Multivalent Hygrothermal Material System for Double-Skin Envelope Dehumidification Cooling and Daylighting

Aletheia Ida, PhD

ABSTRACT

A unique paradox exists between the early and modern architectural and mechanical means of dealing with humidity in and around buildings. Traditional architectural conditions of biopolymeric thatch dwellings accommodated human thermal comfort through dehumidification by the materials employed at the building envelope. Original mechanical developments for dehumidification processes were developed specifically for removing moisture from materials in industrial applications. However, today, the modes by which humidity is treated for human comfort and material protection is inverted: buildings now utilize mechanical conditioning for dehumidification cooling functions and moisture protective materials in the building enclosure systems.

Emerging multivalent hydrophilic materials are able to process humidity and moisture transport in new ways to allow for a systemic return to dehumidification cooling functions integrated in the building envelope system. The hydrophilic polymers are synthesized with low energy methods and poured into molds and then lyophilized to create macroporous networks that enhance both the sorption and thermal characteristics in the proposed application. The thermal and optical properties of novel hygrothermal materials are identified and used as inputs for simulation modeling for the proposed multivalent building enclosure system. The initial results provide improvements on annual energy loads and consumption for hot-humid climate conditions (Miami and Mumbai).

The introduction of a sorption coefficient for the dehumidification function provides a unique contribution to design and performance analyses of double-skin envelopes. In addition, the dynamic modeling for temporal variations of material properties at the envelope also provides a new contribution to the field of building performance simulation. The challenges of these novel modes for moisture processing in the building envelope materials are addressed, with future work required for microbial identification and monitoring. The advantages from initial analytical and simulation modeling convey improvements for building energy conservation, natural daylighting, and water recuperation potential.

INTRODUCTION

Almost half the world's population lives in hot-humid climate regions (Lime Agency 2011) where one third of typical commercial building cooling loads can be attributed to building envelope glazing and more than 40% to electric lighting (Harriman and Lstiburek 2009). In these buildings, upwards of 70% of energy consumption is from the mechanical ventilation system of which almost 90% is a latent load (Harriman and Lstiburek 2009). If a double-skin glazing enclosure system is designed to integrate climate control embodiments with passive dehumidification cooling functions while maintaining natural daylighting transmittance options, then great energy conservation benefits can be achieved.

Aletheia Ida is an assistant professor in the School of Architecture, University of Arizona, Tucson, AZ.

The proposed building enclosure system builds upon existing knowledge for double-skin envelopes with the introduction of novel hygrothermal materials for the daylighting blinds in the wall cavity (Figure 1). The concept is also modeled upon existing knowledge about the performance advantages of dedicated outdoor air systems (DOAS) for ventilative cooling, which when combined with chilled ceiling panels may conserve up to 42% on electric energy use in comparison with conventional VAV systems (Jeong et al. 2003). The proposed design potentially allows for the elimination of a centralized mechanical cooling system in exchange for distributed climate control and ventilation around the façade and perimeter zones, but the effectiveness is dependent in part on the building footprint and space planning layout. In order for the proposed system to function primarily in a passive mode, the effectiveness is also dependent upon the climate location and building orientation. The hygrothermal materials also provide the capacity to recuperate water from humidity sorption and condensate release.

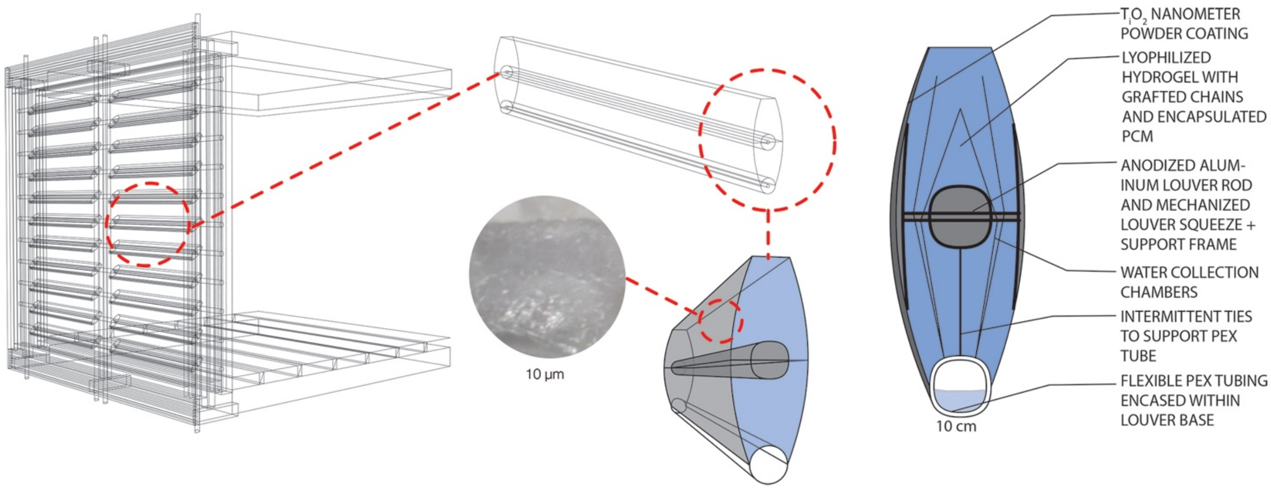

Figure 1 Double-skin envelope façade system with integrated hygrothermal louvers.

The current work incorporates proof of concept studies that include empirical tests on physical samples with material data results introduced as variables in system and building scale simulation modeling. The design has not yet been scaled up to prototype testing and also not yet optimized for any specific condition. The studies to date assess relative performance capability across varying hot-humid climate conditions, and provide assumptions for seasonal energy and water conservation benefits. This paper incorporates an overview of the collective research to date for the proposed double-skin envelope hygrothermal dehumidification cooling and daylighting façade system.

HISTORIC CONTEXT OF HUMIDITY AND BUILDING MATERIALS

Early means to provide shelter in hot and humid climates typically included locally available materials such as wood and thatch (biopolymers) that are relatively effective at absorbing moisture. The spatial conditions of the lightweight huts included narrow floor plates, raised floors, high roofs, and large overhangs to encourage movement of airflow, stratification of heat, and self-shading of the structure. These examples can be found in the thatch building skins of the Yucatan Peninsula Mayan Indians (16th c.), of the Chickees of the South Florida Seminole Indians (19th c.), as well as incorporation of pressed fiber boards in attic spaces to maximize material surface area for moisture absorption in traditional houses in Japan.

Modern building-integrated methods to address humidity in hot climates are comparable to these traditional examples. The incorporation of desiccant boards and beds in attic spaces allow for absorption of humidity at night when coupled with vents for stack ventilation and with skylights in day for solar regeneration. The Florida Solar Energy Center developed a desiccant-impregnated hollow concrete block wall system intended to serve in moisture removal from air flowing through the wall cavities (Givoni 1994). However, there was inconclusive evidence on the effectiveness of this strategy and speculation that the temperature of the desiccant in the blocks may be too hot for sorption to occur.

