Multivalent Analysis of Double-Skin Envelope Dynamic Hygrothermal Louver System

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ABSTRACT

This research introduces a novel lyophilized hydrogel for double-skin envelope (DSE) integration as a dynamic louver system to provide dehumidification of moisture, daylighting modulation, and recuperation of water condensate. The work links empirical experiments for thermal, optical, and sorption properties of the hygrothermal materials alongside system scale analytical models to inform energy and water conservation measures. The system scale analyses are conducted with LBNL WINDOW7 in combination with numerical analytical models, in addition to select computational fluid dynamic (CFD) studies for development of louver geometries to optimize sorption effectiveness in the DSE cavity air-stream.

Effective heat transfer and visible transmittance values for the dynamic states of the DSE hygrothermal louver system are then linked to building scale analyses in the Rhino-Grasshopper platform using the Honeybee plug-in to run EnergyPlus. The dynamic state envelope system is assessed through annual integration modeling for hot-humid climate conditions. The work introduces new aspects in simulation modeling with integration of the standard mechanical air-handling system functions to be coupled with multi-state dynamic properties for the envelope system in building scale analyses. A sorption coefficient is identified for analytical modeling of the DSE hygrothermal louver cavity thermodynamics. The work also integrates a new calculation tool in the simulation platform for evaluating potential water recuperation from humidity sorption and condensate release functions.

Author Keywords

Responsive Facades; Building Comfort; Energy Performance; Hygrothermal; Dehumidification Cooling; Daylighting; Water Recuperation.

ACM Classification Keywords

Applied Computing – Physical Sciences and Engineering – Engineering – Computer-aided design

1 INTRODUCTION

Building designers are increasingly faced with the environmental challenges attributed to our industry. The energy consumption and carbon dioxide emissions resulting from building construction, operation and maintenance practices is often cited as accounting for almost half of total global energy use and carbon dioxide emissions. To address a necessary shift in building design towards more effective resource management, new strategies are emerging for energy and water conservation. Building technologies are evolving to converge functions and eliminate redundancies traditionally found between building enclosure systems and mechanical heating and cooling systems [8]. This is accomplished in part by innovations in material science as well as novel conceptions for spatial conditions responsive to thermodynamics and climate variables.

The simulation methods that designers engage with are thus also in need of evolving to accommodate this convergence of functions embedded in building enclosure systems. The analysis engines for environmental performance must now incorporate new algorithms to account for the temporal dynamics of these multivalent systems and their unique time-step state changes. Modifications to assumptions for conventional mechanical system designs require customization to shift the physics of air-handling and psychrometrics primarily to material and spatial conditions of the architecture. In addition, new functions, such as water condensate collection through novel materials or air-cleaning processes, need to be added to traditional simulation platforms to inform data and phenomena about these environmental potentials.

This design research explores some of the convergent functions of a multivalent hygrothermal louver system enclosed in double-skin glazing of the building envelope. Simulation techniques are modified and adapted to facilitate the analysis of the proposed system. Selective aspects of the research project are presented here, including multi-state dynamic envelope properties for the building simulation and introduction of a water recuperation calculation tool integrated in the simulation platform.

