resistance: R = 1.12 + 0.8 = 1.92

and the U value: $\frac{1}{1.92} = 0.52\ W/m^2K$

New linear heat loss coefficients:

- along window perimeter (zero if frame in the plane of insulation) –
- along the outer corner 3 * 0.15 = 0.45
- along the external wall – internal wall joint
  (one edge only) 3 * 0.06 = 0.18
- along the external wall–floor slab joint
  (half at edge on the floor, half at the ceiling) 4 * 0.06 = 0.24

sum of the linear heat loss coefficients 0.87

The resultant U value:

$$U_R = \frac{8.25*0.52 + 0.87}{8.25} = 0.62\ W/m^2K$$

Note that without considering the thermal bridges the U-values (thus the heat losses) decrease by 41% (0.89→0.52). However, the resultant U-values decrease by 48% (1.19→0.62).

Depending on the type of the joints and on the position of the added insulation the ratio of the resultant U-values can be either lower or higher than that of the U-values calculated on the basis of one dimensional flow. Either positive or negative difference is possible, depending on the geometry and constructional details of the building. This important fact should be kept in mind.

2.9 Radiant heat transfer

All surfaces emit radiant energy. The total rate of energy emission per unit area depends on the absolute temperature, on the emittance of the surface itself and of the receiving surfaces. The heat radiated by a body consists of electromagnetic waves of many different wavelengths. The spectral distribution of the energy depends on the surface temperature.

The product of the wavelength of the maximum emissive power and the absolute temperature of the surface is a constant

$w_{max} * T = 2898$ (µm.K) ...2.11)

where w = wavelength in µm

This relationship is the basis of many passive systems.

If the emittance does not depend on the wavelength the surface is called *gray*. Several important classes of surfaces approximate this condition in some regions of the spectrum. For other surfaces emittance is a function of wavelength. These are called *selective surfaces*. The important wavelength bands distinguished are: that of solar radiation and that of long wave infrared radiation. External surfaces are exposed to the first and emit radiation in the second. Terrestrial surface temperatures being around 300°K, the emission max. is at a wavelength of about 10 µm, whilst solar radiation peaks around 0.5 µm (≈ 550 nm).

When radiant energy falls on a surface, it can be absorbed, reflected or transmitted through the material. The sum of the corresponding three coefficients is:

$\alpha + \rho + \tau = 1$ ...2.12)

where α = absorptance

ρ = reflectance

τ = transmittance (more precisely 'optical transmittance' to distinguish it it from thermal transmittance or U-value)

If $\alpha = 1$, the surface is black. If $\tau = 0$, the material is *opaque*. If $\tau > 0$, the material is *transparent* or *translucent*.

ε = emittance

is a measure of the emission ability of a surface; it is a fraction of such emission from a 'black body', the perfect emitter/absorber.

For any surface with an absorptance independent of the angle of incidence, or where the surface is diffuse, the emittance, $\varepsilon_w = \alpha_w$.

For gray surfaces $\varepsilon = \alpha$ at all wavelengths.

For selective absorber surfaces (eg. in solar collectors) $\alpha_{6000\,K} > \varepsilon_{350\,K}$,

but for a white painted surface (especially titanium oxide white)

$\alpha_{6000\,K} < \varepsilon_{300\,K}$.

The radiation heat flow can be measured as the instantaneous ***irradiance*** (power density) in W/m², or as ***irradiation*** (energy density) over a specified period of time, in Wh/m² or MJ/m².

2.10 Radiant heat exchange between terrestrial bodies

In the following discussion radiant heat exchange between "terrestrial bodies": building elements, heat emitters, occupants, is analysed. It can be assumed that

- the surfaces are gray
- radiation and reflection are diffuse
- the medium (air) between the surfaces does not emit or absorb radiation
- absorptance and emittance are constant over the surfaces and do not depend on temperature (the range of temperatures is quite narrow)

The radiant energy transfer rate between two surfaces that "see" each-other is always proportionate to the difference between the 4th power of their absolute temperatures (°K). Between two parallel plane surfaces (provided they "see" each-other and nothing else, ie. they are large and close together) this energy flow rate will be

$$Q = \bar{\varepsilon} * \sigma * (T_1^4 - T_2^4) \qquad ...2.13)$$

where $\bar{\varepsilon}$ = effective emittance of the two surfaces = $\frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$

σ = the Stefan-Boltzmann constant: $5.67*10^{-8}$ W/m^2K^4

As this constant is a very small number, often it is more convenient to use the 5.67 characteristic only and leave the 10^{-8} mantissa to the temperature term:

$$Q = \bar{\varepsilon}*5.67*\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad \text{as} \qquad \left(\frac{1}{100}\right)^4 = 10^{-8} \qquad ...2.14)$$

The concept of shape factor

If both surfaces are of area A, then the above expression will be multiplied by that A. If the surfaces are not equal or not parallel, then another term, the *shape factor* (F_s) will have to be included.

The radiant energy transfer between an emitting surface and a part of a hemisphere facing it is proportionate to the cosine of the angle between the surface-normal at the centre point (P) of the emitting surface and the line connecting this point with the centre of the part of the hemisphere considered. Thus the radiant heat exchange between two surfaces depends on their relative geometric position: on how they "see" each other.

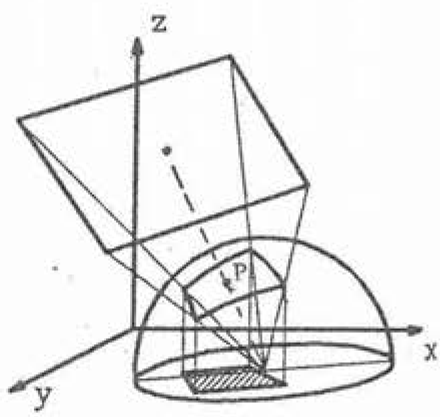


Fig.2.12 Geometry of the 'shape factor' or 'angle factor'

This relationship is expressed by the *shape factor*, which is defined as the fraction of diffuse radiant energy leaving one surface and falling directly upon the other surface (Fig.2.12). The shape factor can be determined by numerical and graphic techniques. Ready-made data are available in various design guides.

Equation 2.14 is used (with F_s included) to calculate radiant heat exchange

- between the boundary surfaces of a room in detailed analysis (eg. for large halls with radiant heating)
- between boundary surfaces and occupants to check thermal comfort conditions.

Note that if a given surface "sees" n other surfaces, the sum of the n shape factors is 1, ie. all radiation leaving the first surface must end up on one or other of the surrounding surfaces.

In practical work it is often convenient to calculate the radiant heat transfer rate by using a *radiation coefficient*, (h_r) as

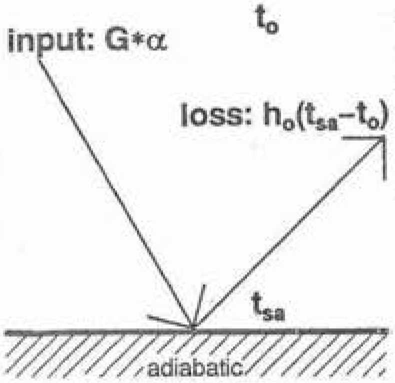
$$Q = h_r * A * (t_1 - t_2) \qquad ...2.15)$$

where

$$h_r = \frac{F_s * \bar{\varepsilon} * 5.67 * \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]}{t_1 - t_2} \quad \text{...2.16)}$$

and Fs is the shape factor, otherwise this is derived from eq. 2.14

2.11 Radiative balance of opaque elements



equilibrium when:
input = loss
$G*\alpha = h_o(t_{sa}-t_o)$
from which:
$t_{sa} = t_o + G*\alpha / h_o$

Fig.2.13 Derivation of the sol-air temperature

An opaque surface exposed to solar radiation will be heated until its temperature increases to a point when the convective heat loss equals the net radiant gain. If we assume the surface to be adiabatic (i.e. there is no heat flow into the body behind the surface), then the surface temperature will be referred to as the *sol-air temperature*. The equilibrium condition will occur when loss = gain (Fig.2.13), ie.

$$h_o * (t_{sa} - t_o) = G * \alpha - \varepsilon * \Delta E \quad \text{...2.17)}$$

where α = absorptance for solar radiation
G = global solar irradiance
h_o = surface conductance (a lumped parameter: h_c+h_r)
t_{sa} = surface (sol-air) temperature
t_o = outdoor air temperature
ε = emittance for long-wave infrared radiation
ΔE = difference in long wave radiation input (from sky and surroundings) and the emission by a black-body at air temperature.

From this the unknown t_{sa} can be expressed

$$t_{sa} = t_o + \frac{G*\alpha - \varepsilon * \Delta E}{h_o} \quad \text{or} \quad t_o + (G*\alpha - \varepsilon*\Delta E)*R_{so} \quad \text{...2.18)}$$

This is the definition of *sol-air temperature*, the term indicating that it combines the effects of outdoor air temperature and solar radiation. Although the term sol-air temperature may imply climatic data, its value depends also on surface properties of building elements.

The heat transfer then, through an envelope element will be (modifying eq.1.6):

$$Q = A*U*(t_{sa} - t_i) \quad \text{...2.19)}$$

The terms "dark" and "light" normally refer to surface properties for visible light: wavelengths 380 - 780 nm (nano-metre = 10^{-9} m). Solar radiation is dominantly visible, but contains some UV and much IR wavelengths (up to 3000 nm). Surface temperature depends on the absorptance for solar radiation *and* the emittance of the surface in the "long wave" infrared band (longer than 3000 nm).

In some cases the visual impression may be "light", but for the infrared band the surface is dark (in the thermal sense). This is the case of selective surfaces mentioned above (in section 2.9), eg. snow cover and most white paints. Very high or very low surface temperatures can be achieved by the deliberate use of such **selective surfaces**, with the appropriate α and ε values. The α/ε ratio (more precisely the $\alpha_{6000\,K}/\varepsilon_{350\,K}$ ratio) can be as high as 18 for some solar collector surfaces, such as chromium black.

Emittance of flat roofs may have an important role in both winter and summer, during the night. Flat roofs "see" the sky and their radiant emission depends on the apparent sky temperature. Their radiant heat exchange takes place with the small particles of the atmosphere (primarily water-vapour), the temperature of which decreases with the altitude. If the air is drier, water particles are fewer, the probability of striking one of them in the lower layers of the atmosphere is less, ie. mostly the particles in higher layers will form the cool receiving surface and the radiant heat loss of the roof will be greater. Conversely, at higher air humidity the probability of striking a water vapour particle in lower layers is larger, the receiving surface is warmer and the radiant heat loss is less (Fig.2.14). As a result of this phenomenon extra heat losses have to be taken into account while calculating heat load. For normal roof surfaces (except bright metal) it is usual to take the value of $\varepsilon * \Delta E$ as 90 W/m² in a clear sky situation, 50 for a partly cloudy and 20 W/m² for an overcast sky.

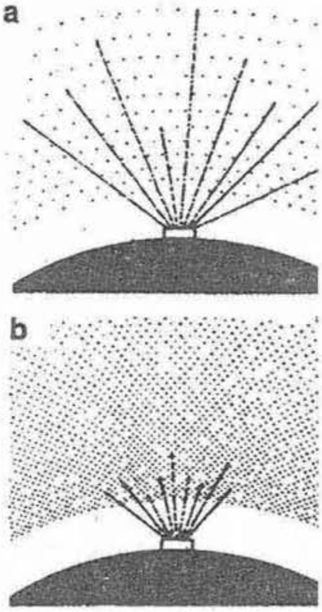


Fig.2.14 Radiation to the atmosphere, a: dry, b: hun

This process is the basis of one of the passive cooling techniques in hot-dry climatic conditions.

Roofs are most exposed to such radiant loss, but also to a wide temperature range; therefore thermal movements and the strength of materials must also be considered while designing the waterproofing and thermal insulation.

2.12 Non-steady one dimensional heat flow

In this case the difference of the flows, entering and leaving the system (the wall) results in the variation of stored heat. This variation is proportionate to the thermal capacity of the body (J/K), which is the product of its mass (M) and the specific heat of the material (*c*), as well as to the temperature variation. The value of c is usually given in J/kg.K (sometimes on a volumetric basis as J/m³K). For building materials (except wood and metal) the values of c are in the narrow range of 850 - 1000 J/kg.K, thus often only the mass of materials is compared without mentioning the specific heat.