The architectural response to humidity in temperate and cold climates is primarily for protection of the building materials from mold and corrosive discharge that can develop as a result of vapor transport through exterior walls when interiors are mechanically heated. This phenomenon was discovered in the mid-19^{th} century Haussmann plan apartment buildings in Paris when ducted heating systems were first introduced (Jarzombek 2005). Ultimately, the resulting solution to the large vapor pressure differentials between exterior and interior conditions was the introduction of an air cavity and later the development of the vapor barrier around 1950. While the cavity wall was first introduced in these cold climate regions, it became a standard construction method in hot-humid climates according to ASHRAE guidelines (Harriman and Lstiburek 2009).

Mechanical means of addressing humidity in buildings originates with early developments of air-conditioning for the protection and drying of paper products in industrial applications at the turn of the twentieth century (Ingels 1952). It wasn't until the 1920's that the first applications of mechanical air-conditioning for human comfort cooling were seen (Ingels 1952). The first applications were atypical architectural conditions, such as movie theaters, privileging centralized branch and truck ducted systems in spaces entirely void of access to natural light and air. The other atypical application that emerged around the 1930's was the compact vapor compression air-conditioning unit developed by Carrier for railroad dining cars (Ingels 1952).

Today, mechanical air-conditioning systems are a ubiquitous commodity and the primary means for providing human comfort in most hot climate conditions. ASHRAE established guidelines for indoor dew point temperatures to remain below 55 ^{o}F for both comfort and to limit formation of surface condensation (Harriman and Lstiburek 2009). Since the outdoor dew point temperature typically resides around 75^{o}F in hot-humid climates, there is an exorbitant latent load to process that becomes extremely energy-intensive for standard vapor compression systems. More recently, desiccant mechanical systems are recognized as the plausible alternative to vapor compression air-conditioning. These systems incorporate either a solid or liquid desiccant material to dry the air prior to heat exchange or evaporative cooling cycles that provide sensible cooling. This process greatly reduces the energy required to address the large latent loads of humid conditions, as well as eliminate output of CFCs and concomitantly absorb air contaminants and particulate matter.

Dehumidification Paradox

In the historic development for human thermal comfort control of humidity, there is a paradox that arises between the applications in mechanical and architectural solutions (Figure 2). Original experiments for dehumidification technologies were developed for industrial needs of removing moisture from paper-making production spaces, and these mechanical solutions were not intended for human needs. Early architectural examples for dehumidification cooling include the biopolymer thatch huts of hot-humid climates, capturing moisture from the outdoor air before circulation of ventilation through spaces to cool inhabitants. The inversion of these two modes occurred in the early twentieth century, and has since become one of the highest energy consuming processes in buildings – dehumidification cooling for human comfort by mechanical conditioning. Today, we design the building envelope to protect its materials from humidity and moisture transport. At the same time, in humid climate conditions we run high energy consuming mechanical equipment to process and remove moisture for human comfort. The inversion from architectural conditions to mechanical solutions that accommodate human thermal comfort juxtaposes the early intentions of mechanical applications to protect materials from humidity and moisture to modern architectural protection of materials.

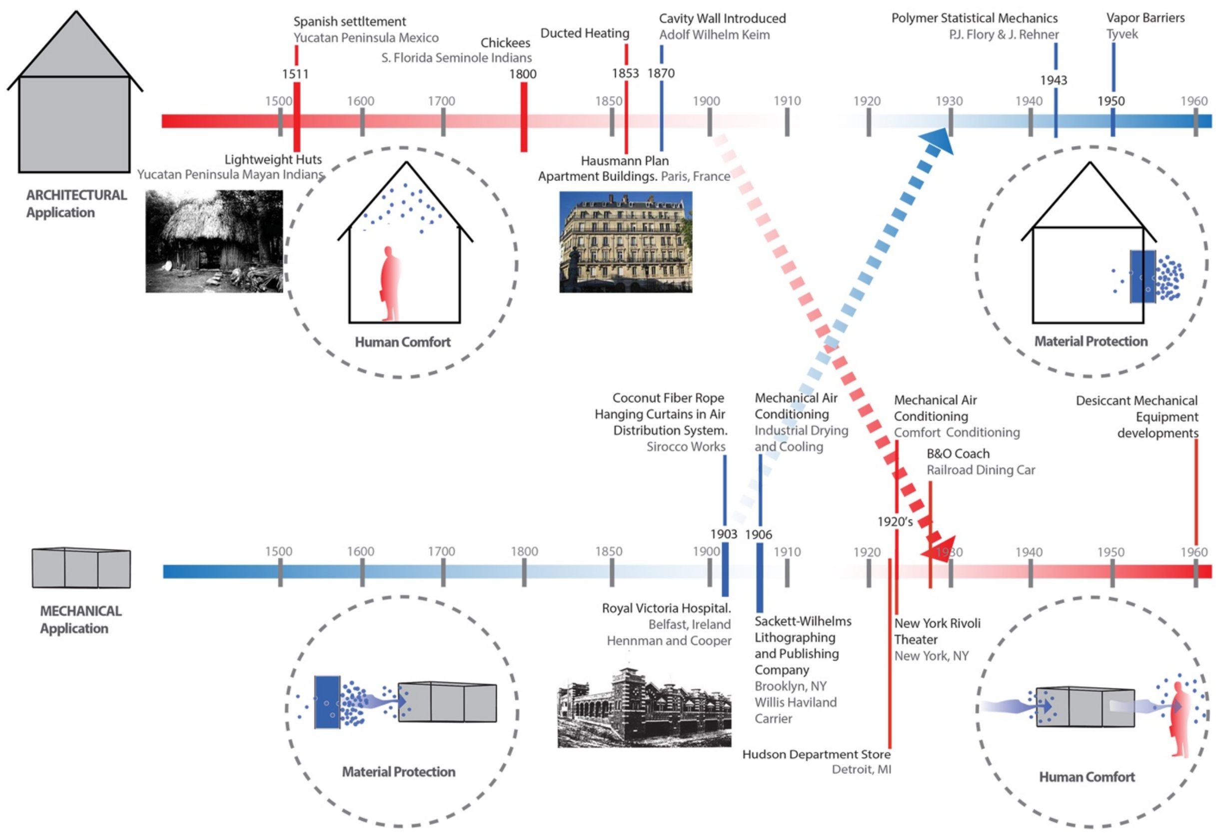

Figure 2 Dehumidification paradox: history timeline of architectural and mechanical applications for humidity.