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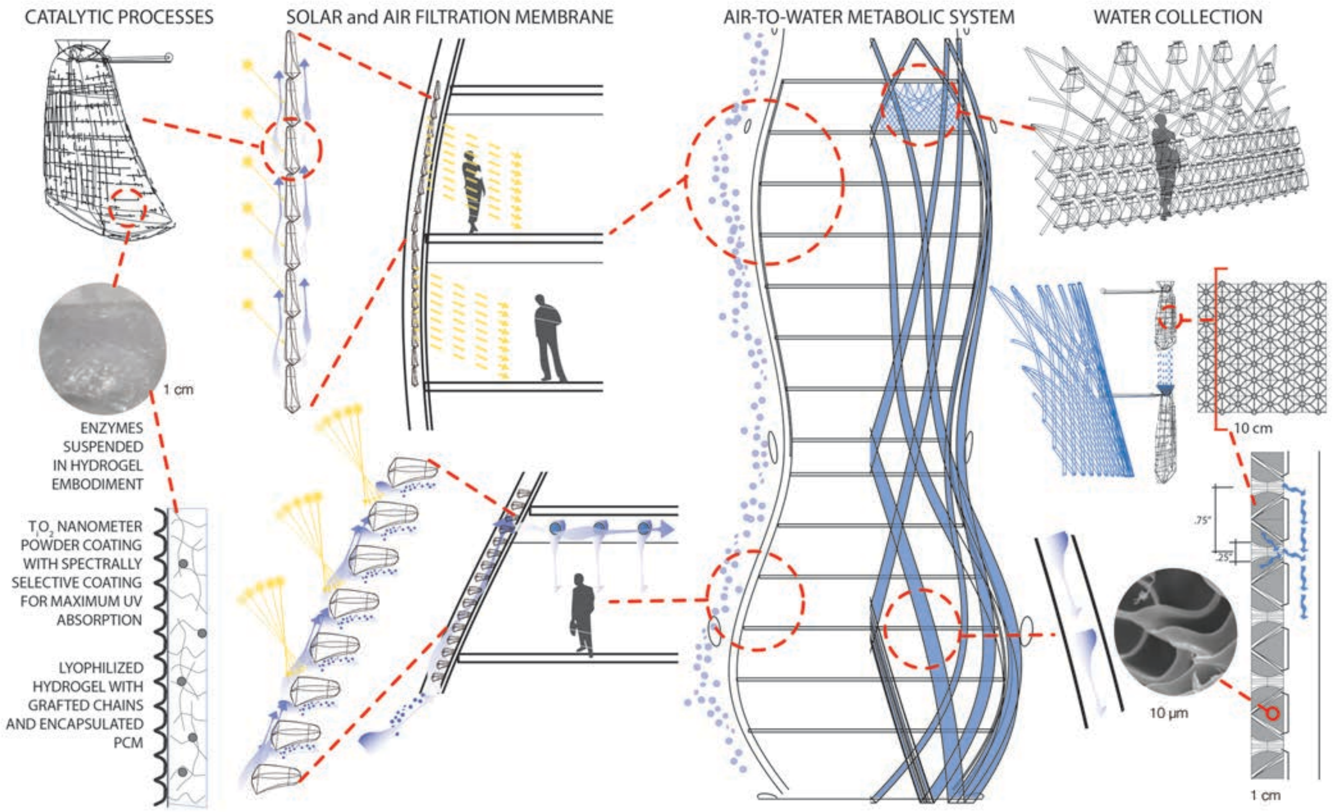

Figure 1. Multivalent double-skin envelope dynamic hygrothermal louver for dehumidification cooling, daylighting, air-cleaning, building enclosure thermal management, and water recuperation.

2 DSE HYGROTHERMAL LOUVER SYSTEM

The proposed double-skin envelope (DSE) louver system is developed around a concept for multivalent functions embedded in the thermodynamic and chemical processes of the building enclosure (Figure 1). The proposed system expands on existing knowledge of double-skin envelopes with the introduction of novel materials and form for the louvers in place of standard integrated solar blinds. The concept also addresses knowledge regarding the performance advantages of dedicated outdoor air systems (DOAS) for ventilative cooling, providing up to 42% energy savings when combined with chilled ceiling panels in comparison with conventional variable air volume (VAV) systems [4]. With an appropriate building configuration and space planning layout, centralized mechanical cooling system could be eliminated in exchange for the distributed perimeter climate control and continuous ventilation through the façade DSE cavity. The system is conceived effective for hot-humid climate conditions, and has the potential for variation in thermal control to allow for application in mixed climates.

2.1 Hygrothermal Material

The louver module is comprised of a novel hydrophilic material that is capable of effectively capturing humidity from the airstream. The material is comprised of a hydrogel that is freeze-dried to create a superporous foam network, which can be mechanically compressed to extract water condensate when saturated. The hydrogel chemistry may be based on polyacrylamides, which have covalent bonds, or polysaccharides, which have weak bond associations. Each chemistry composition has different challenges and benefits for the proposed application that are being explored by material science collaborations.

The louver foam is functionalized for potential catalytic processes by the addition of titanium dioxide coatings to aid in cleaning the air-stream of carbon dioxides and nitrogen oxides. The louver foam may also incorporate suspended enzymes that prevent mold and biofilm development. The lyophilized hydrogel is combined with encapsulated phase-change materials (PCMs) to assist in thermal management of the material's temperature and thus prolong effective sorption periods. Iterative analysis throughout the design process ultimately resulted in a modular form for each hydrogel foam louver unit for various reasons that will be explained. The louver modules are attached to a diagrid support frame that also serves as the capillary network for water collection, and feeds into larger water collection vessels in the building system.