Heat transfer can be calculated by subdividing the wall into thin layers. Each has a mass, proportionate to the thickness of the layer and the density of the material. Between two such layers the thermal resistance is proportionate to the distance between the center-planes of the layers and is inversely proportionate to the conductivity (Fig.2.15). The temperature (or heat flux) versus time function is given on the boundary as well as the temperature distribution within the wall in a given moment (initial conditions). The energy balance is to be calculated step by step for $\Delta\tau$ small time intervals. The balance of the j-th layer for the i-th time interval is:

$$\frac{t_{i,j-1}-t_{i,j}}{R_{j-1,j}}-\frac{t_{i,j+1}-t_{i,j}}{R_{j,j+1}}=\frac{t_{i,j}-t_{i-1,j}}{\Delta\tau}\Delta x_j\rho_j c_j \qquad \text{... 2.20)}$$

where t = temperature (°C)
Δx = thickness of the layer
ρ = density
c = specific heat
$\Delta\tau$ = small time interval,
R = thermal resistance

Indices $j-1$, $j+1$ refer to the geometric position of the layers
$i-1$, i, to the consecutive time intervals.

The number of equations is the same as of unknown temperatures, thus again we "only" need a computer and a fast algorithm.

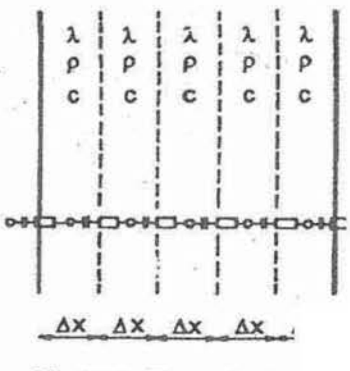


Fig.2.15 The schema layers: resistances an capacitances in series

2.13 Periodic heat flow

In many cases thermal factors (outdoor temperature, solar radiation) change periodically (the most obvious one being the 24 hour period). In this case the heat transfer can be calculated with analytical methods. The following concepts, originate from such analytical solutions.

These are usually the ratios of values of two harmonic functions. These values and the ratio itself are complex numbers. The imaginary part represents the amplitude (or amplitude ratios), whilst the difference in phase angle [$\tan^{-1}$(imaginary/real)] between the external and internal surface vector gives the phase lag. On the basis of the angular frequency (2π radians or 360° corresponds to the period, 24 hours) the phase lag can be transformed into time lag (see Figs.2.16 – 2.17).

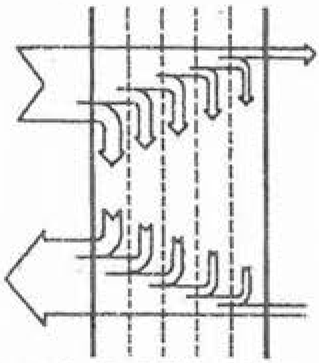
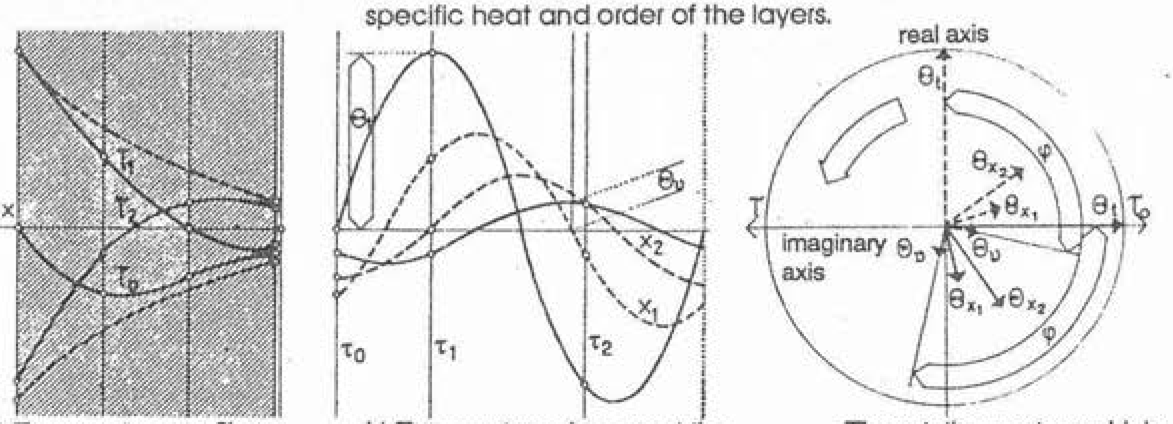


Fig.2.16 Periodic heat flow through a wall: charging and discharging half-cycles

In the first half of the period, the temperature of one of the surfaces is increaseed. A heat flow starts towards the opposite surface. A part of this heat is "consumed" by the first thin layer which is cooler than the surface and has to be heated up before it can transmit any heat to the next layer. The process is continued this way, each layer "consuming" (storing) some heat. Thus, only a fraction of the starting flux reaches the opposite surface, as meanwhile, in the second half of the period, the surface temperature is lowered and reverse flows develop from and in the wall, releasing the heat stored in the first part of the period (Fig.2.16). The ratio of the transferred and stored heat, the movement of the temperature wave towards the opposite surface and back, the depth of penetration achieved by the "temperature front", the time lag between the peak flows on the opposite surfaces, etc. depend on the conductivity, mass, specific heat and order of the layers.



a) Temperature profiles at three time-points

b) Temperature changes at the surface, 1/3 and 2/3 of thickness

The rotating vectors which produce the sine curves of (b)

Fig.2.17 Periodic heat flow through a wall. External and internal surface temperatures and values within the cross section are represented (**c**) by vectors (complex numbers). The length of vectors is proportionate to their amplitude, the angles between them to the time lag. Projecting the rotating vectors produces a set of sine curves showing the temperature versus time functions for different planes (**b**). Temperatures at a given moment are given by the temperature versus x-axis (thickness) functions (**a**).

The following are the most common concepts (refer to Section 1.7):
Decrement factor: the ratio of amplitudes (about the mean) of ambient and internal surface temperature variations (some authors interpret it as the effect of heat storage capacity or of both capacity and resistance). Its possible maximum value is 1: for elements with zero heat storage capacity. The **time-lag** is usually 1 to 14 hours. Note that for asymmetric cross sections these values depend also on the direction of heat flow.
Thermal admittance: a measure of the ability of internal surfaces to admit or release heat (dimensionally same as the U-value: W/m²K).

The sense of these concepts is the following: for a period, **mean** values of temperatures and heat fluxes can be calculated on the basis of steady state assumptions, using the mean driving temperature values. For any one time point the **swing** (amplitude) of heat flow will be caused by the driving temperature 'timelag' hours earlier and reduced by the decrement factor. From this **swing** in heat flow the amplitude of the other parameter (eg. t_i) can be calculated. Swings are to be added to the mean values to get final results. Figs.2.18–19 show time lag and decrement factor values for solid homogeneous walls.

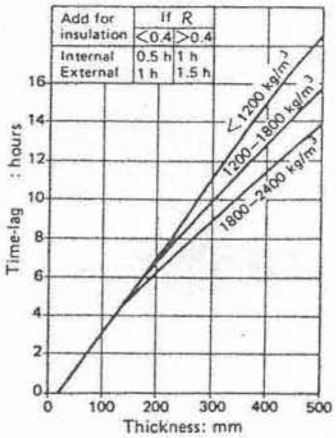


Fig.2.18 Time-lag of solid homogeneous walls

2.14 Heat storage capacity

Effective heat storage capacity: The concept of *active thermal mass* has been introduced to simplify the design process. The concept of *mass* is more easily understood than diffusivity, thermal capacity or other accurate physical quantities. To find the active thermal mass, the depth of penetration of the heat flow must be determined, i.e. the thickness, where significant temperature swings accompany the storing and discharging of heat. This depends on the period: the longer it is, the thicker the layer will be. Normally the *diurnal period* (24 hours) is considered.

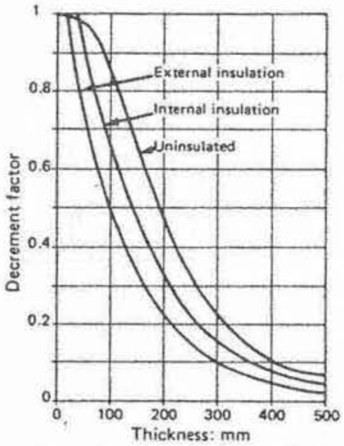


Fig.2.19 Decrement factor of solid homogeneous walls

The depth of penetration can be calculated quite accurately, but in practice simple rules of thumb are used: the effective thickness (b*) is one of the following, whichever is the least:

- half of the total thickness of the construction
- 100 mm
- thickness from surface of interest to the first insulating layer,

The reason for the last one is that the heat storage capacities of layers outside of the insulation are practically isolated from the room. Often (*for a 24 hour period*) a major part of heat storage capacity of walls and floors is inactive, due to the limited depth of penetration.

The time constant : The stored heat is proportionate to the temperature, the mass and the specific heat. Fig.2.20 illustrates the stored heat in different walls. The effect of the thermal insulation position can be seen as well as that of the air temperature at the surfaces. The stored heat of a room or building is the sum of the heat stored in the envelope elements and internal partitions. From this point of view the internal partitions and the envelope elements with external insulation are dominant.

The greater the amount of stored heat, the more "reserve" the building has: after the heat input ends, the stored heat is released and covers the heat losses for some time. With a lower overall heat loss coefficient the stored heat covers the losses longer. This is expressed by the *time constant* (Tc in seconds): the ratio of stored heat to the heat loss coefficient:

$$Tc = \frac{H}{q} \qquad \text{... 2.21)}$$

where H = the stored heat (J/K)

q = the overall heat loss coefficient (W/K)

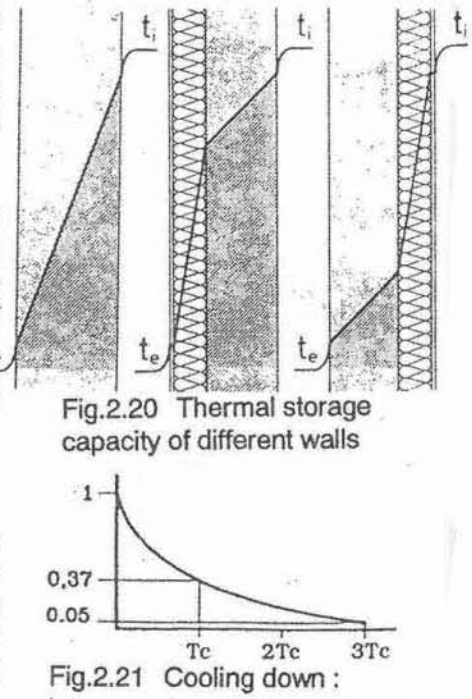


Fig.2.20 Thermal storage capacity of different walls

Switching off the heating, the temperature will decrease exponentially versus time: consuming more and more stored heat the indoor temperature and thus the losses decrease (Fig.2.21). A low heat loss coefficient increases the time constant. A high time constant, thus a slow response, are important features of solar buildings – this is why thermal insulation improves the "solar" performance.

Fig.2.21 Cooling down : interpretation of time constant

Part 3 MOISTURE TRANSPORT

3.1 Dalton's law

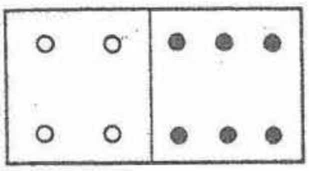


Fig.3.1 Two gases in two compartments

The atmosphere and air within buildings may be considered as a two-component gas mixture of dry air and water vapour. Consider some properties of such a mixture. Take the box in (Fig.3.1) hermetically divided by a partition. One part contains *n* "black" gas molecules, the other part *m* "white" ones. The pressure on the box wall is proportionalte to the number of molecules.