MULTIVALENT HYGROTHERMAL MATERIALS

This research explores ways to distribute dehumidification functions through ambient materials to improve energy conservation as well as health and wellbeing through elimination of components associated with mechanical system filtration that lend to microbiome challenges on building interiors. Emerging hydrophilic and hydrophobic composite materials are able to process humidity and moisture transport in new ways (Mathiowitz et al. 2001; Gonzalez et al. 2001), allowing for a reconceptualization of the building envelope as a system that can provide dehumidification for building interiors in modified passive design thus reducing dependencies on high energy active mechanical systems for these same functions. The hygrothermal materials consist of novel polymeric blends that are synthesized with low energy methods and poured into molds according to the design embodiment for configuration in the double-skin cavity. The materials are tested independently with thermal conductivity, calorimetric, and visible transmittance analyzers. The physical test data is normalized for material property input to the building simulation platform.

Hydrogels

Hydrogels are characterized as three-dimensional insoluble water-swollen polymers that are classified by network morphology, ionic classification such as neutral, anionic, cationic, ampholytic, and by their crosslinks such as covalent bonds or weak associations such as hydrogen bonds, van der Waals, molecular entanglements (Borzacchiello and Ambrosio 2009). Hydrogels exhibit potential advantages for dehumidification applications including robust sorption and desorption rates and extremely large water-holding capacity (Omidian and Park 1994). Hydrogels can be synthesized from polysaccharides such as cellulose, starch, chitosan, agar, or from polyacrylamides that result in strong chemical bonds. The Flory-Rehner theory establishes that the higher the concentration of crosslinks, the density and relative strength of the hydrogel increases while the pore sizes decrease (Flory and Rehner 1943). The gels become weaker when they are saturated with water.

Lyophilized Hydrogels. The proposed material embodiment for integrating hydrogels in louvers within the cavity of a double-skin glazing system constitutes considerations for support structure, humidity sorption, and condensate release. By freeze-drying the hydrogels, the sublimation process results in a porous foam material that maintains its hydrophilic qualities. After the gels are poured into molds, they are frozen and then lyophilized to create the sponge-like modules with macroporous networks that enhance the sorption characteristics in the proposed application. In addition, the lyophilized hydrogels have high thermal resistance and are lightweight when dry, can be modulated for varying light transmission qualities, may be composited with encapsulated PCMs for enhanced thermal management, may be coated with titanium dioxide to improve air contaminant remediation, and can be compressed mechanically to squeeze out condensate for water recuperation.

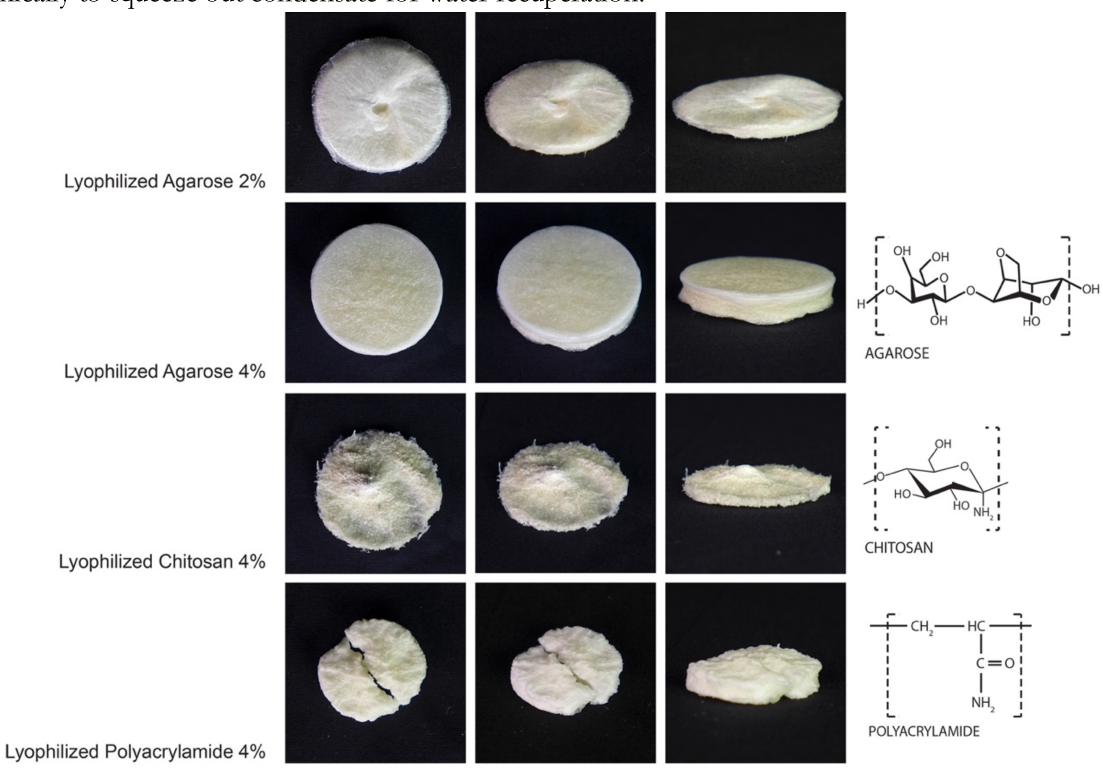

Figure 3 Lyophilized hydrogels: agarose (top rows), chitosan (third row), and polyacrylamide (bottom row).

In this study, three types of hydrogels are used for comparison: agarose, chitosan and polyacrylamide. The lyophilized hydrogel samples were made in 2.5" diameter discs at 2% and 4% concentration ratios (Figure 3). The thicknesses vary dependent upon how each polymer reacts during the lyophilization processing, ranging between 3/16" to 3/8". The 4% lyophilized agarose samples exhibit the cleanest result in form and greatest sponge-like consistency. The 4% lyophilized chitosan are the most fragile and easily flake when handled losing hair-like polymers from the surfaces. The 4% lyophilized polyacrylamide samples resulted in highly brittle pieces that tended to easily break; lower concentration ratios will be studied to determine if this might modify the result. All samples exhibit a whitish color with the chitosan having more yellowish tones.

Thermal Properties. The thermal properties of the lyophilized hydrogels were tested with differential thermal conductivity (DTC) equipment (Figure 4). The polyacrylamide samples were not tested because they did not remain whole in sample size to fit the equipment. Additional polyacrylamides are being prepared to test with the DTC equipment. The samples are identified by preparation letter (i.e. A, B, C, or D), and by percent concentration and chemistry. All samples were tested in dry states. The mean temperature of materials during testing ranged from 20.53^{o}C to 24.34 ^{o}C. Though thermal resistance and thermal conductivity are reciprocal, the results shown indicate the resistance and conductivity each separately as an average of three measured results across three distinct temperatures. Because of the averaging made separately for both thermal conductivity and resistance on these experiments the results do not show pure reciprocity for each material sample.