3 MULTIVALENT FUNCTIONS

Numerous environmental performance functions are conceived and described for the proposed DSE hygrothermal louver system. The work presented here focuses on three primary aspects including sorption dehumidification, daylighting solar control, and water recuperation.

3.1 Sorption Dehumidification

Empirical tests are conducted with lyophilized hydrogel foam samples in environmental test chambers, subjected to humidity in both horizontal and vertical orientations for airstream direction (Figure 2). The sorption rates are identified in correlation to the chamber air temperature, relative humidity conditions, and hydrogel volume and weight. Maximum loading (fully saturated foam) is identified to occur when each side of the test chambers reach equilibrium with each other in temperature and humidity.

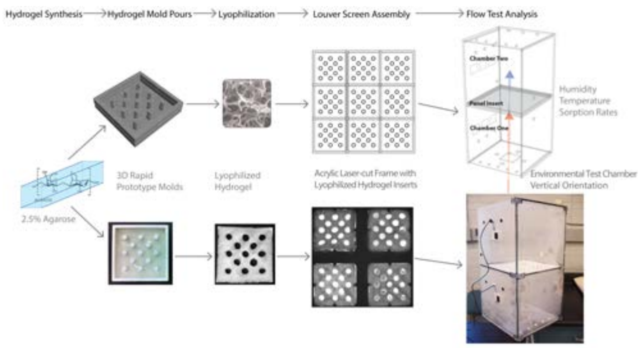

Figure 2. Empirical testing of lyophilized hydrogel foams in environmental chamber subjected to humid airstream.

Sorption coefficients are identified for different types of gels based on these experimental tests. The sorption coefficient is introduced in DSE computational fluid dynamics (CFD) and heat-air-mass (HAM) transfer numerical analyses. Based on the flow-test experiments, effective sorption is best enabled when the airstream is perpendicular to a greater surface area of the material. Development of the unique form of the foam modules is based on this understanding and simulations conducted with CFD visualization modeling to assess positive pressure zones and to maximize material volume in those areas (Figure 3).

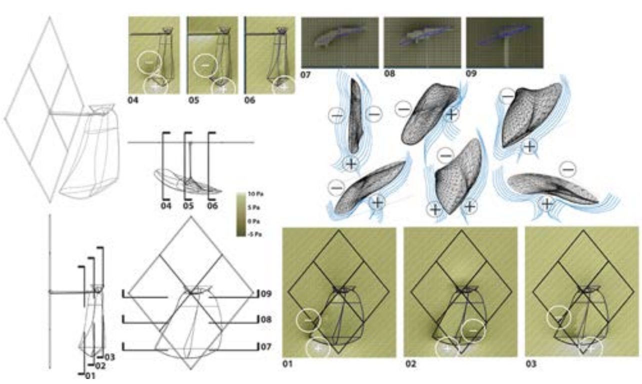

Figure 3. Louver module analysis of positive pressure zones based on active airflow patterns.

3.2 Daylighting Modulation and Solar Control

Each module is connected to the support framework with a heliotropic tracking mechanism to enable solar control by preventing direct radiation to enter habitable spaces while maintaining diffuse daylight conditions (Figure 4). The modules are designed in the Rhino 3D platform and linked to solar path data from climate files through the Grasshopper-Ladybug plug-in. The virtual tracking algorithm is set to follow the sun path based on assuming a direct normal radiation angle maintaining a constant perpendicular to the center-point of the outside face of each module.

Figure 4. Heliotropic two-axis tracking of louver modules.

3.3 Water Recuperation

Various modes for mechanically squeezing the foam modules are investigated, with some success using a surrounding mesh fabric under tension pull. The initial design proposition includes water recuperation by squeezing the modules when oriented in a vertical position and allowing water to drop into the device directly below feeding through collection tubes connected back to the support framework. Effective percentages of condensate recuperation are identified through physical tests for the various hydrogel foams, and used as input data for the material in the water collection calculation tool.

