Bi-directional thermo-hygroscopic facades: Feasibility for liquid desiccant thermal walls to provide cooling in a small-office building

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ABSTRACT: The paper will discuss the design of a bi-directional thermo-hygroscopic façade as a dedicated outdoor air system to cool and dehumidify outside air. The system is a variant of dedicated outdoor air systems to separate dehumidification and cooling in air-conditioning equipment and locates components within the building envelope. The integrated hybrid-building envelope relies on low-grade thermal energy to regenerate the liquid desiccant from southerly and northerly exposure. Southern and northern exposed walls with solution desiccant regenerator, dehumidifiers and direct evaporative cooler provide similar function as a conventional vapor compression air-conditioning system. Liquid desiccant regenerates with temperatures as low as 50ºC (122ºF). The consolidation of components for air-conditioning within the building envelope offers architectural expression and system adjacency to a source of fresh air. The use of the direct evaporative cooler makes use of cool dry dehumidified air to cool chilled water for use in radiant ceiling panels instead of conventional air conditioning equipment and refrigerant to minimize the impact to the environment. Regenerative liquid desiccant thermal walls use low-grade source of heat to reduce system energy consumption and reliance on sources of refrigerant to provide cooling and dehumidification.

KEYWORDS: Thermal-Hygroscopic; Façade; Bi-Directional; Liquid Desiccant; Regenerative

1.0. INTRODUCTION

The proposition for decoupling air-conditioning systems from dehumidification and cooling is not a new idea. The systems can undergo rapid configuration and experimentation. Dedicated outdoor systems provide decoupling of cooling from dehumidification. These kinds of systems operate differently but offer little opportunity for architectural integration or expression. The systems are often located 'out of sight' from occupants. The movement of air conditioning equipment from the building roof or mechanical space to the building envelope is uncertain and risky. It requires consideration for different solutions in the earliest points of building design, energy modeling and simulation. The speculative feasibility is not without issues of risky structural, thermal, cost, and energy issues.

1.1. Indoor air quality, ozone, depletion and global warming potential

Rising demand and adoption rate for air conditioning is commonplace all over the world. With conventional approaches to air-conditioning, poor air quality can make the indoor environment harmful to occupants (Yu, et al. 2009). Conventional air conditioning systems maintain comfortable indoor environments. These systems maintain comfortable interior environments. These systems minimize the growth of microbial fungus, mildew with musty odors in HVAC condensate-pan and moist air in ductwork (Gandhidasan and Mohandes 2011). Typical air loading to conditioned spaces is about 0.0005-0.0094 m3/s (15-20 ft^3/minute) per-person mixture with fresh air (Gandhidasan and Mohandes 2011). Outside air has much more moisture content than the heat load within a space (Gandhidasan and Mohandes 2011). Conventional air-conditioning equipment efficiently removes sensible loads with thin coils and high supply air velocities (Gandhidasan and Mohandes 2011). The equipment cools air temperatures below 7ºC and consumes energy to improve latent thermal energy removal efficiency (Gandhidasan and Mohandes 2011).

Commercial office building data shows a relationship between floor area, number of buildings and primary energy consumption (U.S. Department of Energy (DOE) 2012). The data shows that office buildings account for the largest aggregation of floor area, number of buildings, and energy consumption. Most of the other types have lower primary energy consumption when compared with commercial office space. The building type is characterized with 10% and 17% higher trend than other types.

1.2. Building water and energy consumption

Conventional air-conditioning systems cool air below the dew-point temperature to condense the moisture vapor out of the air and remove latent thermal energy (Yu, et al. 2009). Although not always the case, these systems can consume more electric energy in a second pass to reheat the same air stream after cooling such that the air temperature reaches a point that is a comfortable for occupants before delivery to the intended spaced for conditioning (Yu, et al. 2009). The chilled water system uses more electrical energy to cool water to a temperature lower than fresh air. This allows for larger temperature differences between the cooling water and fresh air to improve system cooling efficiency. Latent heat and sensible heat removal take place in a single heat exchanger system at the same time (Yu, et al. 2009). The system must run longer to reach a lower chilled water temperature (Dieckmann, Roth and Brodrick 2008). It must also operate in an overcooling state. The conventional air-conditioning system operates with three to four Energy-Efficiency Rating (EER), which implies that the Coefficient of Performance (COP) is less than or slighting more than one. Systems with EER of this magnitude must remove heat to provide necessary cooling but at the expense of higher electrical energy consumption per hour.

1.3. Adaptive thermo-hygroscopic building envelope

The building envelope can connect and directly dehumidify fresh air and drive energy expenditure to its lowest level. The components that describe the separation of latent load removal and sensible heat removal within the building envelope are theoretical, experimental, and risky. Liquid solutions can scavenge water vapor from air, including pollutants and separately lower air temperature. These systems have similar strategies the design of conventional systems in that they operate at a distance from the building envelope. An adaptive thermo-hygroscopic building envelope relocates these components to the building envelope at the nearest point of contact with fresh air. A 93 m^2 (1,000 ft^2) commercial office-building prototype provides a test platform to decouple dehumidification and an alternative smaller sized-system size for cooling. The system is biologically inspired and makes use of a benign liquid desiccant salt solution.

2.0. ORIGINS

Early systems research provides data to understand the common traits for the use of hygroscopic materials to absorb and condense the moisture vapor from ambient air. The water absorbing and insulation materials are instrumental in the functioning of certain devices. These common convergences may transfer to a building envelope based liquid desiccant system with absorbent and insulating surfaces.