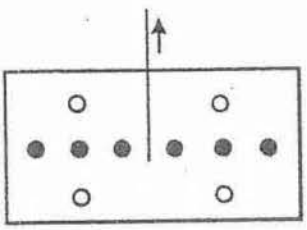


Fig.3.2 Partial pressures of the mixture

When the partition is removed, both gases strive to fill the whole box completely, as if the other gas were non-existent. (Dalton's law, Fig.3.2) The box wall is acted upon by pressure from both gases: the pressures of the "black" and "white" gases p_n and p_m are proportionalte to the number *n* and *m* of "black" and "white" molecules, respectively. Mixture pressure:

$$p = p_n + p_m \qquad \text{... 3.1)}$$

where p -overall mixture pressure

p_n, p_m -partial pressures of each gas making up the mix

Take another box divided by a partition, its compartments containing different gas mixtures of "black" and "white" molecules. The overall pressures on the partition are equal, but on one side, partial pressure of the "black" gas, on the other side, that of the "white" gas is the higher (Fig.3.3).

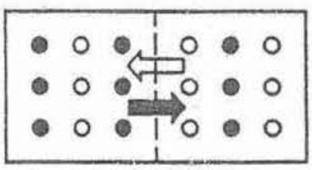


Fig.3.3 Gas diffusion through a permeable partition

If the partition is not completely tight and gas molecules can pass through, then the difference between partial pressures of the "black" gas makes "black" gas to flow to the other compartment in one direction, and so does "white" gas in the opposite direction. This process lasts as long as there is a difference between partial pressures of the component gases on each side of the partition, in spite of the overall pressures of the mixtures being equal. This is the cause (the driving mechanism) of the vapour diffusion through building elements.

3.2 Characteristics of moist air

A gas mixture of dry air and water vapour may be characterised by the partial pressure of water vapour within the overall mixture pressure. The partial pressure of the water vapour in the air cannot increase beyond a certain limit. This limit is the saturation partial pressure, the value of which depends on air temperature. This function is shown in Fig.3.4.

Humidity of the air is most simply expressed by a state characteristic, the relative humidity, expressed as a percentage: 0 % is for perfectly dry air, 100 % for saturated air. **Relative humidity** is the quotient of instantaneous partial vapour pressure in the air, and partial pressure at saturation (Fig.3.5) at the given temperature; expressed as a decimal fraction or a percentage:

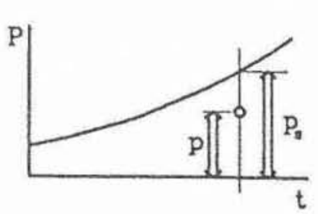


Fig.3.5 Definition of relative humidity

$$RH = \frac{p}{p_s} * (100\%) \qquad \text{... 3.2)}$$

The vapour content of air can be measured by another state characteristic, the **absolute humidity** (or moisture content) which is expressed as the mass (g) of vapour in 1 kg mass of dry air. Its usual symbol is *AH*. A non-dimensional version (eg. kg/kg) of the same quantity is the humidity ratio: eg. AH = 12 g/kg is the same as the humidity ratio of 0.012.

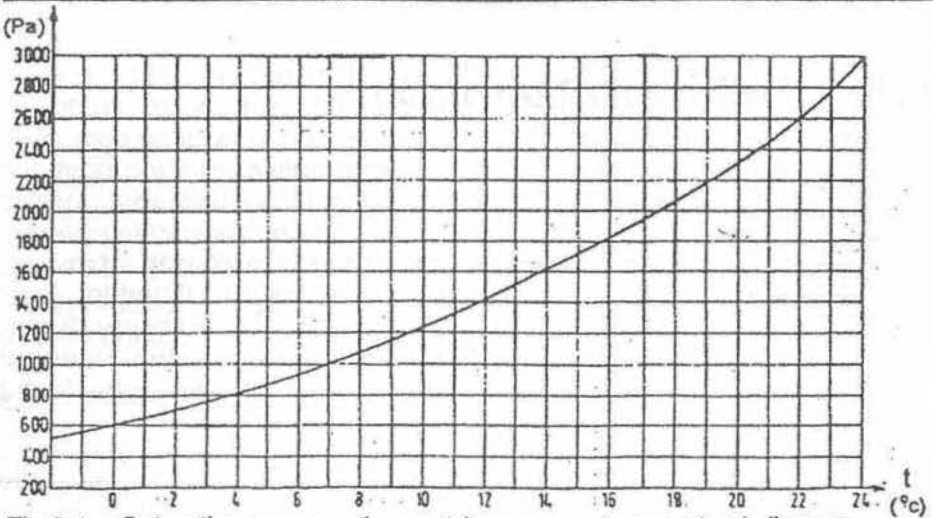


Fig.3.4 Saturation curve on the p – t (pressure – temperature) diagram

Both the saturation vapour pressure (p_s) and the saturation absolute humidity (H_S) are functions of the temperature. This refers to H_2O held in air in vapour state. H_2O in excess of the saturation value, condenses into its liquid state (see below).

In some cases, the concept of **vapour concentration** may be convenient, expressing humidity as grams of vapour contained in unit volume of air.

An important state characteristic related to energy is **enthalpy**, or heat content relative to 0°C, dry (AH = 0 g/kg) air, measured in kJ/kg. It is the sum of two components: latent and sensible heat. The former is the *latent heat* of evaporation of the water vapour content of that air. The latter, the *sensible heat* content again consists of two parts: the heat required to increase the temperature from 0°C to the given temperature (the product of mass, specific heat and temperature) firstly for the air itself, secondly for the moisture content of that air.

Of these quantities temperature alone can be measured exactly. Humidity can be measured through its effect on evaporation rate. It is found by using two thermometers of identical type: one ordinary (or dry-bulb) thermometer and one, the bulb of which is enclosed in a wick, which is kept wet, the *wet bulb thermometer*. To ensure that the evaporation from the wick will be as great as the air allows it to be, an air stream is provided around it either by whirling the thermometer or by a small clockwork-driven fan (Fig. 3.6). This evaporation gives a cooling effect, so the reading on the wet bulb thermometer (the **wet bulb temperature**, WBT) is less than the DBT, measured by the dry bulb thermometer: by what is referred to as the *wet bulb depression*. The instrument consisting of dry and a wet bulb thermometer is known as a whirling or aspirated hygrometer or psychrometer. The relative humidity is inversely proportionate to the wet bulb depression. Zero depression indicates saturated air which allows no evaporation.

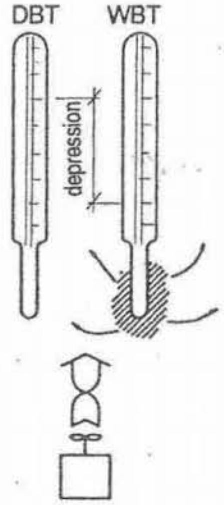


Fig.3.6 Wet and dry bulb psychrometer

Thus moist air can be described by different characteristics: of these the most convenient for a given situation is used. These state characteristics are interrelated and any two of them are sufficient to determine all the others. The relationships are graphically illustrated by the psychrometric chart (Fig.3.7). The top curve is the *saturation* line: the locus of saturated air points, same as in the above p-t diagram. Here the relative humidity RH=100%. The set of curves RH = 10, 20, 30, ...% in the unsaturated zone bear identical relative humidity. The area above RH= 100% is the fog zone.

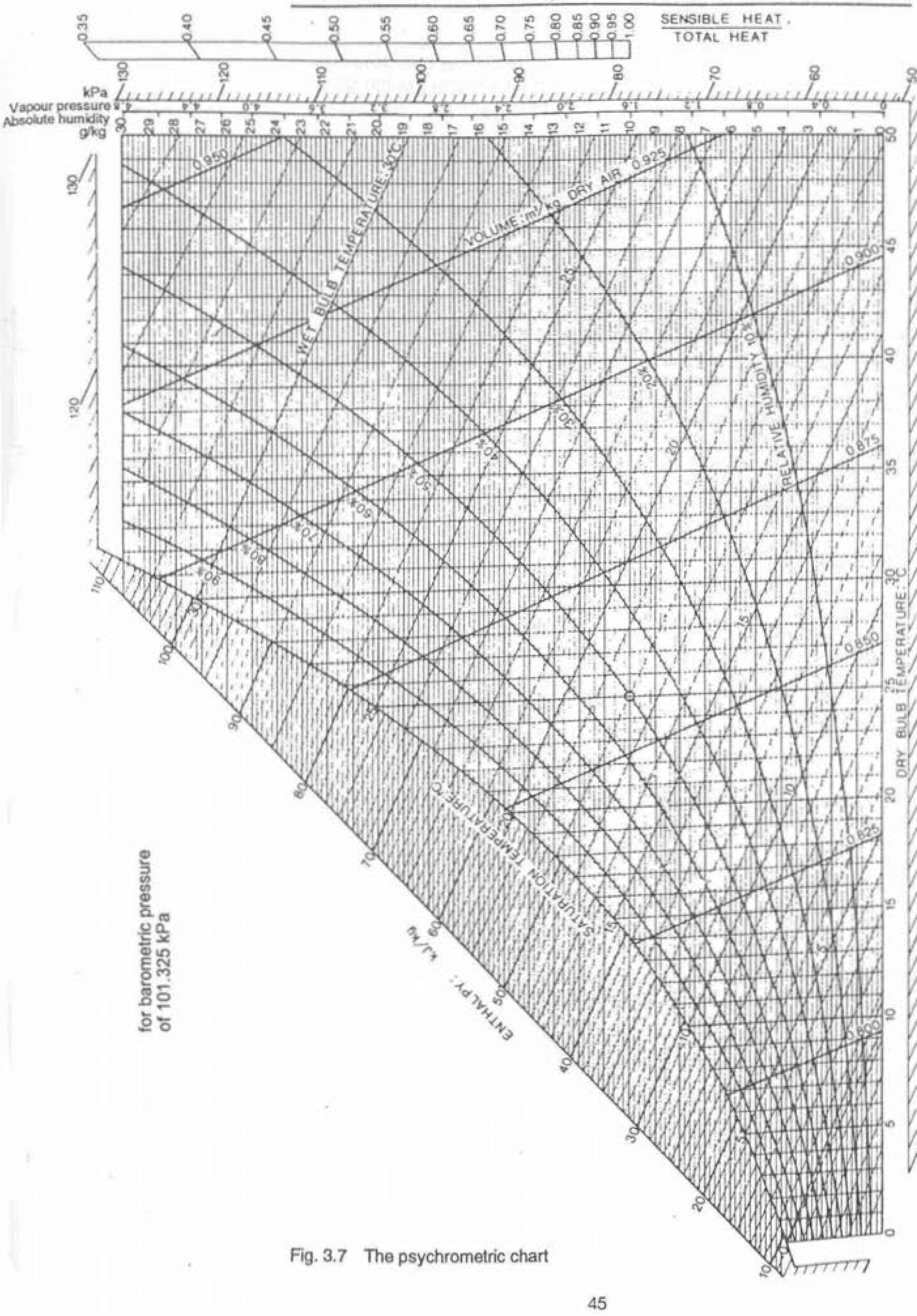


Fig. 3.7 The psychrometric chart

The vertical axis has two scales: AH (in g/kg) and partial pressure of water vapour (in kPa or kN/m^2). Sloping lines indicate the wet bulb temperatures and enthalpy values and another set the density (kg/m^3) of the air-water mix (or its reciprocal, the specific volume, m^3/kg).

Note that saturation limit depends on temperature, so at a low temperature a rather low moisture content (absolute humidity) causes a high relative humidity, whilst at a high temperature, for a comparatively low relative humidity there is a high absolute humidity.

Condensation is due to cooling. As being cooled, the relative humidity of unsaturated air starts increasing. The absolute humidity, and the partial pressure of vapour, remain constant. At a given temperature, the saturation limit is reached (the relative humidity value of RH = 100%). This is the **dew-point temperature**. Upon further cooling, the air can not hold that saturation humidity, but only that allowed by the saturation limit at the new, lower temperature. The excess condenses out as fog (ie. fluid), or as frost (ie. solid). Condensation also occurs on surfaces with a temperature below the dew-point temperature.