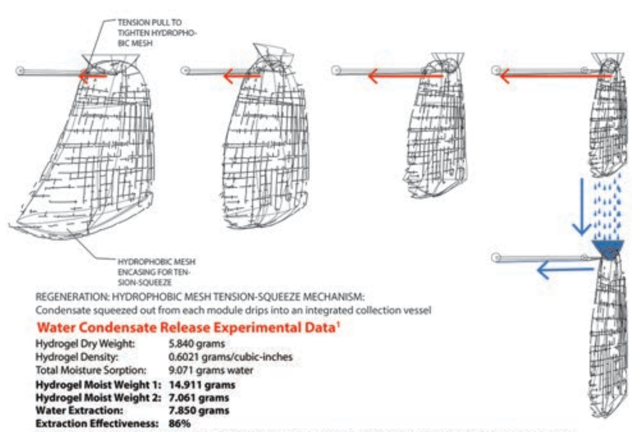

Figure 5. Water recuperation mechanical tension squeeze with hydrophobic mesh around module.

4 DSE ANALYTICAL AND SIMULATION MODELS

The proposed double-skin envelope system analysis is developed based on prior knowledge of DSE models. Most heat transfer studies focus in part on the computational fluid dynamics within the DSE cavity, especially if blinds or louvers are involved. There are some basic physics phenomena that help define the variables to be considered when analyzing the DSE integrated louver system, but a new layer of complexity is added in this scenario because of the humidity sorption function.

4.1 DSE Heat Transfer Properties Modeling

Heat transfer variables are accounted for at all surface interfaces of the DSE and louver system, as well as air temperature conditions of the outdoor, indoor, and DSE cavity (Figure 6). Angles of beam radiation and resultant absorption, transmission, and reflection must be considered at all material surfaces. In addition, both radiant and convective heat losses from material surfaces should be accounted for [11].

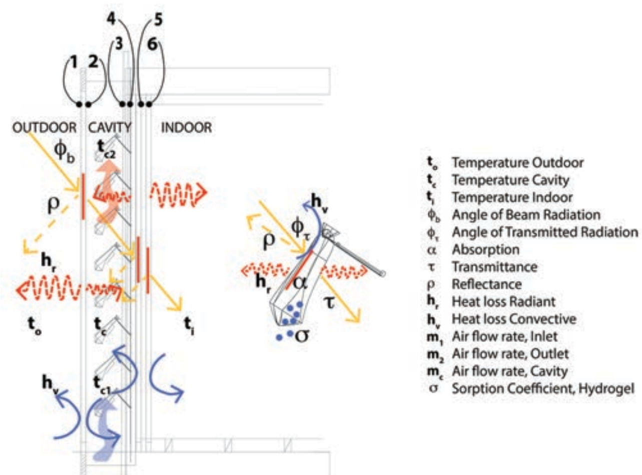

Figure 6. DSE louver analysis variables for heat, air, mass transfer.

The hygrothermal louver itself incorporates each of these phenomena, in addition to a sorption coefficient for the lyophilized hydrogel foam to address drying of the air and latent heat of sorption. There is a gradient in the air temperature within the cavity from bottom to top, resulting in higher sensible temperatures at the top of the chamber. The airstream direction is assumed to be entering at the base of the cavity and leaving at the top of the cavity (either flushed to the outdoors or drawn in to ceiling plenum spaces across chilled beams for sensible cooling to habitable rooms). In hot-humid climate conditions upwards of 70% of energy consumption is from the mechanical ventilation system of which almost 90% is a latent load [3]. The hygrothermal louvers serve in part to address these high latent loads through relatively passive desiccant functioning within the outdoor intake air-stream, thus reducing the overall energy consumption for the building.

Prior DSE Simulation Methods

The combination of all of the variables to be considered in heat, air and mass transfer of a DSE system can become very complex and typically requires physical testing for realistic results and validation of numerical analyses. Prior DSE analyses provide a range of methods that incorporate CFD two-dimensional analyses to accompany the heat transfer conditions [2, 5, 9, 10, 11]. However, none to date have incorporated humidity sorption or sorption isotherms for cavity louver functions. Some extrapolation of knowledge from desiccant mechanical equipment flow rates and operating temperatures for effective humidity sorption could be applied in this design scenario for initial proof-of-concept simulations [1, 6, 7].

4.2 DSE Dynamic States and Timeframes

Three basic states and associated diurnal timeframes are established for the dynamic functions of the DSE hygrothermal louver system (Figure 7). The first state occurs overnight from 6pm to 8am for sorption dehumidification of humid airstream and night-flush cooling of the DSE cavity (Figure 7a). The second state occurs during the morning from 8am to 12noon and in the afternoon from 2pm-6pm for dehumidification cooling fresh air intake and daylighting control by solar-tracking of the louver modules (Figure 7b). The third state occurs in the middle of the day from 12noon to 2pm when the temperature of the cavity airstream and of the hygrothermal louvers is assumed to be too high for effective sorption to occur (Figure 7c). This state allows for a regeneration cycle as the louver modules are oriented in vertical position and dried out by a mechanical squeeze function for water collection and by heat regeneration to dry.