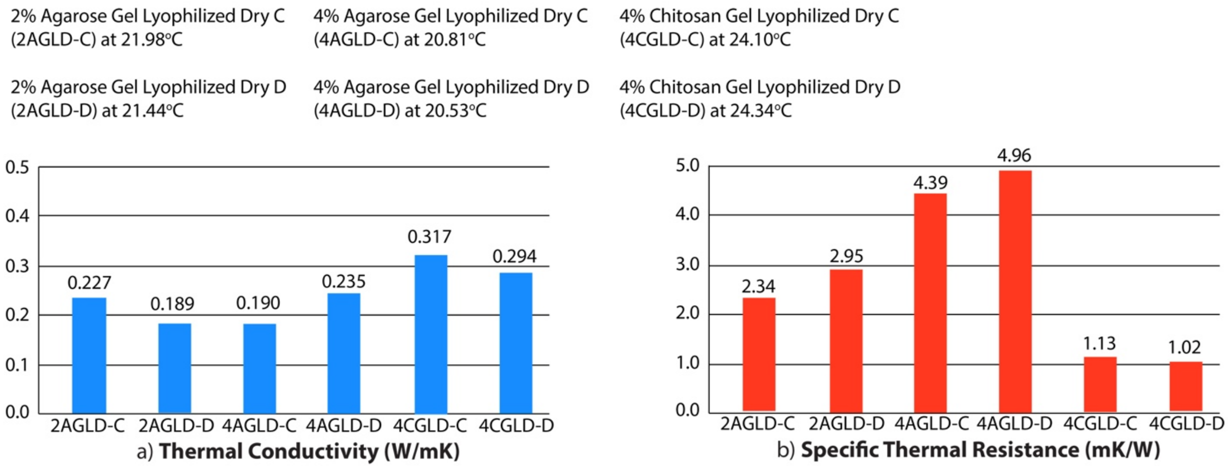

Figure 4 (a) Thermal conductivity of lyophilized hydrogel samples, and (b) specific thermal resistance of lyophilized hydrogel samples.

The thermal conductivity values range from 0.189 W/mK to 0.317 W/mK. The specific thermal resistance values range from 1.02 mK/W to 4.96 mK/W. The 4% lyophilized chitosan samples exhibit the highest conductivity, while the 4% agarose samples exhibit the highest thermal resistance.

Optical Properties. The dry lyophilized hydrogel samples were also tested for optical properties with a light transmission meter (Figure 5). All samples exhibited complete rejection of UV light, and typically around 99.7% rejection of IR light. Visible light transmission values range from 10% to 50%, dependent in part on the material thicknesses, which were not entirely consistent. The 4% lyophilized chitosan gel exhibited greater visible light transmission than the 2% lyophilized agarose gel. Both the 4% lyophilized agarose and 4% lyophilized polyacrylamide samples exhibited the lowest visible light transmission, which correlated with their denser structures and resulting opacity.

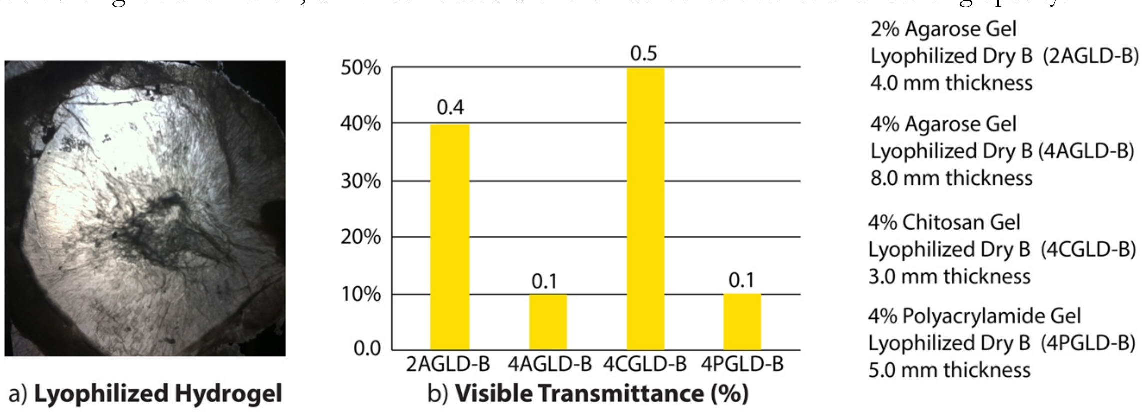

Figure 5 (a) Lyophilized agarose hydrogel with light transmission, and (b) visible transmittance values for lyophilized hydrogel samples.

DOUBLE-SKIN ENVELOPE SYSTEM DESIGN AND ANALYSIS

The thermal and optical properties of novel hydrophilic-hydrophobic composites are identified and used as inputs for simulation modeling for the dynamic enclosure system. The building enclosure system assumes a double-skin façade with the hygrothermal materials configured as daylighting control louvers in the cavity space. The introduction of a sorption coefficient for the dehumidification function provides a unique contribution to design and performance analyses of double-skin envelopes. In addition, the dynamic modeling for temporal variations of material properties also provides a new contribution to the field of building performance simulation. The modeling tools allow for unique geometry configurations of the hygrothermal embodiments in Rhino linked to Honeybee plug-in through the Grasshopper interface for energy simulation via EnergyPlus. Specific algorithms are developed for the dynamic modeling of the multivalent material properties at the interface of Honeybee and EnergyPlus. The initial results provide improvements on annual and cooling season energy loads and consumption for three comparative climate conditions (New York, Phoenix, and Miami).

Multivalent Functions

There are a number of variables to consider with the environmental performance functions of the hygrothermal louvers integrated in a double-skin façade. The base assumptions in this case include outdoor air intake at the base of each floor plate with a spandrel vent in the façade panels, and natural buoyancy driven airflow stratification through the cavity of the façade, with air entering the ceiling plenum at the top interior side of the double-skin system. While the hygrothermal louvers inside the double-skin cavity are assumed to deal with dehumidification of the humid air stream, chilled beams in the ceiling plenum are assumed to address sensible cooling for comfort conditioning with the fresh air to the adjacent interior building spaces. The heat and mass transfer functions of the double-skin envelope system with integral hygrothermal louvers are depicted in Figure 6.