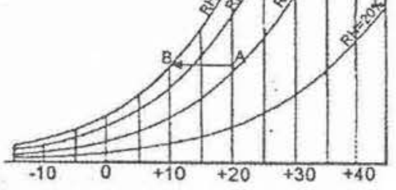


Fig.3.8 Condensation as a consequence of cooling

This process is shown in the psychrometric chart (Fig.3.8). Here point A represents the internal air condition. If this air is cooled, it will reach its dew-point at point B (10°C). If it is cooled further, condensation will occur.

3.3 Sorption

Most building materials (especially insulation materials) have a porous structure. The developed area of internal surfaces of the pores is quite large, which is important for moisture absorption and fixation. Moisture absorption of materials is characterised by their sorption isotherms. These curves are usually of the form seen in Fig.3.9. The curves are recorded at constant temperature by determining the equilibrium moisture content of a specimen kept in air at constant temperature and relative humidity.

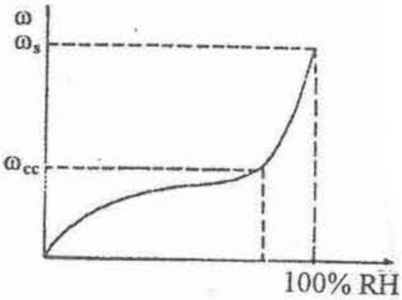


Fig.3.9 A typical sorption isotherm. X-axis: relative humidity Y-axis: moisture content of material (mass or volume %)

The horizontal axis of the sorption isotherm indicates relative humidity of air in contact with the specimen, while the vertical axis indicates the moisture content of the material, expressed as mass or volume percentage (ω). The saturation moisture content is denoted ω_s.

The sorption isotherm curve generally has an inflection point where its ascent abruptly increases. This is the starting point for **capillary condensation** where moisture does not only coat the pore surfaces but starts to fill up full cross sections of capillaries. This so-called capillary condensation develops at a relative humidity RH ≈ 75% for usual building materials. This point is shown in Fig. 3.9 as ω_{cc}. It should be noted that such capillary condensation would begin even if the surface is not below the dew-point temperature.

3.4 Convective moisture transport

In an indoor space moisture is produced by occupants and their activities (see Data sheet 7). Excessive moisture production increases the risk of harmful effects to the building and its users, but moisture production cannot be reduced below a threshold without curtailment of the building's normal use. Most of the moisture produced in the room leaves with the ventilation air. There is also vapour diffusion through walls and floors, although, for moisture balance in a room, the quantity of moisture leaving by diffusion is negligible.

With this assumption (and in the absence of condensation) the moisture balance in the room is:

$$W = \dot{m}_i - \dot{m}_o \qquad \text{... 3.3)}$$

where W = moisture arising from internal sources, g/h

$\dot{m}_i$ = quantity of moisture leaving with ventilation air, g/h

$\dot{m}_o$ = quantity of moisture entering with ventilation air g/h

Introducing the concept of vapour concentration:

$$W = Lcv_i - Lcv_o = L\Delta cv \qquad \text{... 3.4)}$$

where cv = vapour quantity per unit volume of air g/m^3

L = volume flow of ventilation air m^3/h

$$\Delta cv = \frac{W}{L} \qquad \text{... 3.5)}$$

which expresses the increase of humidity per unit volume flow of ventilation air: this is the removed quantity.

Relying on the temperature and relative humidity of outdoor air the relative humidity of internal air of a specified temperature at a given vapour concentration increment Δcv can be calculated.

There is an unambiguous correlation between the air condition in the room and the air condition in contact with the surface. For instance, if surface temperature is 14°C and the maximum permissible relative humidity is 75% (if capillary condensation is to be avoided), then in a room at 20°C, the relative humidity may be 50%. The absolute humidity determined from the first pair of values is AH = 7.5 g/kg, which gives a relative humidity of 50% at 20°C .

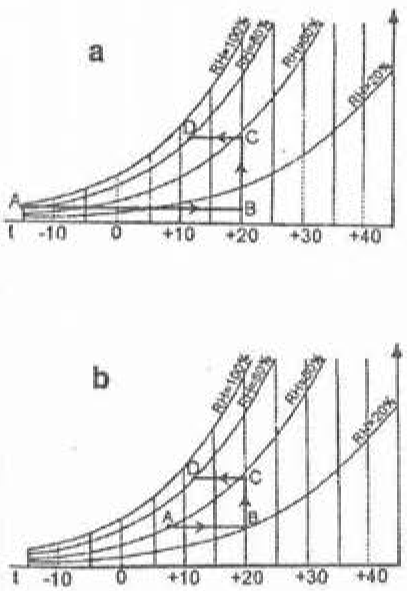


Fig.3.10 Psychrometric processes: fresh air warms up, picks up moisture and cools down at the wall surface. Note that the warmer air absorbs less moisture, because of its higher initial AH

The process described above is shown in Fig.3.10a. Here point A represents the external air. The process can be visualised in three consecutive steps:

A→B: temperature of air, entering the room increases up to the indoor temperature (no change in moisture content)

B→C: humidity of the air, entering the room increases by Δcv, point C representing the indoor condition;

C→D: temperature of indoor air decreases to that of the surface, at constant absolute humidity. Point D represents the condition at the surface.

To prevent mould growth the *RH* at point D should be less than 75%

The designer's task is to harmonise the above parameters. Thus, if the surface temperature and moisture development are given values, Δcv, minimum air change and acceptable indoor relative humidity can be calculated. Higher outdoor temperatures are more "risky" as ventilation air entering from outdoors has a higher absolute humidity (Fig.3.10b). Although at higher outdoor temperatures the *RH* is lower, the absolute humidity rises with increasing t_o values.

The evolution period of capillary condensation and mould growth is about five consecutive days, therefore shorter periods can be neglected.

3.5 Vapour diffusion through walls

With a closed building, due to the different air conditions indoors and outdoors, normally there is a difference between the partial water vapour pressures of indoor and outdoor air. This pressure difference is the driving

mechanism of vapour flow (usually called diffusion) through permeable building elements.
Note that only the partial water vapour pressure difference is considered. The barometric pressure of the indoor and outdoor moist air are the same. (Refer to Fig. 3.3). At equal barometric pressures, if the vapour pressure is higher inside, the partial pressure of the dry air is higher outside, thus whilst water molecules will migrate outwards, a dry air flow develops in the opposite direction.

The quantity of vapour, leaving the room by diffusion is very small in comparison with that leaving with the ventilation air. However vapour flow through building elements has to be calculated in order to check the partial pressure distribution within the element and to prevent the phenomenon of *interstitial condensation*. It follows from the above that vapour diffusion should be analysed if

- there is a significant vapour pressure difference between the indoor space and the outdoor environment, and
- there is also a significant temperature difference.

In practice steady state conditions are assumed. Vapour diffusion is a very slow process: the mean temperature and the mean relative humidity of the outdoor air in the coldest winter-month are taken as design values.

Resistance to this vapour flow is offered by the envelope elements depending on the materials used. The material property analogous with thermal conductivity is **permeability**, (δ) (or vapour diffusivity in some texts). This is the quantity (g) of vapour flow in unit time (s) at unit pressure difference (Pa) between to opposite surfaces of a cube of unit size of the material (m/m²). The flow is one-dimensional.

The unit of permeability is

$$\delta : \quad \frac{g.m}{s.m^2 Pa} = \frac{g}{s.m.Pa}$$

but as the values encountered in practice are very small, normally the m (milli-) prefix (10^{-3}) is attached and kPa is used as the pressure unit, thus permeability is measured in: **mg/s.m.kPa**

Permeance is the quantity analogous with conductance and its value for a layer is

$$P = \frac{\delta}{b} \qquad \text{(unit: } \mathbf{mg/s.m^2kPa}) \qquad \ldots 3.6)$$

where δ = permeability
b = thickness (breadth)

Vapour resistance is the reciprocal:

$$R_\delta = \frac{b}{\delta} \qquad \left[\frac{m}{mg / s.m.kPa} = \frac{m.s.m.kPa}{mg} = \frac{m^2 s.kN / m^2}{mg} = \frac{kN.s}{mg}\right] \qquad \ldots 3.7)$$

Resistances are additive, the vapour resistance of a multilayer element is

$$R_v = \sum R_\delta = \sum \frac{b}{\delta} \qquad \ldots 3.8)$$

In vapour transfer the surface resistance is very small, in practical calculations it can be neglected. Thus, partial pressure at the surface is assumed to be the same as in the air in contact with the surface.

3.6 Vapour pressure distribution in cross section

Similarly to the temperature gradient, the vapour pressure gradient can be established by finding the pressure drop for each layer on the basis of

For a multilayer building element

$$\dot{m} = \frac{p_i - p_o}{R_v} \qquad \text{... 3.9)}$$

and, for any layer

$$\dot{m}_j = \frac{\Delta p_j}{R_j} \qquad \text{... 3.10)}$$

where p_i = partial water vapour pressure in the indoor air,
p_o = partial water vapour pressure in the outdoor air,
Δp_j = pressure difference between the two boundary planes of j-th layer;
R_v = resistance of the element;
R_j = resistance of j-th layer
$\dot{m}$ = vapour flux (mass flow rate).

Thus

$$\frac{\Delta p_j}{p_i - p_o} = \frac{R_j}{R_v} \qquad \text{... 3.11)}$$

or

$$\Delta p_1 : \Delta p_2 : \Delta p_3 : .... = R_1 : R_2 : R_3 : .... \qquad \text{... 3.12)}$$

Partial pressure values are to be calculated for the surfaces and planes between two layers. Within one homogeneous layer the pressure distribution is linear (Fig.3.11).

The task in this stage of design is to check whether the calculated partial pressure values are below the saturation values everywhere in the cross section. The saturation value of the partial vapour pressure is the function of the temperature (Fig.3.11). Plot the temperature distribution in the cross section and, in several points, plot the saturation pressure from Fig.3.4. If there is no intersection of calculated and saturation pressure distribution, no condensation is expected.

3.7 Design approach

From Fig.3.11 the actual and the saturation values, p and p_s, of vapour pressure can be read. By definition, their ratio is the relative humidity:

$$RH = \frac{p}{p_s} \qquad \text{... 3.13)}$$

From the sorption isotherm (Fig.3.9) the moisture content (ω) of the material, belonging to a given relative humidity can be read and can be plotted on a cross-section of the wall (Fig.3.11, lower curves).

The risk of condensation is the highest in the outside half of the thermal insulation layers. Thermal insulation materials have high resistance against heat flow (→ big temperature drop), but their resistance against vapour flow is usually small. The opposite is true for materials of load-bearing and outside surface coating layers. This is why the calculated partial pressure is near the saturation value in the outside half of the thermal insulation layer: the temperature is low, the partial pressure is high (Fig.3.11).

The risk can be avoided and condensation prevented if

- thermal insulation is on the outside (the whole cross section is kept warm, the only problem is the resistance of the outside surface)
- there is a slightly ventilated air gap between the outside surface layer and the thermal insulation; in this gap the partial pressure is practically the same as in the outdoor air (if the thickness of the air gap is minimum 20 mm and it is well ventilated)

- there is a vapour barrier in the construction (a vapour-tight membrane, eg. a thin plastic sheet) having a large resistance (Fig.3.12). In the USA a membrane is taken as a vapour barrier if its permeance is less than 0.067 mg/s.m².kPa.