2.1. Dewponds 10,000 B.C. to 2,000 B.C.

Neolithic humans develop larger dewponds nearer the end of the period around 2000 BC. The basic construction of the dewpond is a round artificial depression in the ground with a neighboring embankment. The dry clay soil performs as the hygroscopic material. The dewponds may have provided over a thousand sheep with daily water requirements from one single dewpond (Hubbard and Hubbard 1916). Dewponds use a dynamic hygroscopic process cycle and fill with water each morning day.

2.1.1. Dewpond construction

Modern construction of ancient dewponds uses a process that excavates out the earth with a larger radius than required for the final pond (Hubbard and Hubbard 1916). An insulating coating of dry straw covers the hollow depression (Hubbard and Hubbard 1916). A layer of puddled clay covers over the straw. Next, a layer of stones covers the puddled clay (Hubbard and Hubbard 1916). The observation of the earth works shows that the ponds fill with water in the absence of rainfall, and larger depression ponds fill more rapidly.

2.1.2. Dewpond constraints

Dewpond thermodynamic performance is highly dependent upon the stable dry straw insulation layer. The insulation layer must not become moist or wet as this lowers the insulation resistance between the puddled clay and subsurface ground. Conduction of heat from the subsurface ground to the puddled clay will interrupt the performance of the condenser surface. Dewponds work because of their insulation layer construction.

2.2. Air wells

In the early 20th century, F.I. Zibold reinvents the dew condenser based on the work of ancient Greeks in Theodosia, a city on the Crimean peninsula in Ukraine near to 700 B.C. Dew condensers condenses water from moisture laden fresh air. The dew condenser features a cone and funneled shape structure made from stacked sea-beach pebbles (Nikolayev, et al. 1996). The cone and funnel mound sits atop a concrete base in the shape of a bowl (Nikolayev, et al. 1996). Zibold’s dew condenser did not work.

2.2.1. Air well thermodynamics

In 1996, the researchers Nikolayev et al investigated Zibold’s original manuscripts, documents, and earth-work remains to understand the cause for the failure of the dew condenser (Nikolayev, et al. 1996). The operation of the dew condenser relies on the different in temperature between a surface receiving solar radiation and the ground. After the sun has set, the surface radiates heat to the immense cold night sky. The once warm surface cools from heat loss to the night sky. The rate of cooling from the surface lowers significantly when it connects thermally to the ground. Thermal isolation with the ground improves cooling capacity between the radiating surface and the night sky. In this situation, the surface will radiate more heat to the night sky surface with a smaller amount to convective heat air currents. Ground decoupling and thin double-sided surface geometry can improve the performance of the air wells. Air wells tend to work better with low thermal lag construction.

3.0. PAST RESEARCH

Biological analogues offer useful models of inspired design for their adaptation and deployment of low-energy and resource economy (Pawlyn 2011). Biologically inspired design can learn from analogues and their unique methods of innovative adaptations for airflow movement in nature. Biological adaptations resemble the human technological design in function, but differ in energy expenditure. Air-conditioning systems rely on high-energy intensive functions that require high-grade energy to provide indoor air comfort. Biological analogues offer strategies that use low-grade energy expenditures for airflow regulation, temperature, and humidity control.

3.1. Biological inspired design as performance adaptation

Biological analogues for airflow control, temperature and humidity control make use of their immediate environment to create an associative, connective, and functional physical habitat. The leaf-cutting ant harnesses the wind through adaptations to nest architecture. The Great Plains prairie dog harnesses the wind through its tunnel architecture. The architectural characteristics of leaf cutting ant nest and prairie dog tunnel may offer adaptations for passive airflow control of temperature, humidity, and ventilation.

3.1.1. Leaf cutting ant harnesses wind

The leaf cutting ant nest works similarly to a building envelope in that it provides protection from predators and climatic conditions. The nest structure allows for a dynamic relationship between inflow of air, gases and an outflow of air (Bollazzi, Forti and Roces 2012). The nest adaptation for passive nest ventilation uses wind-induced airflow (Kleineidam, Ernst and Roces 2001). Deployment of key components of the nest hierarchical structure allows a highly inter-connective strategy to achieve multiple low energy functions and resource economy.

3.1.1.2. Leaf-cutting ant nest performance

The nest habitation relies on the manipulation of nest openings and subtle gas exchange in the upper and lower areas. The interconnected dependency on interactions to direct the flow of air and tune torrent definition offers transferable characteristics of wind-induced apertures such as an articulated ventilation flap for buildings.

3.1.2. Great Plains prairie dog harnesses wind

The Great Plains prairie dog burrows harness wind energy through the development of changes in laminar flow along the ground surface. The adaptations allow the small animal to survive in extended below grade tunnels for long periods with adequate air mass exchange.

3.1.2.1. Great Plains prairie dog burrow performance

Similarly, to the leaf-cutting ant, the prairie dog orients its inlet an outlet mound to a direction parallel to the wind flow with articulation characteristics. The offset inlet and outlet mound openings have similarities to offset ventilation. The small number of openings resembles strategies for minimizing openings in buildings.