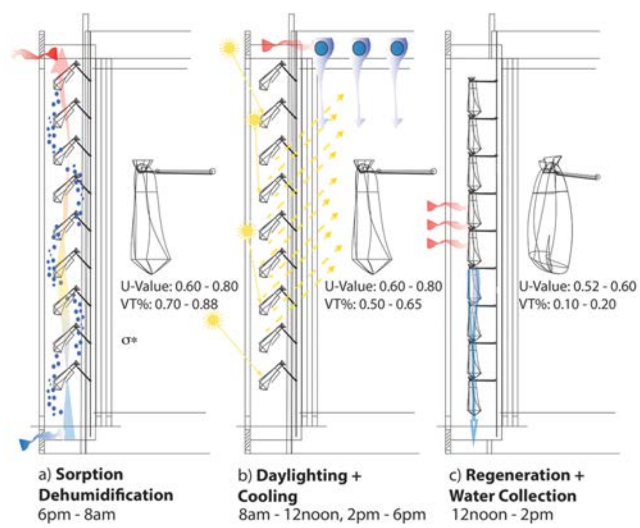

Figure 7. DSE louver system dynamic states and timeframes.

Thermal and optical values for the lyophilized hydrogel foams were collected from empirical tests and used as inputs for LBNL WINDOW7 analyses of the various DSE louver configurations. The WINDOW7 results provide both U-Values and Visible Transmittance values (Figure 7) that