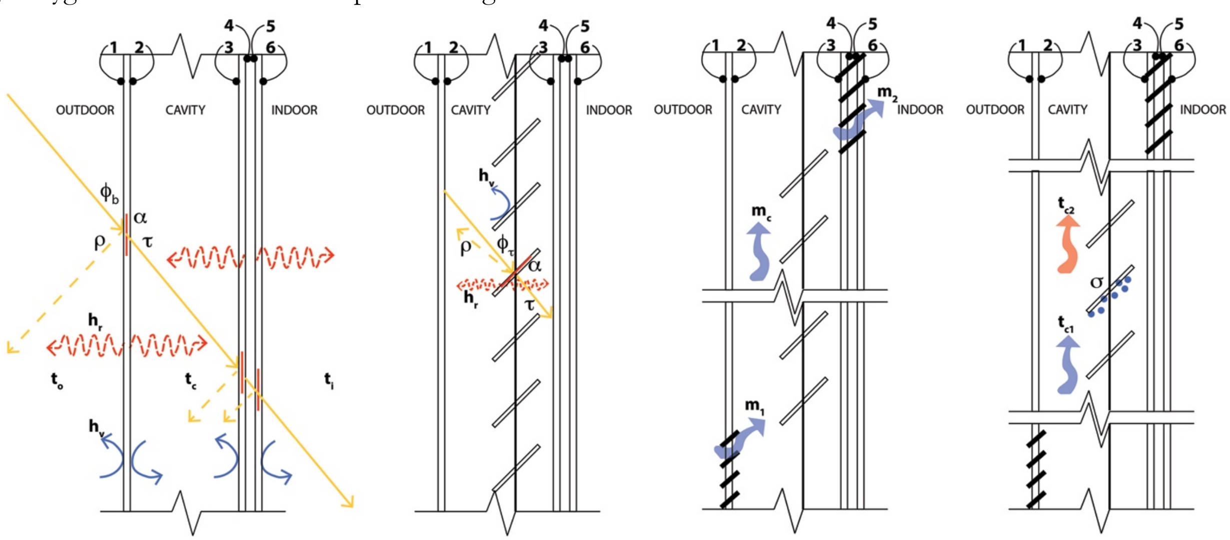

Figure 6 Double-skin envelope environmental performance values with integrated dehumidification louvers for multivalent functions.

For numerical analyses, the heat transfer variables are accounted for at every surface of the system in cross-section. These variables include outdoor, indoor, and cavity temperatures, angles of beam and transmitted radiation, absorption, transmittance, reflectance, as well as radiant and convective heat losses (Xu and Yang 2008). The mass transfer variables are accounted for within the cavity of the system for air stream across and around the hygrothermal louvers. These variables include air flow rates at inlet, cavity and outlet, air temperature gradient within the cavity, and sorption coefficient of the hydrogel louver. The sorption coefficient must be defined by empirical testing, which is taking place through humidity chamber experiments but the data is not yet publishable. Combining all of these variables together can account for the thermal performance of the double-skin façade with integrated hygrothermal louvers, but there are many complexities in the heat and mass transfer dynamics that require CFD simulations as well as validation through physical testing. Literature reviews for prior double-skin envelope system analyses show a variety of methods that might enable more accurate depiction of the heat transfer and airflow dynamics (Pappas and Zhiqizng 2008; El-Sadi et al. 2010; Shameri et al. 2011; Jiru and Haghighat 2008; Xu and Yang 2008), but none to date incorporate humidity sorption and sorption isotherms. In addition, some extrapolation of knowledge from analysis methods for desiccant flow rates and operating temperatures for effective humidity sorption functions may be applied to this double-skin envelope scenario (Koronaki et al. 2013; Awad et al. 2008; Mei et al. 1992).

In this design proposal, there are additional micro-materials integral to the hygrothermal louver functions that result in even more complexity for heat transfer and also air quality analysis. The integration of micro-encapsulated phase change materials (PCMs) in the lyophilized hydrogel matrix are intended to provide a heat sink for the latent energy from adsorption. This will stabilize the temperature of the sorption material and maintain more reasonable air temperatures in the cavity, thereby extending the length of time for humidity to be absorbed prior to regeneration cycles. The phase transition temperature for the PCMs may be tuned in the chemical synthesis for the specific climate application conditions, within the range of 26.0 ^{o}C – 32.0 ^{o}C. Modeling and numerical analysis for PCMs is quite complex, yet there are a number of research studies emerging on the topic of PCMs in exterior envelope systems (Kalnaes and Ielle 2015; Schossig et.al. 2005; Zhang et.al. 2007; Zhu et.al. 2009). The outside face of the hygrothermal louver may be coated with titanium dioxide nanometer powder combined with spectrally selective coatings for enhanced UV absorption to initiate photocatalysis of air contaminants in the cavity stream (Farhanian et al. 2013; Vohra et al. 2006; Xiao et al. 2013). Physical experiments would be required to validate this proposed air-cleaning function.

Dynamic Performance Analysis

The proposed double-skin envelope system is not a static enclosure design due to the variability of louver orientation and of environmental performance functions. For purposes of simulation analysis and initial proof of concept work, three states of the enclosure system are identified for simplification of performance variables to be used as inputs for the building simulation analyses (Figure 7). The position of the louvers is identified as either horizontal (sorption dehumidification), angled (daylighting and cooling), or vertical (regeneration).

During sorption dehumidification, the surface area exposure of the hygrothermal louver is intended to be maximized to create positive pressure zones facing the path of humid airflow. This orientation is introduced for the nighttime in combination with night-flush cooling of the façade chamber and intended for maximizing water recuperation as a resource from the humid air steam.

During daytime cycles, the louvers can be adjusted to angles to control daylight transmission, while maintaining some functions for dehumidification cooling. This configuration occurs during hours of daylight to allow for UV absorption to interact with the titanium oxide coating for photocatalytic air-cleaning processes.

The regeneration stage requires the louvers to be in vertical position for the squeeze mechanism for condensate release and drying of the lyophilized hydrogel. This cycle is shown mid-day, and can provide additional insulative thermal barrier in the envelope system once the hydrogel louvers are in a dry state. Dependent on the rate of sorption to maximum loading, additional reservation cycles may need to be introduced, but the current assumption is once per day for a two-hour period. The system integrates condensate collection with flexible PEX tubing that links in to water treatment for potable use or greywater plumbing in the building.

Normalized U-Values and Visible Transmittance Values were calculated in combination with simplified envelope glazing system simulations in LBNL's WINDOW5 program. The median from the range of values shown in Figure 7 are used in association with the timeframes shown for each system state as the input conditions for the building scale energy simulations. The author acknowledges this is an extremely simplified mode for dynamic system analysis, but provides a first step in assessing potential effectiveness of multivalent temporal functions in the building enclosure in conjunction with an identified building configuration and program type.