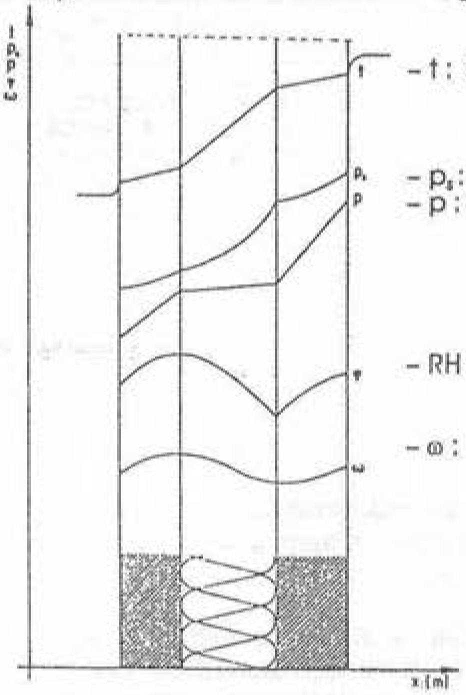


Fig.3.11 Temperature and pressure gradients through a sandwich wall

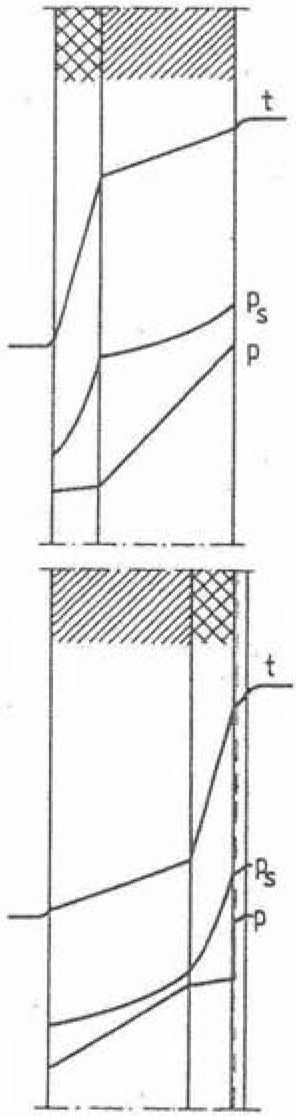


Fig.3.12 Condensation risk reduced by external insulati or a vapour barrier

3.8 Graphic analysis

The most time-consuming step of the Glaser-method, presented in Section 3.6 is to plot the calculated and saturation partial pressure curves, point by point in the cross section of the wall. A saturation partial pressure versus temperature curve is available (Fig.3.4). The analysis of the construction becomes easier and faster if the calculated pressure values are transformed into this temperature-partial pressure coordinate system. The basis of this transformation is, that the position of the surfaces and the planes between the layers in the *p-t* coordinate system are defined by their temperatures. The mutual equivalence of surfaces and planes of a given temperature can be shown by a simple geometrical transformation (Fig. 3.13) from the wall's temperature gradient to the p-t diagram.

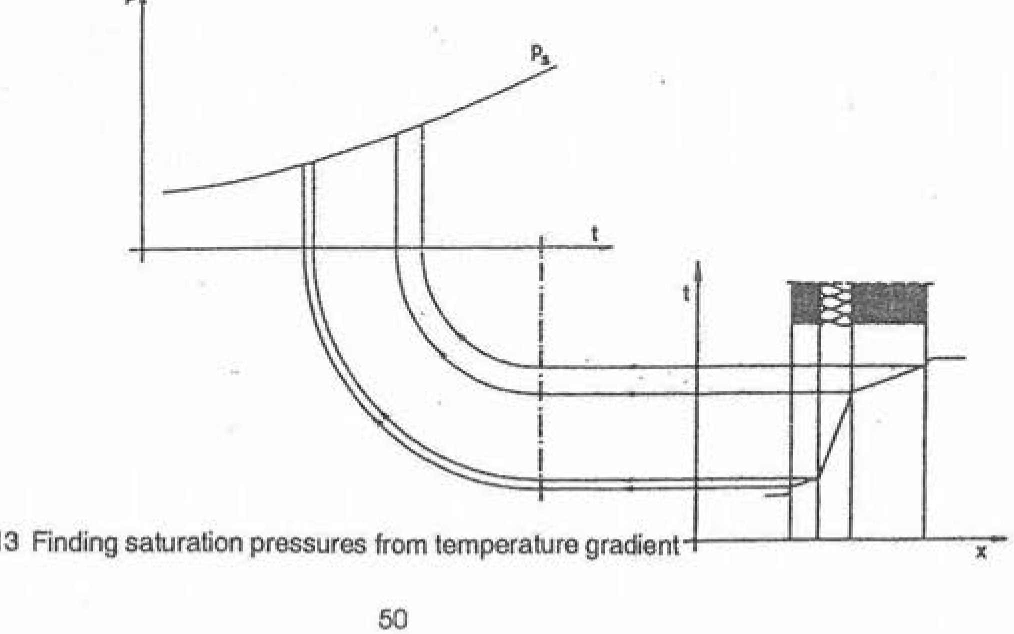


Fig. 3.13 Finding saturation pressures from temperature gradient

Determining the position of the above planes, the plotting of the calculated partial pressure distribution is the same as in the cross section: calculated values should be marked at the surfaces and layer boundaries and interconnected with straight lines. If calculated partial pressure distribution does not exceed the saturation value, no interstitial condensation is expected. If the calculated pressure gradient goes above the saturation curve condensation is possible (Fig.3.14).

Note that the intersection of the calculated vapour pressure distribution line and the saturation curve does not necessarily mean condensation. At the beginning of the heating season the wall is drier. It is charged by the vapour flow and its moisture content increases, according to the sorption isotherm. It takes time to reach the saturation partial pressure moisture content. If the process of charging is longer than the heating season, condensation will not occur.

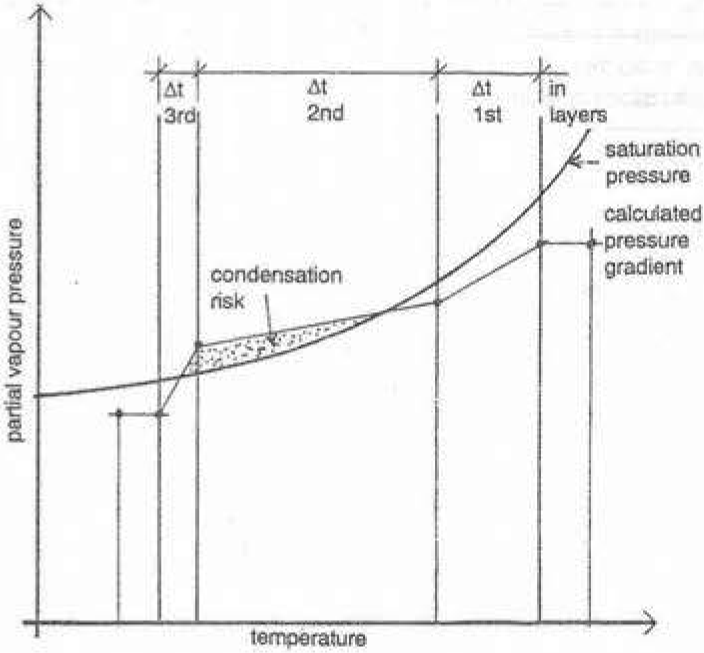


Fig. 3.14 The zone of interstitial condensation

Example 12 Prediction of condensation risk

Calculate the vapour pressure gradient in a multilayer wall:

No	Material	b m	λ W/m.K	δ mg/s.m.kPa
1	Plaster	0.015	0.80	0.024
2	Brick	0.30	0.65	0.030
3	Expanded polystyrene	0.06	0.04	0.002
4	Plaster	0.01	0.80	0.024

Temperatures and humidities:

t_i = 20°C t_o = -2°C RH_i = 65% RH_o = 90%

(Note that the design temperature for vapour diffusion is higher than that of the heat loss calculation. The first one is usually the mean outdoor temperature of the coldest month)

The saturation pressures (from Fig. 3.5) are   inside : 2340 Pa
outside : 516 Pa

The partial pressure values are inside: $p_i = 0.65 * 2340 = 1520$ Pa
outside: $p_o = 0.90 * 516 = 464$ Pa

The difference: 1520 – 464 = 1056 Pa

As in example 1 (p.30), the conductivity of the expanded polystyrene layer is to be corrected with regard to the "wet technology" of plastering. The correction factor is κ=0.25, the design value is λ_{des}=(1+0.25)*0.04= 0.05
The thermal resistances are:

inner surface	R_{si}	= 0.12
1st layer	$R_1 = \frac{0.015}{0.80}$	= 0.019
2nd layer	$R_2 = \frac{0.30}{0.65}$	= 0.462
3rd layer	$R_3 = \frac{0.06}{0.05}$	= 1.200
4th layer	$R_4 = \frac{0.01}{0.80}$	= 0.013
outside surface	R_{so}	= 0.04
air-to-air resistance		= 1.854

$\therefore$ U- value = 0.54

Calculation of temperature gradient

	R_n/R_{a-a}	Δt	t
Indoor air			20.00
	0.065	1.42	
Inner surface			18.58
1st layer	0.010	0.23	
			18.35
2nd layer	0.249	5.48	
			12.87
3rd layer	0.650	14.24	
			-1.37
4th layer	0.007	0.15	
External surface			-1.52
	0.022	0.48	
Outdoor air			-2.00

As it was pointed out in Section 2.1, transfer processes are similar and the alogrithm of the calculation is the same. Thus, for vapour diffusion the same procedure is to be repeated, substituting a different content into the equations.

The vapour resistances are (surface resistances are negligible):

1st layer ($\frac{b}{\delta}$)	$\frac{0.015}{0.024}$	= 0.625 / 41.042 = 0.015
2nd layer	$\frac{0.30}{0.03}$	= 10.000 / 41.042 = 0.244
3rd layer	$\frac{0.06}{0.002}$	= 30.000 / 41.042 = 0.731
4th layer	$\frac{0.01}{0.024}$	= 0.417 / 41.042 = 0.010
vapour resistance		= 41.042 (air-to-air)

The partial pressure distribution will be checked in a p-t diagram (Fig. 3.15.) The thickness is drawn to a temperature scale: planes of the wall can be pinpointed according to their calculated temperature. Thus 18.39 °C corresponds to the inner surface, 18.15°C to the boundary of the 1st and 2nd layers, 12.01°C to the boundary of the 2nd and 3rd layers, etc. Here the corresponding pressure values are to be marked. These points are to be connected with straight lines (Fig. 3.16.). The lines do not cross the saturation curve, thus no condensation is expected.

Calculation of vapour pressure gradient

	Rv_n/Rv_{a-a}	Δp	p
Indoor air			1520
	negligible		
Inner surface			1520
1st layer	0.015	15.84	
			1504.16
2nd layer	0.244	257.66	
			1246.50
3rd layer	0.731	771.94	
			474.56
4th layer	0.010	10.56	
External surface			464
	negligible		
Outdoor air			464

In this example the calculation of heat and vapour flows are shown separately. Calculation of thermal and diffusion resistances, ratios, temperature and partial pressure values can be shown in one comprehensive table.

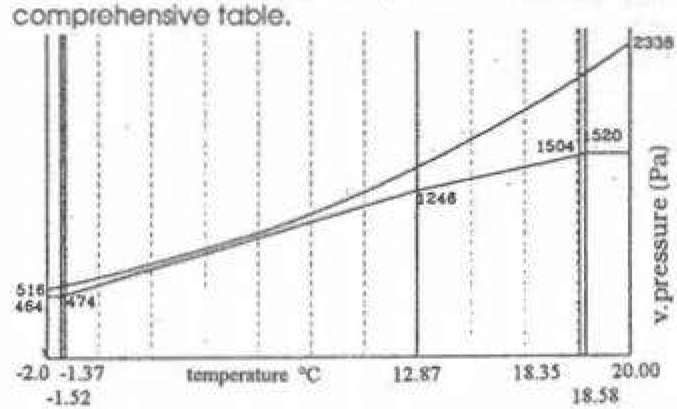


Fig. 3.15 Example 12: comparing vapour pressure gradient with saturation curve

An alternative is to find the dew-point temperature at each layer boundary, from the psychrometric chart (Fig.3.7), plot the dew-point temperature curve and compare this with the temperature gradient constructed.