4.0. SYSTEMS

The north and south facade features a theoretical reversible solar liquid desiccant air conditioning with dedicated outdoor air system to provide decoupling of air conditioning from dehumidification. Each floor level is equipped with its own independent system. Each facade can provide dehumidification of fresh air while the opposite facade provides dehumidification or humidification of operational process air.

Hygroscopic building envelopes like the one proposed for the south and north facades have limited dry duct systems. The system affords less vapor moisture air and dust-free environment to prevent dust collection and fungus, mold and bacterial growth, which can lower indoor air quality. High levels of vapor moisture introduction increase operational maintenance to remediate mold, mildew, corrosion, and replacement of wall and window coverings and carpet. Outdoor air systems like the liquid desiccant system remove latent heat energy and improve dehumidification management when compared with other mechanical ventilation systems (Dieckmann, Roth and Brodrick 2008). They remove moisture without cooling air supply temperatures to the point of condensation. Relative humidity levels below 70 percent keeps surfaces dry and free of mold and bacterial growth (Dieckmann, Roth and Brodrick 2008). The hygroscopic solution in these systems scavenges airborne contaminants and increases fresh air volumes (Dieckmann, Roth and Brodrick 2008) (Yu, et al. 2009).

4.1. Direct-expansion vapor compression refrigeration air conditioning system

Figure 1 shows the layout and components of the direct-expansion vapor compression system. The system moves refrigerant around a closed loop. It removes heat from fresh air and feeds cool air into a space. Figure 1 and 2 describe the thermodynamic state of the refrigerant as it cools and dehumidifies the warm outside air. Numbers in ‘RED’ color show the relationship between state conditions in the diagram. Outside air at state ‘0’ mixes with return air at state ‘4’. The mixed air stream enters the evaporator coil at state ‘5’. The supply air is in direct contact with the evaporator cooling coils. The cool and dry air stream leaves the evaporator at 13ºC (55 ºF) and 50% relative humidity at state ‘1’. The mechanical system warms and slightly humidifies the air temperature to 23ºC (74ºF) with near constant relative humidity while coinciding with state ‘2’ or the conditioned space. The supply air and recirculation air mix, heats up and humidifies in the conditioned space as represented by the line segment from state ‘2’ to states ‘3’ and ‘4’ in Figure 2. A fan draws air from the space or state ‘3’ to state ‘4’. The process repeats with outside air at state ‘0’ entering the mixing box. The system here provides a simpler case for heat transfer by refrigerant from fresh air than more complex systems where air flows over an intermediate fluid; the fluid or chilled water then flows over the evaporator coils of a chiller.

4.2. Thermo-hygroscopic solar liquid desiccant air conditioning system

In the Figure 3 plans, sketches show different arrangements of length and width for stair and elevator core. A dashed line represents the location for the thermo-hygroscopic building envelope. Figure 4 shows the section sketches of the plan configurations and liquid desiccant solar regenerator. The ‘X = Y’ plan configuration refers to length and width dimensions for external core on either the west or east side offers improvement to day-lighting. Solar liquid desiccant regenerators use incline path to direct flow downward by gravity to desiccant dehumidifier. The regenerator panel requires an appropriate tilt angle and orientation with the least amount of shading from site elements that are self-shaded by building. Figure 4 shows dual sided options for thermo-hygroscopic envelope facing north and south. North-facing envelopes do not line up with solar access. A different configuration moves the liquid desiccant regenerator further away from dehumidifier components to overcome building self-shading on the north facade.

The thermo-hygroscopic building envelope decouples thermal energy removal through an air ventilation system and waterside cooling and heating system. The system uses hydronic cooling, radiant ceiling panels for sensible energy loads, and solar liquid desiccant air-conditioning system for latent energy loads. The ceiling panels use chilled water to transfer heat by radiation and convection. The work is related to a system proposed by Yin et al for their liquid desiccant dehumidification radiant cooling system (Yin, Zhang and Chen 2007) (Yin, Zhang and Chen 2008). Their system uses similar components, including solar regenerator, dehumidifier, direct evaporative cooler, and ventilation units. The system in the paper integrates an additional dehumidifier and configuration of these components within the building envelope. Figure 5 shows the system re-imagined within the building envelope.

Radiant ceiling panels circulate chilled water through small tubing to remove sensible heat energy. To prevent condensation issues chilled water must be above ambient dew point usually between 13ºC and 16ºC (55ºF and 60ºF). The higher chilled water and room temperature reduces temperature differential to