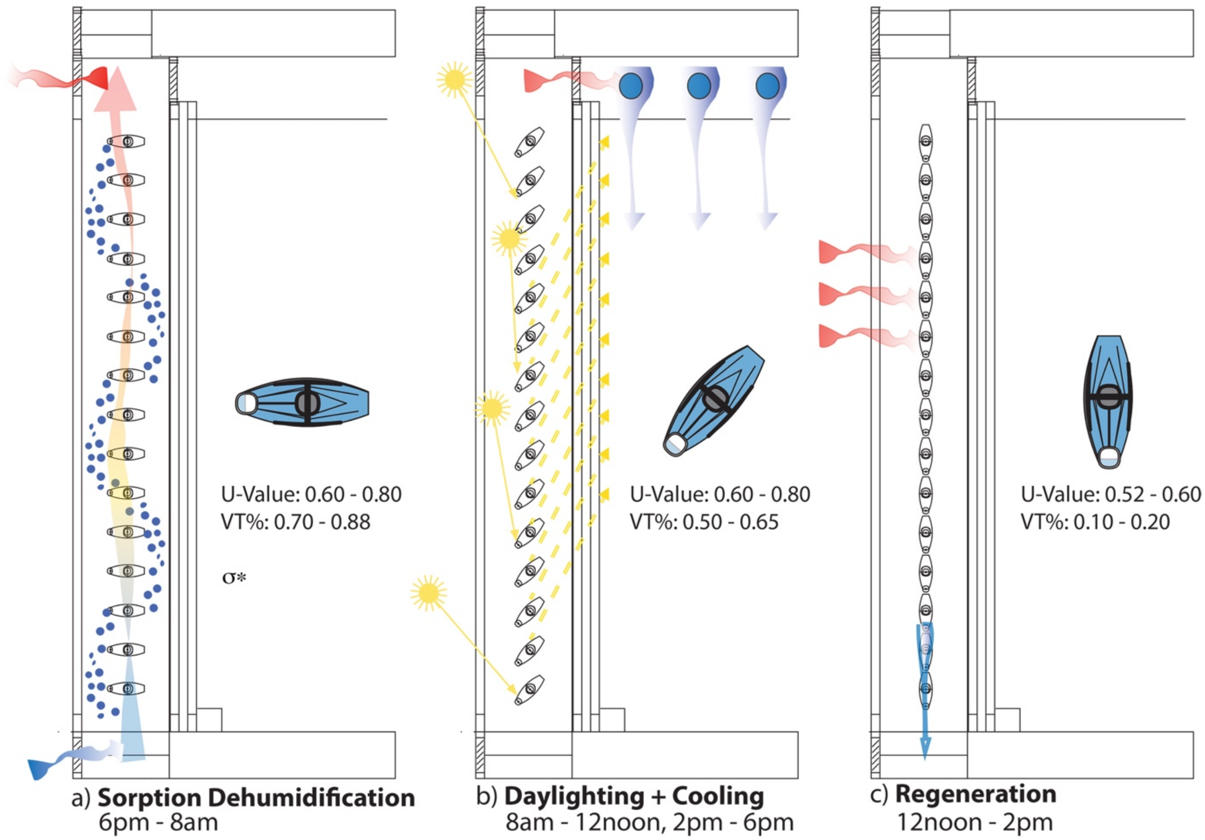

Figure 7 Double-skin envelope dynamic louver temporal performance values for system analysis: (a) sorption dehumidification stage, (b) daylighting and cooling stage, and (c) regeneration stage.

Building Energy Analysis

Climate. Initial building scale energy simulations are conducted to convey the potential effectiveness of introducing a dynamic state double-skin envelope system with integral dehumidification functions as the enclosure for commercial building program in hot-humid climate conditions. The two hot-humid climate locations used for comparison are Miami, Florida (TMYIII data) and Mumbai, India (ISHRAE data), both of which are within the ASHRAE 169 (2006) Standard Climate Zone 1 (very hot-humid). The annual temperature and humidity conditions are depicted in the psychrometric charts in Figure8a, where the majority of hours fall outside and above comfort zone temperature and relative humidity.

Base Building Design. The base building design for the energy analyses is a ten-story commercial building with plan dimensions of 32-meters by 16-meters, with the long facades facing north and south (Figure 8b). The building envelope assumes a 70% glazing to 30% wall ratio on all facades. ASHRAE 189.1 Standard for High Performance Green Buildings is followed for the basecase constructions for steel frame walls and metal roof, and for the double-skin envelope glazing system. The typical floor plan is an open office, with 'Air Wall' adjacencies designated in the EnergyPlus model for separating the five thermal zones (north, east, south, west and core). The east and west zones each have a depth of 8-meters, while the north and south perimeter zones have a depth of 7-meters each resulting in a 2-meter wide core zone. The habitable spaces are conditioned with an ideal air loads system. The office occupancy schedule assumes an 8am-6pm weekday operation throughout the year. No context is included for the building simulations so that each façade of the building is fully exposed without any shading factors.

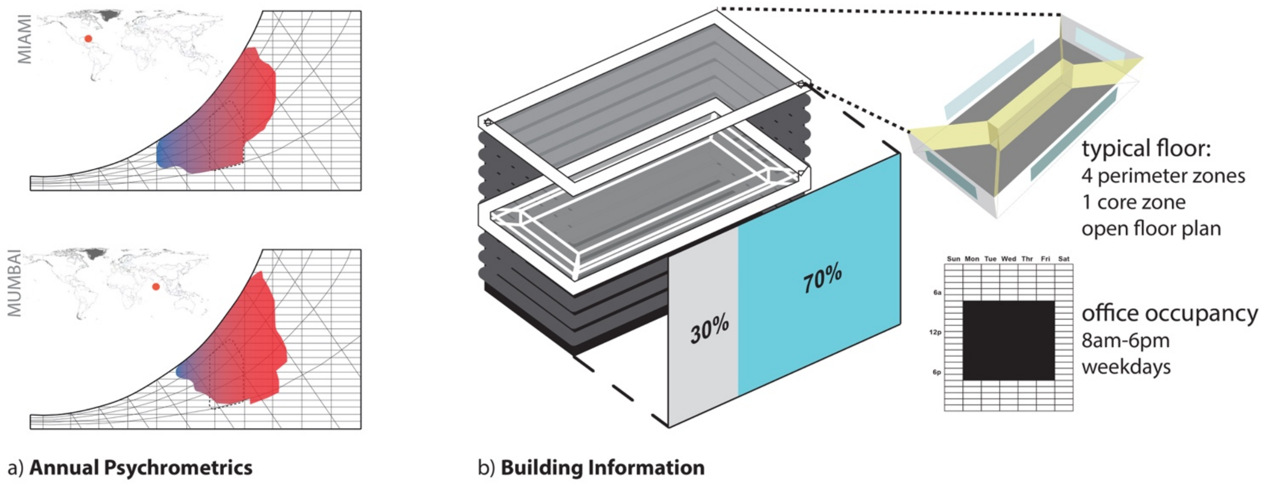

Figure 8 (a) Annual psychrometric charts for Miami and Mumbai climates, and (b) energy simulation basecase 10-story office building with 70% DSE glazing area around envelope and 5 interior zones per typical open floor plan.