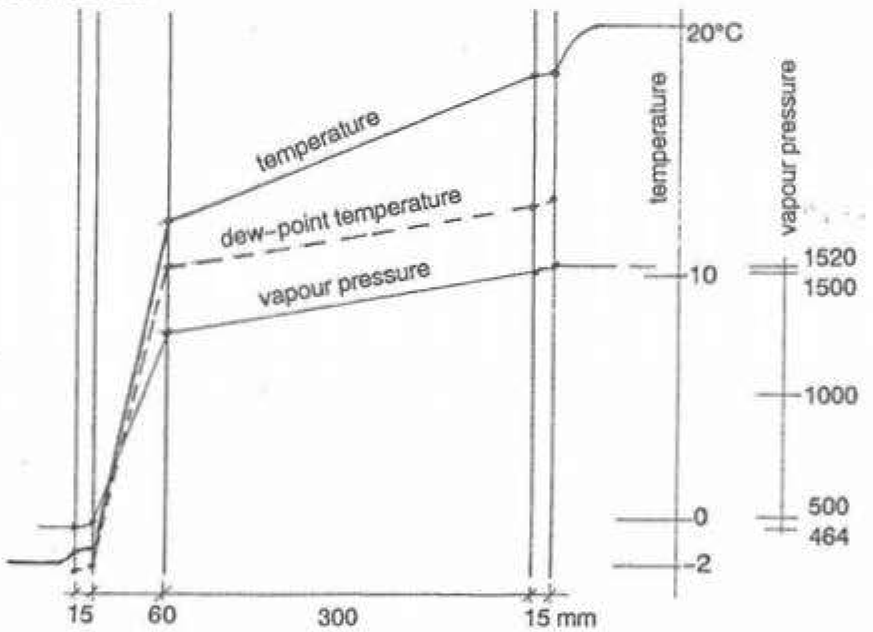


Fig. 3.16 Temperature and vapour pressure gradients

3.9 Moisture transport through flat roofs

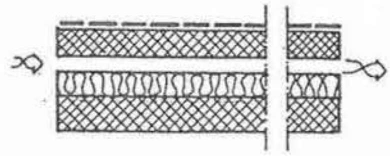


Fig.3.17 Ventilated double roof

The special problem of flat roofs if the very high diffusion resistance of the waterproof membrane. If it is on the top of the thermal insulation, interstitial condensation would be inevitable unless the appropriate structure of the thermal insulation is ventilated (through vents as in Fig.3.18 or along the parapet wall). A safe solution is the double roof with ventilated air gap (Fig.3.17).

There is no vapour-diffusion related interstitial condensation if a continous high-resistance vapour barrier is located on the supporting structure and the thermal insulation guarantees that the temperature in the plane of the vapour barrier will be above the dew point temeprature of the indoor air, even on the coldest days.

This solution alone would not be safe enough. There may be moisture in the thermal insulation from the very beginning (eg. rain during construction), or damage of the vapour barier cannot be ruled out. A small quantity of condensed (liquid) water between the vapour barrier and waterproof membrane may not be great problem in itself. However, at higher outdoor temperatures and intensive solar radiation the roof warms up, the water evaporates - and the specific volume of the vapour being about 500 times that of the liquid H_2O, it expands. If there were no "exit", the pressure of this vapour would lift up the membrane, forming blisters which may also split.
This is why the construction between the vapour barrier and the waterproof membrane should be depressurised (Fig.3.18).

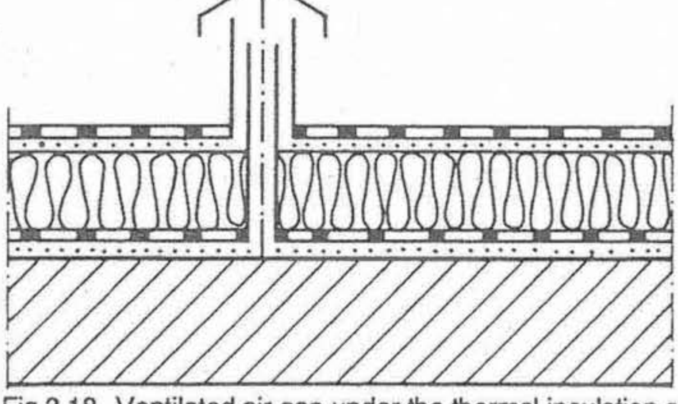


Fig.3.18 Ventilated air gap under the thermal insulation and depressurisation air gap between the thermal insulation and the waterproof membrane, both connected to the atmosphere through vents or along the parapet wall.

Deperessurisation demands
- relief vents to the atmosphere (vents on the roof or along the parapet)
- horizontal flow paths to the vents (eg. a layer of gravel, of appropriate texture for the downfacing surface of hard foam panels, etc.)

In the *Inverted Roof Membrane Assembly* the waterproof membrane is placed directly on the load supporting structure. The extruded polystyrene thermal insulation is outside, on the top (Fig.3.19). This material is not vulnerable to moisture, the temperature at the plane of the membrane is over the dew point temperature of the indoor air (at least theoretically: it can happen that cold rain water flows down between the polystyrene slabs and cools the construction). This phenomenon can be prevented with the dual system where a further thermal insulation is between the supporting structure and the waterproof membrane.

Fig.3.19 The inverted roof : insulation on top of the membrane

Part 4 ECONOMICS OF THERMAL INSULATION

(note that symbols and abbreviations used in this Part are not included in the list given on p.4; are defined here and are valid only in this part)

4.1 Attenuation of heat losses in winter

The higher the surface to volume ratio, the more sensitive the building to added insulation. It is another question, what the role of transmission losses is in the complete energy balance of the building.

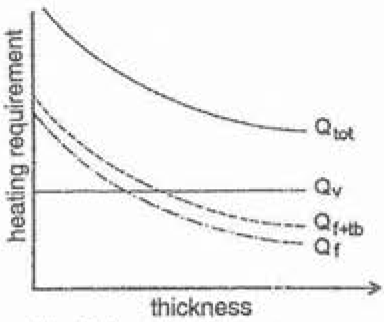


Fig.4.1 Heat loss as a function of insulation

At a given building geometry, transmission losses depend on the overall thermal insulation. Thermal insulation can be improved theoretically without limitation, however besides technological aspects the economics of this approach has to be considered. In Fig.4.1 fabric losses are shown as function of the thickness of a given insulation material. The lowest curve (Q_f) indicates fabric losses. With a simple calculation of one-dimensional heat flow (for a given building) similar curves can be produced. The next higher curve (Q_{f+tb}) also includes the thermal bridge effects. The better the insulation, the greater the relative importance of thermal bridges.

The ventilation heat loss (Q_v) is taken as constant: independent of insulation. The top curve is the total heat loss. It can be seen that beyond a limit the energy saving due to an added thickness of insulation is reducing. A classic example of the *law of diminishing returns.*

It can also be seen that, beyond a limit, ventilation losses prevail and represent the dominant component of the total losses. In this case, implementation of a heat recovery system can be more effective than the further improvement of thermal insulation. This limit strongly depends on the number and activity of occupants: in non-residential buildings the ventilation is usually more important than in dwellings.

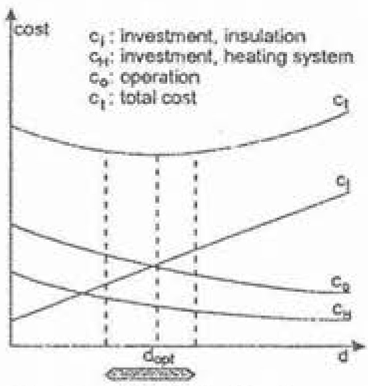


Fig.4.2 "Optimisation" of insulation thickness

4.2 The "optimum" of the thermal insulation

The minimum of thermal insulation is determined by fabric protection and thermal comfort requirements. Up to this limit the necessity of thermal insulation cannot be disputed. Beyond this limit the further improvement is a question of energy balance, economy and pay-back time.

In this context often an "optimum thermal insulation" is referred to. This optimum is usually presented as in Fig.4.2, where a series of curves are presented as a function of the insulation thickness:

- investment cost of insulation (c_i)
- investment cost of heating system (c_H)
- operating cost of heating for a given number of years (c_o)
- the total of the above costs (c_t).

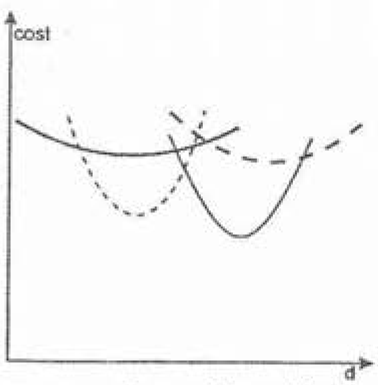


Fig.4.3 Comparison of the "optima" of different materials

The thickness where the total cost has a local minimum is taken as the "optimum". As insulation products are normally available in discreet thicknesses, usually an interval of "optimum" thicknesses is marked, where the total cost shows limited variation only.

The method, illustrated in Fig.4.2 is an ***oversimplification,*** which can produce misleading results. It must be qualified by the following.

First, here the thickness of only one insulating material is analysed. Other materials, with other investment costs (including the cost of the material itself, that of the technology, the additional layers, such as a vapour barrier and surface finishing) have to be included in the analysis as well (Fig.4.3).

Some curves in Fig.4.2. (namely: investment cost of insulation and total cost) have a singularity at zero insulation, marked with small circles in Fig.4.4). This may represent a real option, possibly the "optimum", if the base wall itself (eg. thermal brick) met the minimal requirements. Otherwise only a thickness beyond that fulfilling the minimal requirements can be chosen.

Following the law of diminishing returns, the effect of the initial thickness of added insulation is dramatic, especially if the U-value of the base construction is high. Increasing the thickness, the effect of further increments becomes less and less, as it was seen in Fig.4.1. This fact suggests, that the rational thickness is quite small. However, the components of the investment cost must not be forgotten. The costs of the new surface finishing, a possible vapour barrier, scaffolding and labour change very little (if at all) beyond the very first small thickness of insulation. The cost of the insulation material itself is only a fraction of the total investment cost. Increasing the thickness, (up to a technological limit) increases only the material cost, thus, the energy saving effect of the further added thickness should be compared with the incremental cost of the material only.

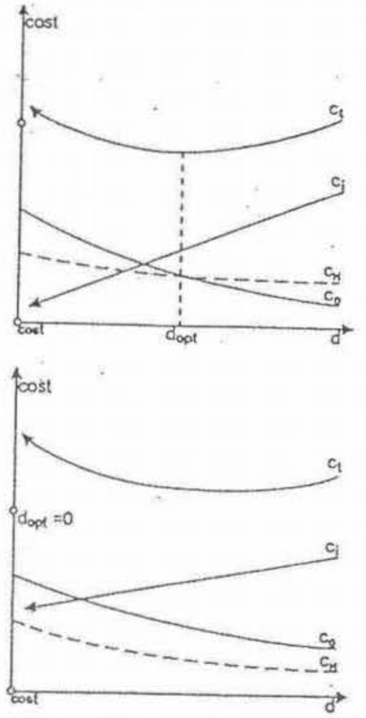


Fig.4.4 Singularities of the total cost curve: the load bearing wall without insulation (c_o) may or may not have an optimum

The investment cost of thermal insulation is often represented by a stepped function, partly due to the discreet thicknesses of industrial products, partly because beyond a given thickness mechanical reinforcement, support or other measures may become necessary.

Similarly, the investment cost of the heating system may also show singularities. In case of a central heating system it is likely that a small increment of thermal insulation allows a reduction of the surface area and cost of heat emitters, whilst the distribution network, pumps, control system and boiler remain unchanged. A further improvement of insulation may allow a reduction of boiler capacity, etc. (Fig.4.5).

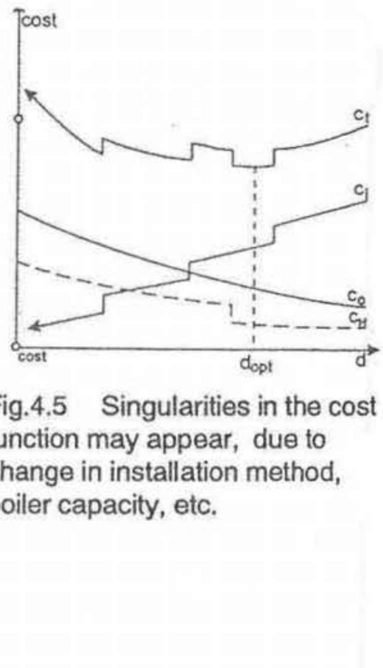


Fig.4.5 Singularities in the cost function may appear, due to change in installation method, boiler capacity, etc.

It is evident that improved thermal insulation should be applied in the most efficient way, but it requires a very keen and detailed analysis of numerous possible combinations, far beyond the simplified approach, illustrated by Fig.4.2.