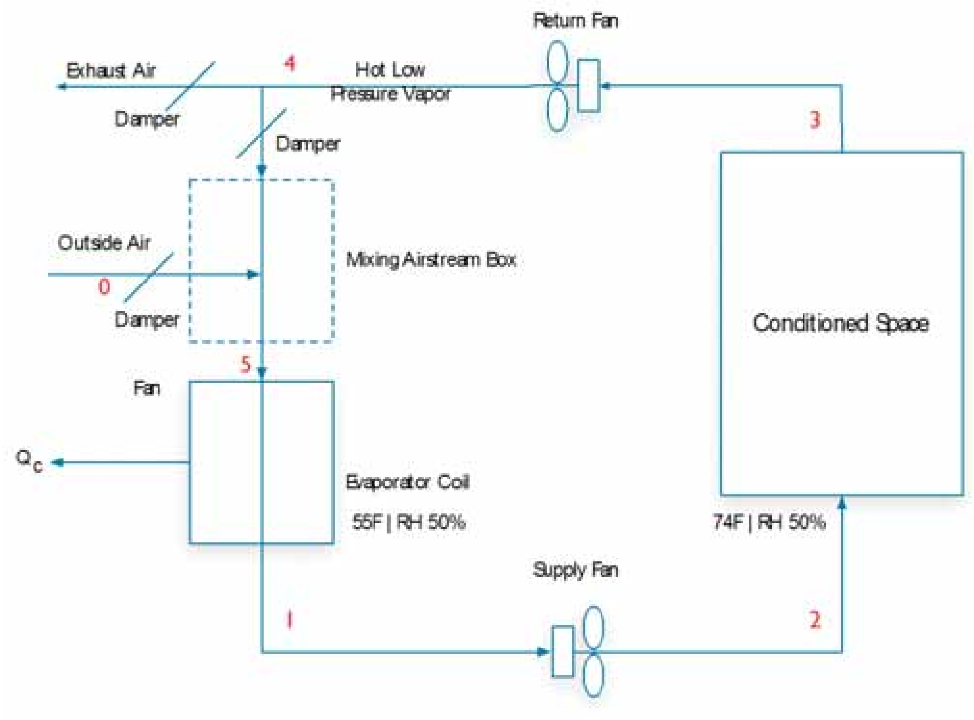

Figure 1: Building air conditioning process sketch, derived from (Kreider 1994).

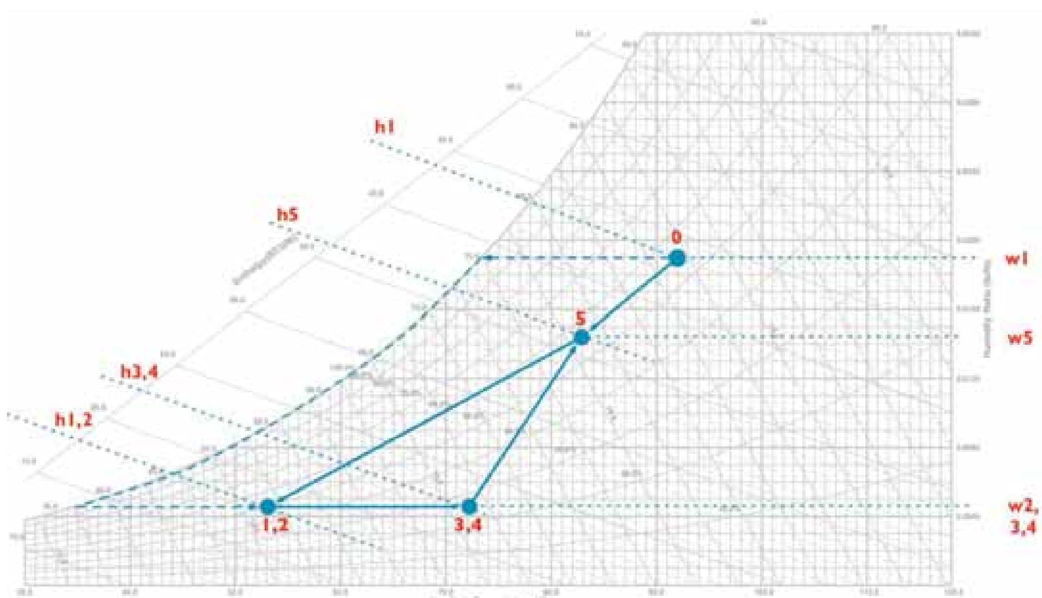

Figure 2: Direct expansion vapor compression refrigeration process psychrometric chart.

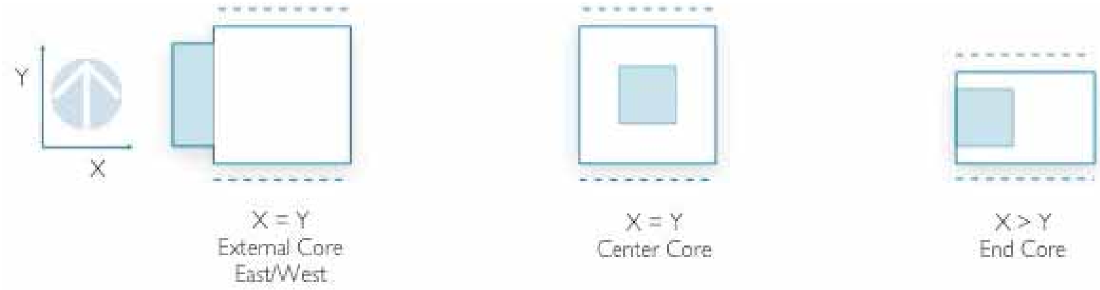

Figure 3: Plan sketch of north and south thermal-hygroscopic envelope design.

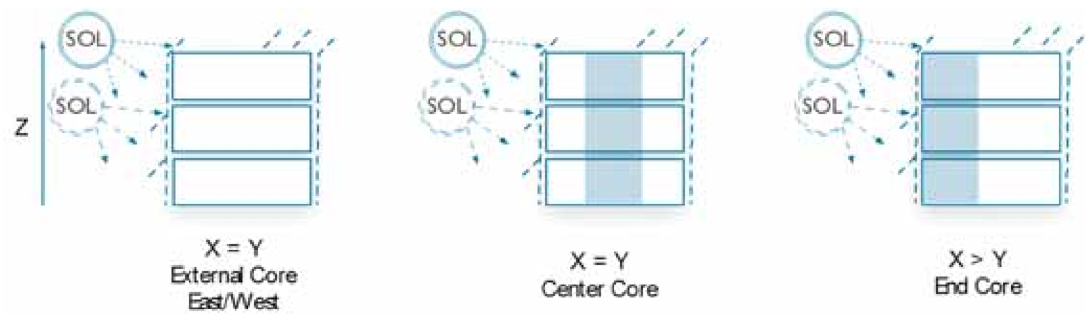

Figure 4: Section sketch of north and south thermal-hygroscopic envelope design.