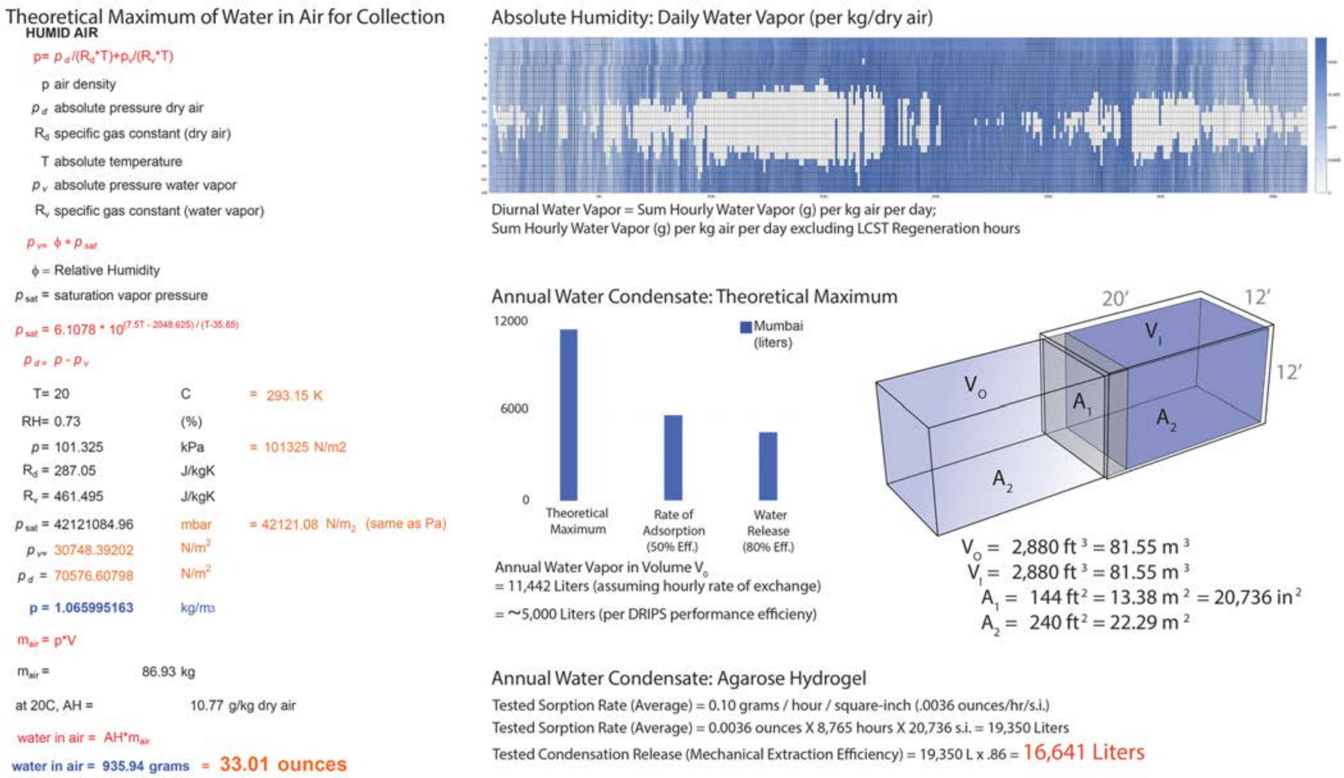

Figure 8. Water collection calculation variables and analytical methods for humidity sorption condensate recuperation.

modulate from state to state based on the thermal and optical properties of each DSE dynamic function. The output file for each state is linked to the EnergyPlus building envelope as custom material definitions with the Honeybee tools in Grasshopper.

4.3 DSE Water Recuperation Analytical Model

The potential water collection variables and methods are based on water vapor per volume of air from climate data information, and on conversion calculations from gas to liquid water (Figure 8 left and top). In order to assess the potential amount of water that can be recuperated by the hygrothermal louvers, many other variables must be identified for input values in the calculation tool. Both the sorption rates and condensate release rates of the hydrogel foam must be known (Figure 8 bottom). The given surface area of DSE louvers in humid airstream as well as timeframes for sorption and regeneration processes must also be identified (Figure 8 right and top).

In this analytical model, an assumed volume of outside air is identified as equivalent to an indoor volume served by the dehumidification cooling system. These volumes are then scaled with multipliers when a building simulation model is defined. The rates of exchange in the diurnal sorption and condensate release process are calculated on an hourly basis to align with the standard time-step in typical building simulation platforms. A sorption and condensate release percentage effectiveness can be applied in the model for conservative assumptions. The model includes a toggle option for unit conversions between Imperial and Metric systems.

5 BUILDING INTEGRATED SIMULATIONS

Integration of dynamic modeling for temporal variations of material and envelope system properties is an emerging field of building performance simulation. Existing prior dynamic envelope system analysis functions are limited to two-state conditions (i.e. electrochromic glazing with opaque and transparent states). Utilizing the Grasshopper platform for custom parametric control of the time-step functions in the Honeybee tools for the EnergyPlus simulations provide for new capabilities for simulating dynamic multi-state envelope system for more complex responsive facades and enhanced environmental performance assessment.

These modeling tools also 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 the Mumbai hot-humid climate condition.

5.1 Base Building Model Assumptions

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 hot-humid climate location used for analysis example here is Mumbai, India (ISHRAE data), which is within the ASHRAE 169 (2006) Standard Climate Zone 1 (very hot-humid). The annual temperature and humidity conditions are depicted in the psychrometric chart below (Figure9a), where the majority of hours fall outside and above comfort zone temperature and relative humidity.

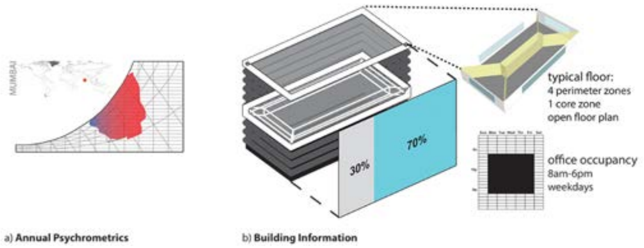

Figure 9. Building analysis basecase information and assumptions.

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 9b). The building envelope assumes a 70% glazing (basecase DSE U-value 0.89) to 30% wall (R-22) 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, metal deck and concrete floors, 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.

5.2 Building Energy Simulation Analysis Results

Building simulation results are selectively identified for specific aspects of the system performance in comparison with the basecase building. The performance values of interest presented here include cooling loads, DSE energy exchange loads, and water recuperation values.

Cooling Load Results

The building simulations are performed for the basecase DSE and the DSE with hygrothermal louver system for an annual timeframe to compare cooling loads and effects of the hygrothermal louver system thermal values on envelope heat transfer dynamics.