4.3 Cost-benefit analysis

To put it simply: an investment (eg. in insulation) is worthwhile if the benefit (B) is greater than the cost (C), ie. if

$C < B$

If C is the capital (investment) cost of insulation and A is the resulting annual saving in heating costs and we are considering a period of y years, then the benefit will be $B = A * y$ and the investment is warranted if

$$C < A * y \qquad \ldots 4.1)$$

The limiting condition is when $C = A * y$, from which we get the *simple pay-back period* as

$y = C/A$

ie. the number of years when the savings will equal the capital cost.

However, the *cost of money* itself should be taken into account. If the money is borrowed, an interest must be paid. If the owner's money is used, it could earn some interest if invested elsewhere. It is usual to carry out the above *cost / benefit analysis* in terms of the *present worth* of any future costs or benefits. The present worth (P) of a single sum (S) payable in the future, y years hence is

$$P = \frac{S}{(1+i)^y} \qquad \text{... 4.2)}$$

where i is the annual rate of interest (or 'discount rate') expressed as a decimal fraction.
From this the *present worth factor* is

$$F_1 = \frac{1}{(1+i)^y}$$

thus, eq. 4.1 can be written as
$C < S * F_1$

The present worth of a regular annual sum (A) (eg. heating cost savings) over y years is

$$P = A * \frac{(1+i)^y - 1}{i(1+i)^y}$$

from which the second term is the *regular series present worth factor*

$$F_R = \frac{(1+i)^y - 1}{i(1+i)^y}$$

Thus the investment criterion (eq.4.1) becomes
$C < A * F_R$

In an inflationary economic climate the inflation rate (f, expressed as a decimal fraction) must be taken into account in any investment decision. Thus the present worth factor will have to be adjusted:

$$F' = \frac{1}{i-f}\left[1-\left(\frac{1+f}{1+i}\right)^y\right]$$

Furthermore, if the inflation will cause the annual savings (the benefit) also to increase, a further adjustment is necessary:

$$F'' = \frac{1+f}{i-f}\left[1-\left(\frac{1+f}{1+i}\right)^y\right] \qquad \text{... 4.3)}$$

Besides the above cost analysis, a similar technique can be used taking into account (instead of the cost) the energy content (embodied energy) of building and insulation materials, that was used for production, fabrication and transport, as well as recycling. In this case the minimum value of the resultant curve represents the minimum of the energy used for erection, operation and demolition of the building, ie. its life cycle energy cost.

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THERMAL PROPERTIES OF BUILDING MATERIALS

		conductivity W/m.K	density kg/m³	specific heat J/kg.K
WALL MATERIALS				
adobe blocks		1.250	2050	1000
brickwork,	outer leaf	0.840	1700	800
brickwork,	inner leaf	0.620	1700	800
concrete, cast,	dense	1.400	2100	840
	lightweight	0.380	1200	1000
concrete block,	heavy	1.630	2300	1000
	medium	0.510	1400	1000
	light	0.190	600	1000
fibreboard (softboard)		0.060	300	1000
fibrous cement	sheet	0.360	700	1050
	decking	0.580	1500	1050
glass		1.100	2500	840
plasterboard		0.160	950	840
plywood		0.138	620	1300
stone :	marble	2.000	2500	900
	sandstone	1.300	2000	800
	granite	2.300	2600	820
tile hanging		0.840	1900	800
timber,	softwood	0.130	610	1420
	hardwood	0.150	680	1200
wood chipboard		0.120	660	1300
SURFACING				
external rendering		0.600	1300	1000
plastering,	dense	0.500	1300	1000
	lightweight	0.160	600	1000
ROOF AND FLOOR MATERIALS				
asphalt or bitumenous felt		0.500	1700	1000
concrete slab,	dense	1.130	2000	1000
concrete slab,	aerated	0.160	500	840
metal deck		50	7800	480
screed		0.410	1200	840
stone chippings		0.960	1800	1000
tiles		0.840	1900	800
thatch (straw)		0.070	240	1420
timber board or wood blocks		0.140	640	1200
INSULATING MATERIALS				
cellulose fibre (fireproofed)		0.039	42	
	same	0.047	83	
cork		0.038	144	1800
eel grass (zostera marina)		0.046	21	
EPS (exp.polystyrene slab)		0.035	25	340
glass fibre	quilt	0.040	12	840
	batts (slab)	0.035	25	880
mineral fibre slab		0.035	35	920
	dense	0.044	150	920
perlite, loose fill		0.046	65	
phenolic foam		0.040	30	1400
polyurethane board, new		0.016	24	450
	aged	0.025	30	450
strawboard		0.037	250	1050
	compressed, paper faced	0.081	320	1450
UF (urea-formaldehyde)foam		0.040	10	1400
vermiculite, exfoliated		0.069	128	
wood wool slab		0.100	500	1000
METALS				
aluminium		236	2700	877
copper		384	8900	380
iron		78	7900	437
lead		37	11300	126
steel (mild)		47	7800	480
stainless steel		24	7900	510

THERMAL PROPERTIES OF SURFACES AND CAVITIES

RADIATION PROPERTIES		for 6000° solar radiation abs.& emittance	reflectance	at 50°C abs.& emitt.
brick,	white, glazed	0.25	0.75	0.95
	light colours	0.40	0,60	0.90
	dark colours	0.80	0.20	0.90
roofs	asphalt or bitumen	0.90	0.10	0.96
	red tiles	0.65	0.35	0.85
	white tiles	0.40	0.60	0.50
	aluminium (oxidised)	0.20	0.80	0.11
paint	white	0.30	0.70	0.95
	matt black	0.96	0.04	0.96
weathered surfaces:	light	0.50	0.50	0.60
	medium	0.80	0.20	0.95

SURFACE RESISTANCES (m^2K/W)			normal surfaces	low emittance surfaces
inside,	walls		0.12	0.30
	ceiling,floor:	heat flow up	0.10	0.22
		heat flow down	0.14	0.55
	ceiling, 45°	heat flow up	0.11	0.23
		heat flow down	0.13	0.38
outside,	walls,	sheltered	0.08	0.11
		normal exposure	0.06	0.07
		severe exposure	0.03	0.03
roofs		sheltered	0.07	0.09
		normal exposure	0.04	0.05
		severe exposure	0.02	0.02

CAVITY RESISTANCES (m^2K/W)		mm	DIRECTION OF HEAT FLOW: horizontal	upward	downward
non-ventilated	normal	1	0.035	0.035	0.035
		5	0.11	0.11	0.11
		10	0.15	0.13	0.15
		20	0.17	0.14	0.20
		50	0.17	0.14	0.21
	low emissivity	1	0.07	0.07	0.07
		5	0.22	0.22	0.22
		10	0.30	0.25	0.30
		20	0.35	0.28	0.40
		50	0.35	0.28	0.42
ventilated	normal	1	0.17	0.17	0.17
		5	0.05	0.05	0.05
		10	0.07	0.06	0.07
		20	0.08	0.07	0.10
		50	0.08	0.07	0.10
	low emissivity	1	0.35	0.35	0.35
		5	0.10	0.10	0.10
		10	0.14	0.12	0.14
		20	0.16	0.14	0.20
		50	0.16	0.14	0.20

THERMAL PROPERTIES OF BUILDING ELEMENTS : WALLS

note: EPS = expanded polystyrene slab	U-value W/m²K	admittance W/m²K	time-lag hours	decrement factor
brick, single skin 105 mm	3.28	4.2	2.6	0.87
220 mm	2.26	4.7	6.1	0.54
335 mm	1.73	4.7	9.4	0.29
brick, single skin 105 mm plastered	3.02	4.1	3.0	0.83
220 mm plastered	2.14	4.5	6.5	0.49
335 mm plastered	1.79	4.5	9.9	0.26
brick, cavity 270 mm plastered	1.47	4.4	7.7	0.44
- same with 25 mm EPS in cavity	0.72	4.6	8.9	0.34
- same with 40 mm EPS in cavity	0.55	4.7	9.1	0.32
- same with 50 mm EPS in cavity	0.47	4.7	9.2	0.31
concr.block, solid, 200 mm plasterboard	1.83	2.5	6.8	0.35
- same but foil-backed plasterboard	1.40	1.82	7.0	0.32
- same + 25 mm EPS (no cavity)	0.93	1.2	7.2	0.30
- same but 25 cav.+25 EPS +plasterboard	0.70	1.0	7.3	0.29
- same but lightweight concrete	0.68	1.8	7.4	0.46
- same but foil-backed plasterboard	0.61	1.5	7.7	0.42
- same + 25 mm EPS (no cavity)	0.50	1.1	8.2	0.36
- same but 25 cav.+25 EPS +plasterboard	0.46	1.0	8.3	0.34
concr.blck, hollow 100 mm inside plastered	2.50	3.8	2.4	0.89
200 mm inside plastered	2.42	4.1	3.0	0.83
concrete,dense,cast,150 mm	3.48	5.3	4.0	0.70
- same + 50 mm woodwool slab plastered	1.23	1.7	6.0	0.50
- same but lightweight plaster	1.15	1.7	6.3	0.49
concrete,dense,cast,200 mm	3.10	5.5	5.4	0.56
- same + 50 mm woodwool slab plastered	1.18	2.2	7.7	0.36
- same but lightweight plaster	1.11	1.7	7.6	0.35
concr.precast panel, 75 mm	4.28	4.9	1.9	0.91
- same + 25 cav.+ 25 EPS + plasterboard	0.84	1.0	3.0	0.82
concr.precast,75+25 EPS+150L/W concr.	0.58	2.3	8.7	0.41
- same but 50 mm EPS	0.41	2.4	9.2	0.35
brick veneer,105 mm+cavity+plasterboard	1.77	2.2	3.5	0.77
- same but foil-backed plasterboard	1.36	1.7	3.7	0.75
- same with 25 mm EPS or glass fibre	0.78	1.1	4.1	0.71
- same with 50 mm EPS or glass fibre	0.50	0.9	4.3	0.69
- same, 25 EPS + foil-back plasterboard	0.69	1.0	4.1	0.71
block veneer, 100 mm, cav. plasterboard	1.57	2.1	4.1	0.72
- same but foil-backed plasterboard	1.24	1.7	4.3	0.69
- same with 25 mm EPS or glass fibre	0.74	1.1	4.7	0.65
- same with 50 mm EPS or glass fibre	0.48	0.9	4.9	0.62
- same, 25 EPS + foil-back plasterboard	0.66	1.0	4.7	0.64
framed, single fibro or galv.iron	5.16	5.2	0	1
- same + cav. + plasterboard	2.20	2.2	0.3	1
- same + 25 mm EPS or glass fibre	0.86	1.1	0.5	0.99
- same + 50 mm EPS or glass fibre	0.53	0.9	0.7	0.99
framed, 20 mm timber boarding	3.00	3.0	0.4	1
- same + cavity + plasterboard	1.68	1.8	0.8	0.99
- same + 25 mm EPS or glass fibre	0.76	1.0	1.0	0.99
- same + 50 mm EPS or glass fibre	0.49	0.9	1.2	0.98
framed,tile-hang+paper+cav+50 EPS+plb'd	0.54	0.78	1.0	0.99
- same but 100 EPS or glass fibre	0.32	0.71	1.0	0.99