-7ºC and -10º C (19ºF and 14 ºF). Radiant ceiling panels take dehumidified air from the liquid desiccant system through separate diffuser from ceiling-mounted units for further cooling. The design requires less than one air changes per hour, which is within the capacity of the ceiling system. Higher chilled water operating temperature reduces pump size and parasitic energy.

The spatial configuration purposely incorporates a small single thermal zone with ductless air volume. Bio-inspired articulated torrent flaps on the building envelope control the airflow rate by opening and closing. The flaps' articulation is an inspired concept from the leaf cutting ants nest openings and prairie dogs burrow mounds. Outside air flows through articulated flaps into the liquid desiccant dehumidifier. The desiccant flows from top to bottom of the dehumidifier opposite to the air moving from bottom to top. The thermodynamic state of air drives the ventilation rate with supplemental fans. Air temperature varies throughout the system to remove sensible heat energy.

The hygroscopic building envelope is an integrated building solar liquid desiccant air-conditioning system that removes latent heat energy. The system delivers dry conditioned air to the compact office space. The separation of fresh air dehumidification and recirculation air is done to limit issues with air infiltration from crossing air streams and condensation issues through the building envelope. The system uses dry air to reduce the amount of supply air volume needed for ventilation from a lower humidity ratio when compared with an all-air single-stage vapor compression refrigeration (Yin, Zhang and Chen 2008). Fan and flaps control the amount of air volume based on latent thermal loads. Less air volume and movement of dry air reduce fan size and parasitic energy losses. A gas heater regenerates the liquid desiccant in the regenerator for conditions when there is no solar radiation available.

The two systems do not remove sensible or latent energy loads primarily through convection. Lower air volumes from radiant ceilings and dehumidification system minimize air velocities to minimize drafts. Comparison of latent and sensible load for drying air in a single-stage vapor compression and solar liquid desiccant system is possible. Figure 5 shows a sketch of the psychrometric chart of the process for dehumidifying outside air for the system. An inlet at the facade draws in the outdoor air at state '0'. Outdoor air temperature is 34ºC (94ºF). The fresh air indirectly cools by the weak liquid desiccant from state '0' to '1'. Fresh air at state '1' enters a mixing box. The air then mixes with return air from direct evaporator at state '2' and cools. The supply air enters the liquid desiccant dehumidifier and leaves with lower enthalpy. The dehumidifier heats and dries the air from state '2' to '3' with constant enthalpy. The hot dry air leaving the dehumidifier cools with chiller water from state '3' to '4'. The dry air-cools again indirectly from the air leaving the direct evaporative cooler at state '2'. Another dehumidifier heats and dries the return air from state '5'.

The dry air leaving the second dehumidifier cools to state '6'. A portion of the air enters the conditioned space leaving state '6' while another stream of air enters the direct evaporator. The cool and dry air passes over water coils. The temperature of the water in the cooling coil lowers. This water continues on a path to the radiant ceiling panels to cool the interior space. The warmer air leaves the direct evaporator at state '2' to mix with air at state '1'. The process repeats with fresh air drawn into articulated flaps by differential air pressure to the mixing box at state '1'. Table 1-5 and Figure 7 show the total heat removal calculation in the summer.

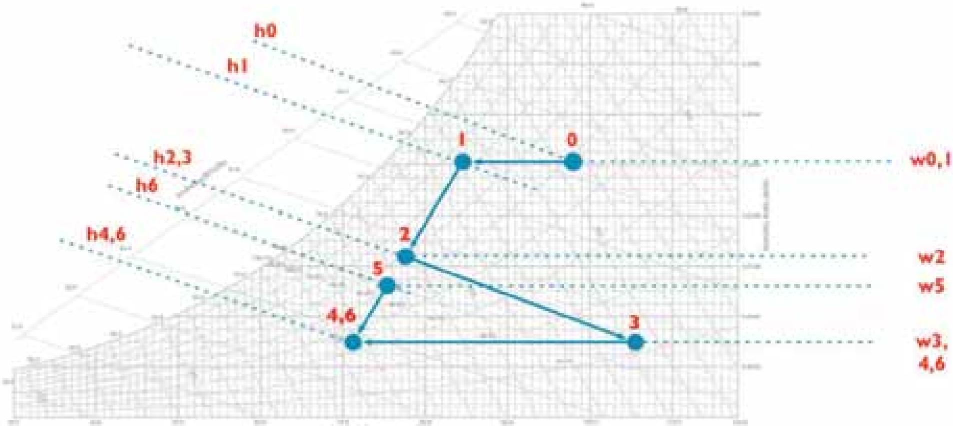

Figure 5: Air conditioning dehumidification process in the psychrometric chart for thesis liquid desiccant.