Total Cooling Loads. The building simulations are performed for the basecase DSE and the DSE with hygrothermal louver system for both climates for an annual timeframe to compare cooling loads and effects of the hygrothermal louver system thermal values on envelope heat transfer dynamics. The total annual cooling loads (kWh/m^2) for both climate locations are higher in each basecase than with the hygrothermal louvers, and the east and west zones show higher cooling loads all scenarios due to sun angle direct radiation (Figure 9).

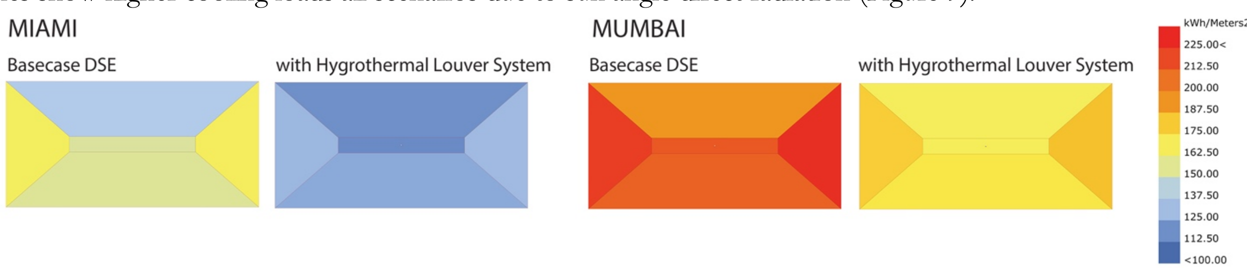

Figure 9 Total annual cooling energy loads by zone for typical floor plate of 10-story office building in Miami and Mumbai for DSE vs. DSE with hygrothermal louver system building envelopes.

Surface Energy Exchange. In the analysis for annual hourly surface energy exchange at the DSE glazing systems (Figure 10), the results graphs start at 1am of January 1st at the lower left corner and read across daily to the right ending with December 31st and by hour through the 24-hour day from bottom to top. Heat energy entering the building through the glazing is depicted by the red end of the spectrum on the legend color scale, while heat energy leaving the building through the glazing is depicted on the blue end of the spectrum. A neutral white color represents no heat energy exchange in either direction. The analysis provides annual hourly results by façade orientation, including south, west, north and east shown vertically for each building case in Figure 10. The basecase for Mumbai shows higher intensity of energy exchange into the building on the south façade from late fall through early spring in comparison with Miami because of the higher temperatures in Mumbai. However, Miami shows more consistent periods of heat energy entering both the west and east facades from spring through fall, where Mumbai has minimal energy exchange during its monsoon season around August and September. The north façade in both locations shows heat energy loss at night with neutral conditions at day throughout the year.

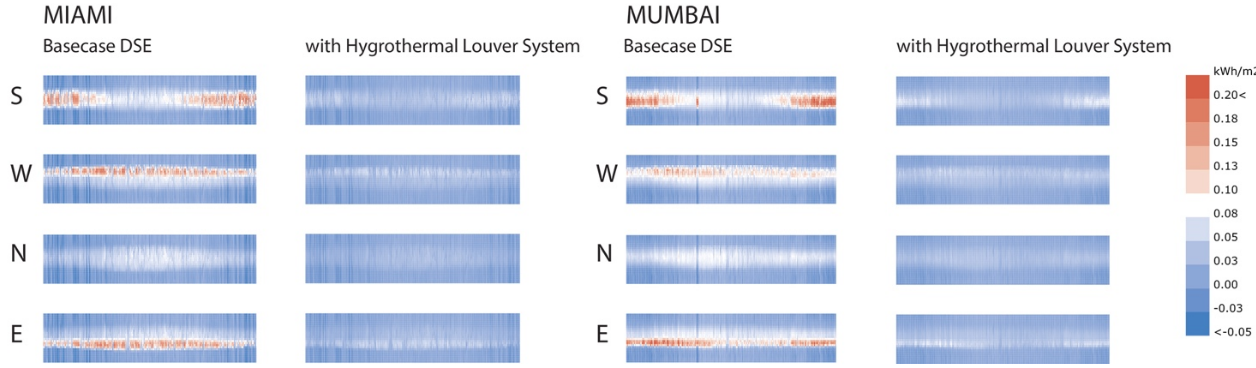

Figure 10 Annual hourly surface energy exchange of glazing systems for Miami and Mumbai comparing basecase DSE system vs. DSE with the integrated hygrothermal louvers for each façade (south, west, north and east).

The annual hourly surface energy exchange for both climate locations shifts primarily to energy losses with the introduction of the hygrothermal louvers embedded in the DSE cavity. In part, this is due to the design of the system to provide shading from direct radiation at all times on any façade. It is also partly due to the dynamic of the regeneration state set at mid-day for the louvers to be fully vertical when drying out, resulting in a higher heat resistance value with minimal radiation transmittance. In addition, the energy losses from the interior through the glazing system are partially attributed to the DSE venting states, which are open in day to the interior for fresh air intake (but might be releasing heat out) and for night flush cooling of the DSE cavity during maximum humidity sorption times.

CONCLUSIONS AND FUTURE WORK

The initial results of the DSE hygrothermal louver system provide positive direction for overall improvements on energy and water conservation in office buildings of hot-humid climates. Further development of the building simulation modeling is required to enhance the accuracy of dynamic state performance conditions with the DSE envelope in conjunction with the daylighting and ventilation modes. CFD models for the DSE cavity incorporating the hygrothermal sorption and desorption functions will ultimately be linked to the full-scale building simulation. In addition, a convergence of the identified mechanical air-handling system in the building model with the DSE hygrothermal façade and chilled ceiling beams will need to be better addressed in the EnergyPlus platform. Scale prototypes of the hygrothermal materials in louver compositions will be pilot tested in an environmental chamber with input devices (heat, light, and humidity) and data sensors for acquisition of dynamic thermal, optical, and moisture conditions. This information will be used to validate the simulation modeling.

Because of the introduction of humidity and moisture within the façade and the DSE cavity, a number of issues will need to be addressed. One of the potential drawbacks of introducing a hydrogel-based desiccant system in the building envelope includes cosorption phenomena that may lead to a limited material life due to the build-up of particulate matter in addition to regeneration cycling and UV degradation. The costs are unknown at this time, and will certainly be higher than a standard DSE façade; however, because the air-handling and cooling functions would be embedded within the DSE system, a deduction in mechanical system and duct distribution networks could be realized. Microbial studies and means to remediate microbe and mold conditions will need to be assessed based on the chemical compositions of various hydrogel louvers. Fatigue cycling tests will need to be conducted for the mechanical compression induced on the hydrogel louver during condensate release regeneration modes. While many experiments, studies, and research remain to be explored, the proposed integrated envelope system builds upon prior knowledge from both historic and contemporary examples for an innovative proposal of dehumidification cooling functions with material techniques and spatial thermodynamics in an architectural application.