U - VALUES OF WINDOWS

W/m²K

			sheltered	normal	exposed
WINDOWS: SINGLE GLAZED					
wood frame	10%	clear glass	4.7	5.3	6.3
	20%		4.5	5.0	5.9
	30%		4.2	4.7	5.5
metal frame	10%	clear glass	5.3	6.0	7.1
	20%		5.6	6.4	7.5
	30%		5.9	6.7	7.9
discuntinuous	10%	clear glass	5.1	5.7	6.7
	20%		5.2	5.8	6.8
	30%		5.2	5.8	6.8
wood frame	10%	low-e glass	3.9	4.6	5.7
	20%		3.7	4.3	5.3
	30%		3.5	4.0	4.9
metal frame	10%	low-e glass	4.4	5.2	6.4
	20%		4.6	5.5	6.7
	30%		4.9	5.8	7.1
discontinuous	10%	low-e glass	4.2	4.9	6.0
	20%		4.3	5.0	6.1
	30%		4.3	5.1	6.2
WINDOWS: DOUBLE GLAZED (6 mm space)					
wood frame	10%	clear glass	2.8	3.0	3.2
	20%		2.7	2.9	3.2
	30%		2.7	2.9	3.1
metal frame	10%	clear glass	3.3	3.6	4.1
	20%		3.9	4.3	4.8
	30%		4.4	4.9	5.6
discuntinuous	10%	clear glass	3.1	3.3	3.7
	20%		3.4	3.7	4.0
	30%		3.7	4.0	4.4
wood frame	10%	low-e glass	2.2	2.5	2.7
	20%		2.1	2.4	2.7
	30%		2.1	2.4	2.6
metal frame	10%	low-e glass	2.6	2.9	3.5
	20%		3.0	3.5	4.1
	30%		3.3	3.9	4.5
discontinuous	10%	low-e glass	2.4	2.7	3.2
	20%		2.6	3.0	3.4
	30%		2.8	3.3	3.8
ROOF LIGHTS (excluding frame)					
single	clear glass		5.7	6.6	7.9
double	clear glass (6 mm space)		3.0	3.5	4.1
double	low-e glass (6 mm space)		2.8	3.1	3.4
plastic dome	single		5.8	6.5	6.8
plastic dome	double		3.2	4.0	4.2
horiz.laylight + skylight or lantern over					
	-	ventilated	3.5	3.8	4.2
	-	non-ventilated	2.8	3.0	3.3

Note: 'sheltered': lowest 3 floors in CBD areas
'normal' : most suburban buildings, floors 4-8 in CBD (taken as 3 m/s)
'exposed' : coastal or hilltop sites, above fl.5 in suburban areas, above fl.9 in CBD areas (city centres)
'low-e' coating is taken as having an emittance of 0.4
%-values indicate frame projected area as fraction of overall window area

U-values OF BUILDING ELEMENTS : ROOFS and EXPOSED FLOORS

note: EPS = expanded polystyrene slab
fc = fibrous cement
ww = wood wool slab

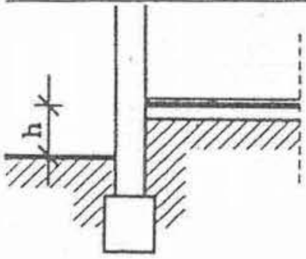
	U-value W/m²K	admittance W/m²K	time-lag hours	decrement factor
FLAT ROOFS				
150 c.slab,plaster 75 screed+asphalt	1.8	4.5	8	0.33
- same but lightweight concrete	0.84	2.3	5	0.77
25 timber deck, bit.felt, plasterboard ceiling	1.81	1.9	0.9	0.99
- same + 50 mm EPS	0.51	0.8	1.3	0.98
10 fc.deck,asph.13 fibreb'd,cav,fc.ceiling	1.5	1.9	2.0	0.96
50 ww.13 scrd.20 asph. cav, pl.b'd ceiling	1.0	1.4	3.0	0.93
13 fibreb'd,20 asph. cavity,10 foil-back plbd	1.2	1.3	1	0.99
metal deck, bit.felt, 25 mm EPS	1.1	1.2	1	0.99
- same + 13 fibreb'd + plasterboard ceiling	0.73	0.91	1	0.99
- same but 50 mm EPS	0.48	0.75	1	0.98
PITCHED ROOFS parallel sloping ceiling				
corrugated fibrous cement sheet	4.9	4.9	0	1
- same + cavity + plasterboard ceiling	2.58	2.6	0.3	1
- same + 50 mm EPS or glass fibre	0.55	1.0	0.7	0.99
tiles,sarking + cavity + plasterboard ceiling	2.59	2.6	0.5	1
- same + 50 mm EPS or glass fibre	0.54	1.0	1.5	0.97
tiles,sarking,25mm timber ceiling	1.91	2.1	1	0.99
- same + 50 mm EPS or glass fibre	0.51	1.5	1.4	0.97
metal sheet (corrugated or profiled)	7.14	7.1	0	1
metal sheet + cavity + plasterboard ceiling	2.54	2.6	0.3	1
- same + 50 mm EPS or glass fibre	0.55	1.0	0.7	0.99
PITCHED ROOFS, horizontal ceiling				
10° metal sheet, attic, 10 mm plasterboard	2.69	2.71	0.22	1.00
same + 50 mm EPS on ceiling	0.56	0.80	0.48	1.00
30° metal sheet, attic, 10 mm plasterboard	2.72	2.74	0.22	1.00
same + 50 mm EPS on ceiling	0.56	0.80	0.48	1.00
same but 100 mm EPS on ceiling	0.31	0.71	0.90	0.99
tiles, sarking, attic 10 mm plasterboard	2.48	2.62	0.39	1.00
same + 50 mm EPS on ceiling	0.55	0.80	0.66	1.00
40° tiles, sarking, attic 10 mm plasterboard	2.52	2.64	0.39	1.00
same + 50 mm EPS on ceiling	0.55	0.80	0.66	1.00
same but 100 mm EPS	0.31	0.71	1.08	0.99
FLOORS, EXPOSED				
150 mm r.c.slab + 25 mm screed	2.96	4.77	4.75	0.61
- same + carpet & underlay	1.19	1.46	5.82	0.45
- same + also 50 mm woodwool under slab	0.75	1.48	8.08	0.14
150 mm lighweight conc.slab+25 mm screed	1.60	3.85	5.92	0.59
200 mm lighweight conc.slab+25 mm screed	1.32	3.89	7.99	0.42
25 mm T&G boarding, no finish	3.30	3.32	0.32	1.00
- same + carpet & underlay	1.81	1.82	0.46	1.00
- same + also 50 mm mineral fibre insulation	0.50	0.99	1.69	0.93
25 mm particleboard + lino or vinyl	2.47	2.58	0.63	0.99
- same + 50 min.fibre ins.+ carpet & underlay	0.48	1.07	2.05	0.90
FLOORS OVER VENTILATED SPACE				
25 mm T&G boarding +lino or vinyl 6 x 4 m	1.13	3.92	0.29	1.00
- same 6 x 6 m	0.99	3.92	0.29	1.00
- same 10 x 6 m	0.88	3.92	0.29	1.00
- same 10 x 10 m	0.72	3.92	0.29	1.00
- same 20 x 10 m	0.62	3.92	0.29	1.00
150 mm r.c.slab + carpet 6 x 4 m	0.93	3.16	2.90	1.00
- same 6 x 6 m	0.82	3.16	2.90	1.00
- same 10 x 6 m	0.74	3.16	2.90	1.00
- same 10 x 10 m	0.61	3.16	2.90	1.00
- same 20 x 10 m	0.52	3.16	2.90	1.00

THERMAL PROPERTIES OF BUILDING ELEMENTS : FLOORS

Ground floor losses

Linear heat transmission coefficients : W/mK

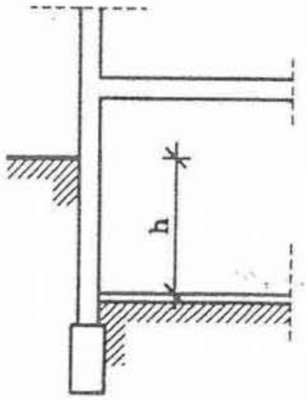
height [h] relative to ground level (m)	if floor thermal resistance is [m²K/W]							
	no insul.	0.2–0.35	0.4–0.55	0.6–0.75	0.8–1.0	1.05–1.5	1.55–2	2.05–3
>|6.0|	0	0	0	0	0	0	0	0
−6.00 to −4.05	0.20	0.20	0.15	0.15	0.15	0.15	0.15	0.15
−4.00 to −2.55	0.40	0.40	0.35	0.35	0.35	0.35	0.30	0.30
−2.50 to −1.85	0.60	0.55	0.55	0.50	0.50	0.45	0.45	0.40
−1.80 to −0.25	0.80	0.70	0.70	0.65	0.60	0.60	0.55	0.45
−1.20 to −0.75	1.00	0.90	0.85	0.80	0.75	0.70	0.65	0.55
−0.70 to −0.45	1.20	1.05	1.00	0.95	0.90	0.80	0.75	0.65
−0.40 to −0.25	1.40	1.20	1.10	1.05	1.00	0.90	0.80	0.70
−0.20 to +0.20	1.75	1.45	1.35	1.25	1.15	1.05	0.95	0.85
+0.25 to +0.40	2.10	1.70	1.55	1.45	1.30	1.20	1.05	0.95
+0.45 to +1.00	2.35	1.90	1.70	1.55	1.45	1.30	1.15	1.00
+1.05 to +1.50	2.55	2.05	1.85	1.70	1.55	1.40	1.25	1.10



Losses through earth sheltered walls

Linear heat transmission coefficients : W/mK

height [h] below ground level (m)	if U-value of wall itself is [W/m²K]							
	0.4–0.49	0.5–0.6	0.65–0.79	0.8–0.99	1–1.19	1.2–1.49	1.5–1.79	1.8–2.2
>6.0	1.40	1.65	1.85	2.05	2.25	2.45	2.65	2.80
6.00 to 5.05	1.30	1.50	1.70	1.90	2.05	2.25	2.45	2.65
5.00 to 4.05	1.15	1.35	1.50	1.65	1.90	2.05	2.24	2.45
4.00 to 3.05	1.00	1.15	1.30	1.45	1.65	1.85	2.00	2.20
3.00 to 2.55	0.85	1.00	1.15	1.30	1.45	1.65	1.80	2.00
2.50 to 2.05	0.70	0.85	1.00	1.15	1.30	1.45	1.65	1.80
2.00 to 1.55	0.60	0.70	0.85	1.00	1.10	1.25	1.40	1.55
1.50 to 1.05	0.45	0.55	0.65	0.75	0.90	1.00	1.15	1.30
1.00 to 0.75	0.35	0.40	0.50	0.60	0.65	0.80	0.90	1.05
0.70 to 0.45	0.20	0.30	0.35	0.40	0.50	0.55	0.65	0.75
0.40 to 0.25	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45



MOISTURE MOVEMENT DATA

INDOOR MOISTURE PRODUCTION

one person	at rest	40 g/h	
	sedentary	50 g/h	
	active	200 g/h	
cooking (gas)	breakfast	400 g	= 3000 g/day
	lunch	500 g	
	dinner	1200 g	
dishwashing	breakfast	100 g	
	luch	100 g	
	dinner	300 g	
floor mopping		1100 g	
clothes washing		2000 g	
clothes drying		12 000 g	
shower		200 g	
bath		100 g	

PERMEABILITY OF SOME MATERIALS

brickwork		0.006 –	0.042	mg/s.m.kPa
cement render			0.010	
concrete		0.005 –	0.035	
cork board		0.003 –	0.004	
expanded ebonite (Onozote)			< 0.0001	
expanded polystyrene		0.002 –	0.007	
fibreboard (softboard)		0.020 –	0.070	
hardboard		0.001 –	0.002	
mineral wool			0.168	
plastering		0.017 –	0.025	
plasterboard		0.017 –	0.023	
plywood		0.002 –	0.007	
polyurethane foam	closed cell		0.001	
	open cell		0.035	
strawboard		0.014 –	0.022	
timber	air dry	0.014 –	0.022	
	wet	0.001 –	0.008	
wood wool slab		0.024 –	0.070	

PERMEANCE OF SOME ELEMENTS

aluminium foil			< 0.006	mg/s.m²kPa
bitumenous paper			0.09	
brickwork	105 mm	0.04 –	0.06	
concrete blocks	200 mm hollow		0.14	
cement render or screed, 25 mm	4:1		0.67	
	1:1		0.40	
corkboard	25 mm	0.40 –	0.54	
paint, 2 coats, oil	on plaster	0.09 –	0.17	
paint, 3 coats, oil,	on wood	0.02 –	0.06	
plaster on lath	25 mm		0.63	
	20 mm		0.83	
	12 mm		0.93	
plasterboard	10 mm	1.7 –	2.80	
plywood, 6 mm	external qual.	0.026 –	0.041	
	internal qual.	0.106 –	0.370	
polyethylene film	0.06 mm		0.004	
softwood (pine)	25 mm		0.08	
	12 mm	0.10 –	0.17	
strawboard	50 mm	0.13 –	0.26	
wood wool slab	25 mm	3.08 –	4.14	

[any layer of less than 0.067 mg/s.m²kPa permeance is a vapour barrier]

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