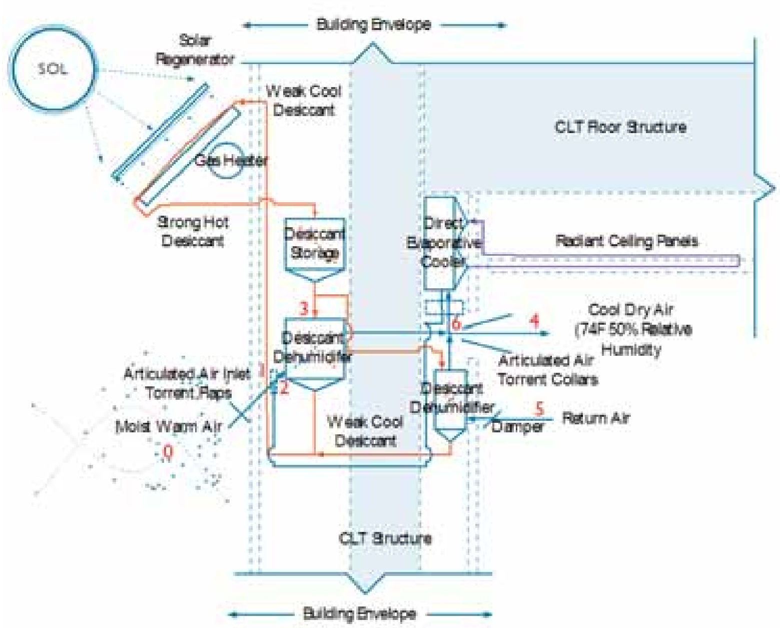

Figure 6: A detail sketch that shows solar liquid desiccant air conditioning building envelope system.

Assumptions for occupant load, ventilation requirement per person allows for calculation of a number of model data points. The heat transmission and solar gain from internal loads allow for computation of sensible and latent loads. Temperature states for outdoor air, conditioning of supply air, and office space air allow for plot on a psychrometric chart. The amount of supply ventilation, room ventilation is calculated. The total heat load allows for sizing of equipment to cool the space.

Table 1: Thermo-hygroscopic model data and conditions for summer heat load.

Design model data	Value	Units
Floor area	94(1,015)	$m^2(ft^2)$
Floor area per person	5(50)	$m^2(ft^2)$
Number of occupants	20.30	Persons
Ventilation per occupant	0.5(17)	m^3/person(ft^3/person)
Supply air temperature	13(55)	ºC(ºF)
Room dry bulb temperature	23(74)	ºC(ºF)
Room relative humidity	50	%
Outdoor temperature	34(94)	ºC(ºF)
Delta T	-7(19)	ºC(ºF)
Window area	30(318)	$m^2(ft^2)$
Wall area	143(1536)	$m^2(ft^2)$
Roof area	95(1024)	$m^2(ft^2)$

Table 2: Heat and solar gain transmission from people, lights, equipment, walls, windows and roof.

Space gains	Value	Units
Sensible load, (Grondzik, et al. 2006)	73(250)	W(Btu/h)
Latent load, (Grondzik, et al. 2006)	59(200)	W(Btu/h)
Sensible load for office equipment, (Grondzik, et al. 2006)	2.5(0.80)	W/m^2(Btu/hr-ft^2)
Sensible load lights, (Grondzik, et al. 2006)	6.3(2)	W/m^2(Btu/hr-ft^2)
Window gains, (Grondzik, et al. 2006)	66(21)	W/m^2(Btu/hr-ft^2)
Wall gains, (Grondzik, et al. 2006)	79(25)	W/m^2(Btu/hr-ft^2)
Roof gains, (Grondzik, et al. 2006)	142(45)	W/m^2(Btu/hr-ft^2)

Table 3: Calculation of the amount of cooling needed for prototype model.

Load Calculation	Load	Units
*Sensible = sensible heat * number of occupants*	1,487(5,074)	W(Btu/h)
*Sensible = lights * floor area*	1,190(4,059)	W(Btu/h)
*Sensible = equipment * floor area*	595(2,029)	W(Btu/h)
Sensible = heat gain window(window/floor area) window gain*	238(812)	W(Btu/h)
*Sensible = heat gain walls (walls/floor area) * wall gain*	2.1(7)	W(Btu/h)
*Sensible = heat gain roof (roof/floor area) * roof gain*	11(38)	W(Btu/h)
*Latent = latent load * number of occupants*	13.2(45)	W(Btu/h)
Sensible total = total summer people and internal gains (sensible heat)	2,346(8,005)	W(Btu/h)
Latent total = total summer people and internal gains (latent heat)	-7(19)	m^3/min(ft^3/min)
Calculation = portion of sensible load heat factor (RSH/RSH+RSH)	0.66	
Calculation = quantity of air (RSH/1.1 delta T) needed to cool	30(381)	m^3/min(ft^3/min)
*Calculation = supply air volume (occupants * cfm per person)*	143(345	W(Btu/h)
Calculation = outdoor portion of supply air (needed air/supply air volume)	91	%

Table 4: Heating load on cooling equipment, tons of cooling required calculation.

Total heat to be removed by cooling equipment	Value	Units
Psychrometric chart, point h_2	94(20.4)	kJ/kg (Btu/lb)
Psychrometric chart, point h_3	5(41.7)	kJ/kg(Btu/lb)
Calculation $Q_t = 4.5* cfm*(h_3\text{-}h_2)$	(33,072)	W(Btu/h)
Cooling required	2,509(2.76)	kg(ton)

Table 5: Psychrometric data for plot of Table 1, 2, 3 and 4.