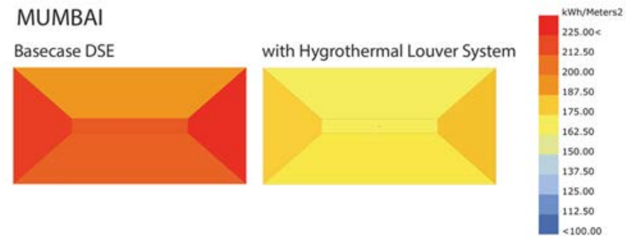

Figure 10. Annual total floor area normalized cooling energy loads.

The total annual cooling loads (kWh/m2) are higher the basecase than with the hygrothermal louvers, and the east and west zones show higher cooling loads for both scenarios due to sun angle direct radiation (Figure 10).

DSE Energy Exchange Results

In the analysis for annual hourly surface energy exchange at the DSE glazing systems (Figure 11), 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 system 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.

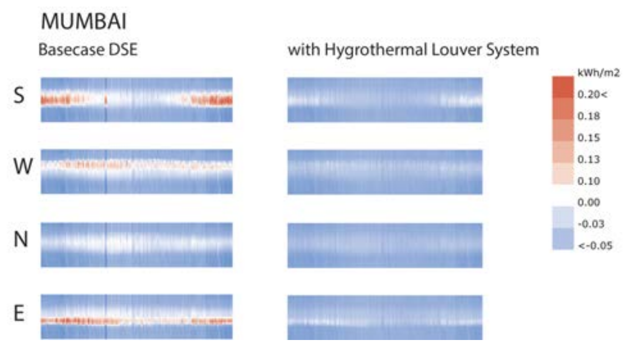

Figure 11. Annual hourly surface area normalized glazing system energy exchange loads.

The analysis provides annual hourly results by façade orientation, including south, west, north and east shown vertically for each building case in Figure 11. The basecase for Mumbai shows higher intensity of energy exchange into the building on the south façade from late fall through early spring because of the high temperatures and solar altitude angle in winter. However, Mumbai has minimal energy exchange during its monsoon season around August and September. The north façade shows heat energy loss at night with neutral conditions at day throughout the year.

The annual hourly surface energy exchange 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.

5.3 Water Recuperation Integrated Tool

The annual total water recuperation potential is calculated with the integrated tool developed by the author in the Grasshopper platform. The tool is linked directly with the absolute humidity data from the EnergyPlus Weather (EPW) file imported with the Ladybug plug-in. Input values for the variables mentioned in section 4.3 are entered manually, and the tool is linked to the building envelope definitions in the Honeybee plug-in to identify appropriate surface area and volumetric conditions.

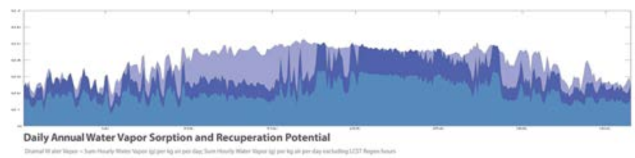

Figure 12. Annual water recuperation daily potentials from humidity sorption and condensate release.

The results can be provided in a few different formats based on what type of graphic information is desired. The example shown here is the annual hourly graph (Figure 12), which is a function available in Ladybug and is linked to the output of the water recuperation tool. Modifiers are included in the water recuperation tool for this graphic output to provide three forms of information: total water available from absolute humidity, total water available from sorption timeframes, and total water available after condensate release.

6 CONCLUSIONS

In the current work, a number of new aspects for simulation modeling are identified and developed. Interscalar modeling is conducted by linking empirically tested material data with system scale analyses to provide inputs to the building scale simulation. Dynamic states of the environmentally responsive façade are identified and used with time-step parametric tools in the building simulation platform. The need for incorporating a sorption coefficient in the analytical modeling of DSE hygrothermal louver system is identified. A new tool is developed for humidity sorption and water recuperation calculation for assessing building scale water conservation potentials.

Limitations

This paper addresses a small selection of aspects related to a complex building envelope system as a general overview of emerging areas needed in building simulation modeling. The paper does not address the details in the system design, including aspects of human interaction, maintenance and operation functions, life-cycle analysis, or costs. Limitations in the simulation techniques are mentioned throughout the paper, but include numerous areas where cross-linking and integration of interscalar simulations and multiple platforms is required.

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 study the comparison of results with standard DSE cavity blinds, and to enhance the accuracy of dynamic state performance conditions with the DSE system 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 cavity 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 to assess human interface experiences. The prototypes will also be evaluated in an environmental test 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. The future work with the physical test chamber will also provide real-time data collection that will inform machine learning algorithms as the training data sets for system optimization in response to varying climate data conditions.

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