ACKNOWLEDGMENTS

The author extends appreciation to the Center for Architecture, Science, and Ecology (CASE) of Rensselaer Polytechnic Institute, where this field of inquiry was established through her doctorate program under Director Anna Dyson and Associate Director Jason Vollen. The material studies presented in this paper would not have been possible without support from the National Science Foundation EAGER award (1650671) and collaborator Professor Pierre Lucas (University of Arizona Material Science Engineering) as well as graduate student Derek Runge.

NOMENCLATURE

t_o = Temperature Outdoor
t_c = Temperature Cavity
t_i = Temperature Indoor
ϕ_b = Angle of beam radiation
ϕ_τ = Angle of transmitted radiation
α = Absorption
τ = Transmittance
ρ = Reflectance
h_r = Heat loss Radiant
h_v = Heat loss Convective
m_1 = Air flow rate, Inlet
m_2 = Air flow rate, Inlet
m_c = Air flow rate, Inlet
σ = Sorption Coefficient, hydrogel
t_{c1} = Temperature Cavity after Inlet
t_{c2} = Temperature Cavity before Outlet

Subscripts

o = outdoor
i = indoor
b = beam radiation
τ = transmitted radiation
r = radiant
v = convective
1 = Inlet
2 = Outlet
c = Cavity

REFERENCES

Awad, M.M., Ramzy, A., Hamed, A.M. and Bekheit, M.M. 2008. Theoretical and experimental investigation on the radial flow desiccant dehumidification bed. *Applied Thermal Engineering* 28: 75-85.

Borzacchiello, A. and Ambrosio, L. 2009. Structure-Property Relationships in Hydrogels. *Hydrogels,* ed. R. Barbucci. Milan, Italy: Springer.

El-Sadi, H., Fariborz, H. and Fallahi, A. 2010. CFD Analysis of Turbulent Ventilation in Double-Skin Façade: Thermal Mass and Energy Efficiency. *Journal of Energy Engineering* 136: 68-75.

Farhanian, D., Haghighat, F., Lee, C.S. and Lakdawala, N. 2013. Impact of design parameters on the performance of ultraviolet photocatalytic oxidation air cleaner. *Building and Environment* 66: 148-57.

Flory, P.J. and Rehner, J. 1943. Statistical Mechanics of Cross-Linked Polymer Networks: II. Swelling. *Journal of Chemical Physics* 11: 521-26.

Givoni, B. 1994. *Passive and Low Energy Cooling of Buildings*. New York, NY: Nostrand Reinhold.

Gonzalez, J.C., Molina-Sabio, M. and Rodriguez-Reinoso, F. 2001. Sepiolite-based adsorbents as humidity controller. *Applied Clay Science* 20 (3): 111-18.

Harriman, L. and Lstiburek, J. 2009. *ASHRAE Guide for Building Design in Hot and Humid Climates*. Atlanta, GA: ASHRAE Inc.

Ingels, M. 1952. *Willis Haviland Carrier: Father of Air Conditioning.* New York, NY: Doubleday & Co., Inc.

Jarzombek, M. 2005. Haacke's Condensation Cube. *Thresholds 30: Microcosms* Summer: 99-103.

Jeong, J.W., Mumma, S.A., and Bahnfleth, W.P. 2003. Energy conservation benefits of a dedicated outdoor air system with parallel sensible cooling by ceiling radiant panels. *ASHRAE Transactions* 109: 627-36.

Jiru, T.E. and Haghighat, F. 2008. Modeling ventilated double skin façade – A zonal approach. *Energy and Buildings* 40: 1567-76.

Kalnæs, S.E. and Jelle, B.P. 2015. Phase change materials and products for building applications: A state-of-the-art review and future research opportunities. *Energy and Buildings* 94: 150–76.

Koronaki, I.P., Christodoulaki, R.I., Papaefthimiou, V.D. and Rogdakis, E.D. 2013. Thermodynamic analysis of a counter flow dehumidifier with different liquid desiccant materials. *Applied Thermal Engineering* 50: 361-73.

limeagency.org. Jan. 2011: accessed Jul. 8, 2013. Lime Agency for Sustainable Hot/Humid Design. http://www.limeagency.org/lime-agency/Lime_Agency_Home.html.

Mathiowitz E., Jacob, J.S., Jong, Y.S., Hekal, T.M., Spano, W., Guemonprez, R., Klibanov, A.M., and Langer, R. 2001. Novel desiccants based on designed polymeric blends. *Journal of Applied Polymer Science* 80 (3): 317-27.

Mei, V.C., Chen, F.C., Lavan, Z., Collier, R.K. and Meckler, G. 1992. *An Assessment of Desiccant Cooling and Dehumidification Technology.* Oak Ridge, TN: Oak Ridge National Laboratory.

Omidian , H. and Park, K. 1994. Introduction to Hydrogels. *Hydrogels and Biodegradable Polymers,* eds. R. Ottenbrite, S. Huang, and K. Park. Washington, D.C.: American Chemical Society.

Pappas, A. and Zhiqiang, Z. 2008. Numerical investigation on thermal performance and correlations of double skin façade with buoyancy-driven airflow. *Energy and Buildings* 40: 466-75.

Schossig, P., Henning, H.M., Gschwander, S. and Haussmann, T. 2005. Microencapsulated phase-change materials integrated into construction materials. *Solar Energy Materials and Solar Cells* 89: 297–306.

Shameri, M.A., Alghoul, M.A., Sopian, K., Fauzi, M., Zain, M. and Elayeb, O. 2011. Perspectives of double skin façade systems in buildings and energy saving. *Renewable and Sustainable Energy Reviews* 15: 1468-75.

Vohra, A., Goswami, D.Y., Deshpande, D.A. and Block, S.S. 2006. Enhanced photocatalytic disinfection of indoor air. *Applied Catalysis B: Environmental* 65: 57-65

Xiao, G., Huang, A., Su, H. And Tan, T. 2013. The activity of acrylic-silicon/nano-TiO2 films for the visible-light degradation of formaldehyde and NO2. *Building and Environment* 65: 215-21.

Xu, X. and Yang, Z. 2008. Natural ventilation in the double skin façade with venetian blind. *Energy and Buildings* 40: 1498-1504.

Zhang, Y., Zhou, G., Lin, K., Zhang, Q. and Di, H. 2007. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. *Building and Environment* 42: 2197–2209.

Zhu, N., Ma, Z. and Wang, S. 2009. Dynamic characteristics and energy performance of buildings using phase change materials: a review. *Energy Conservation and Management* 50: 3169–81.