Point	Description
0	Room Dry Bulb Temperature
1	Supply Air Temperature
2	Outdoor Temperature
3	Calculated From Outdoor Portion Supply Air and Psychrometric Chart

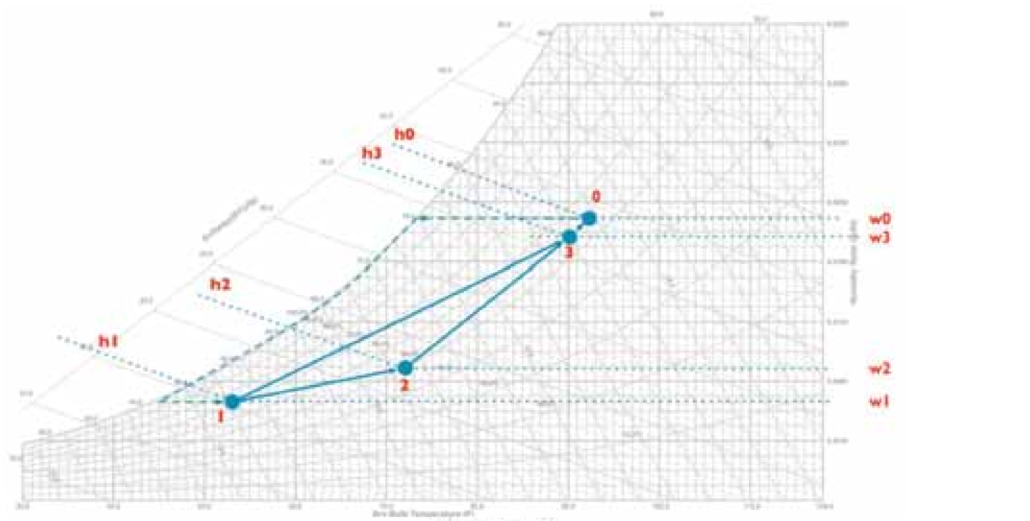

Figure 7: Psychrometric plot of Table 1, 2, 3, and 4.

5.0. SYNTHESIS

The process has led to discovering mechanisms in the historical and biological references that delineate obvious improvements to those that differ too greatly for potential application transfer. The tables show a range of divergences, and convergence triggers between conventional air-conditioning systems and thermo-hygroscopic envelope to dewponds, air wells, prairie dog burrow and leaf-cutting ant nest.

5.1. Historical Implications

The historical implications for the paper provide a working platform to improve the speculative thermo-hygroscopic building envelope. Table 6-7 shows comparable performance criteria between the thermo-hygroscopic 'thick wall' and the earlier discussion of dewponds and air wells in section 1.1. The list shows characteristics that are the same, similar, and different. The differences provide an opportunity for making a change in an existing system to improve it in some way.

Table 6: Bio-inspired comparison of the thermo-hygroscopic envelope to dewponds.

Performance criteria	Thermo-hygroscopic envelope	Comparison	Dewponds
Condensing mechanism	Contact with ambient air	Same	Contact with ambient air
Regenerative mechanism	Heating	Same	Drying
Condensing constraint	Short time	Different	Long time
Condensing Surface Area	Large thin falling film	Same	Large thin surface area
Regenerative shape	Angle of incline	Different	Depression
Regeneration orientation	Vertical	Different	Horizontal
Condensing material	Liquid desiccant	Different	Solid desiccant
Water desorption	Differential vapor pressure	Different	Decoupled from ground
Water generation	Surface vapor pressure	Different	Stable insulation layer

Table 7: Bio-inspired comparison of the thermo-hygroscopic envelope to air wells.

Performance criteria	Thermo-hygroscopic envelope	Comparison	Air wells
Condensing mechanism	Contact with ambient air	Same	Contact with ambient air
Regenerative mechanism	Heating	Same	Drying
Condensing constraint	Short time	Different	Long time
Condensing Surface Area	Large thin falling film	Same	Large thin surface area

Regenerative shape	Angle of incline	Different	Depression
Regeneration orientation	Vertical	Different	Horizontal
Condensing material	Liquid desiccant	Different	Porous desiccant
Water desorption	Differential vapor pressure	Different	Decoupled from ground
Water generation	Surface vapor pressure	Different	Low thermal lag response

5.2. Biological Implications

Table 8-9 shows criteria for selective performance and functional mechanisms to improve conventional air-conditioning systems. Orientation of nest and burrow openings to the wind is a successful adaptation. The articulation of vents flaps offer improvements to intake and exhaust performance. The biological analogue comparison can offer benefits to conventional and speculative air-conditioning systems. The system may also use biologically inspired articulated flaps to control aperture sizes of air inlet areas. The flaps use an energy management system where it can respond to relative humidity levels within the interior office space. The control of air admittance, shaping of flap apertures, and height displacement follow the bio-inspiration from the prairie dog and leaf cutting ant. Vertical height displacement of sets of flaps admits air into the absorber sections of hygroscopic building envelope and allows air to mix with indoor air as dehumidified process air. The data from this process delivers rich untapped resource for further work to improve the design and integration of the thermo-hygroscopic building envelope.

Table 8: Bio-inspired comparison of conventional air-conditioning equipment systems to leaf-cutting ant nest.

Performance criteria	Air conditioning systems	Comparison	Leaf-cutting ant nest
Seasonal adaptation	Fixed	Different	Orient to wind direction
Adaptation mechanism	Variable air volume	Similar	Open/close nest openings
Structure	Parallel connecting ductwork	Similar	Parallel connecting tunnels
Humidity control	Evaporative condenser	Different	Nest cultivation of fungus
Thermal convection	Forced convection	Different	Convective/diffusive
Airflow movement	Forced convection	Different	Convective diffusive
Airflow mechanism	Offset inlet and outlet	Same	Offset inlet and outlet
Airflow performance	Pressure drop	Similar	Pressure drop
Airflow penetrations	Small number	Different	Large number
Airflow adaptation	Vents	Different	Torrent articulation
Directional adaptation	No specific adaptation	Different	Openings orient to face wind
Exergy adaptation	No specific adaptation	Different	Wind harvesting

Table 9: Bio-inspired comparison of conventional air-conditioning equipment systems to prairie dog burrow.

Performance criteria	Air conditioning systems	Comparison	Leaf-cutting ant nest
Seasonal adaptation	Fixed	Different	Orient to wind direction
Adaptation mechanism	Variable air volume	Similar	No specific adaptation
Structure	Parallel connecting ductwork	Similar	Parallel connecting tunnels
Humidity control	Evaporative condenser	Different	Side passages balance
Thermal convection	Forced convection	Different	Induced wind airflow
Airflow movement	Forced convection	Different	Induced wind airflow
Airflow mechanism	Offset inlet and outlet	Same	Offset inlet and outlet
Airflow performance	Pressure drop	Similar	Pressure drop
Airflow penetrations	Small number	Different	Small number
Airflow adaptation	Vents	Different	Torrent articulation
Directional adaptation	No specific adaptation	Different	Openings orient to face wind
Exergy adaptation	No specific adaptation	Different	Wind harvesting

5.3. Energy reductions, consumption, and cost implications

Yu et al decoupled liquid desiccant system consists of a single regenerator and desiccant storage tank serving individual building-level desiccant dehumidifiers (Yu, et al. 2009). The performance of their system shows energy, consumption, and cost reductions for summer and winter. With latent loads between 10% and 50%, the system energy consumption and operational costs are 80% and 75% of conventional air-conditioning systems (Yu, et al. 2009). The reductions and savings can be much less in their model with solar energy to regenerate the liquid desiccant and ground water for radiant ceiling panel system. The cost associated with uncertainty with the high integration of these components within the building envelope requires further investigation.

Adoption of liquid desiccant systems remains an issue for commercial buildings due to their higher-energy costs, first costs, and moisture carryover. Corrosion of metal components leads to more expensive components and design modifications in equipment in these systems. Further development to test liquid concentrations with sodium chloride and calcium chloride improves the consideration for solutions with less corrosion and toxicity issues. Use of low-cost waste heat and solar-energy offer benefits to driving cost of these systems lower. Research on micro-porous membranes that allow water to migrate to air but impervious to desiccant in desiccant dehumidifiers avoids the carryover and corrosion issues (Dieckmann, Roth and Brodrick 2008). Special surfaces that form thin desiccant film flows offer improvements in minimizing carryover and corrosion issues (Dieckmann, Roth and Brodrick 2008). Thinner film flows of liquid desiccant can offer improvements to the solar regenerator with more surface area contact with the absorber surface.

CONCLUSION

The paper discusses the environmental, historical, bio-inspired design, past systems, and materials and components for a hygroscopic building envelope to function. The feasibility of the system limits itself to thermodynamic understanding of liquid desiccant performance and fresh air in this system. The mechanism transfer from beneficial performance criteria in the historical and biological examples provides an array of improvements to the system. Integration of the primary components at a schematic level provides enhanced understanding of the difficulties of the proposition. Bio-inspired design requires future work to advance and incorporate improvements in thermal components for thermo-hygroscopic envelope assembly. Bidirectional solar liquid desiccant units on the north and south elevation offer higher level of system functioning. The system uses flaps to control air volume of fresh air into the two-dehumidifier units. The opening and closing of the system provide inspiration from the leaf-cutting ants' strategy for mound ventilation. The prairie dog offsets and shape of borrow mounds entrances improve the location and shaping of fresh air inlet and return air outlets on the exterior and interior side of building envelope. The regenerator uses solar radiation in the regenerator of the liquid desiccant as a case for system exergy. Future work can improve understanding of energy storage by varying concentration levels. Direct evaporative cooler transfers waste heat from fresh air to exhaust air and conserve energy. The use of other low-grade heat source exchanges provides dry air ventilation and chiller water for radiant ceilings (Yin, Zhang and Chen 2008). Water condenses on the underside of the regenerator glass and flows downward to the collection reservoir. Water use and water use intensity per square meter improves the study of work for water harvesting from the solar regenerator. Future work in calculating building envelope air mass and vapor conversions improves latent energy transformations for condensation and evaporation mass balance, and evaluation of the integrated components. The long lead-time in developing improvements system design shortens with the strategic bio-inspired design process but this requires an integrative approach with engagement with agents from other areas of design, engineering, structure, building science, and biology. In light of these constraints, multiple areas for improvement give rise to breaks in barriers for re-think of alternative decoupling air-conditioning systems that can be responsive to ecological and thermal issues.

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