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Modeling, Simulation and Evaluation of a Double-Sided Hydronic Layer Embedded Opaque Climate-Adaptive Building Envelope

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Abstract

A climate-adaptive opaque building envelope can significantly reduce heating and cooling energy use while improving the indoor thermal comfort. However, insufficient computational modeling and simulation techniques in modern building energy modeling tools are critical barriers to expedite the development of this emerging building technology. This paper explores an alternate modeling technique to model an opaque climate-adaptive building envelope with Modelica. As a case study, an integrated, climate-adaptive structural building energy module that consists of a double-sided hydronic heating and cooling layer embedded in a composite structural insulated panel is introduced. This paper describes energy saving potentials of the proposed systems and discusses the benefits that Modelica offers for the development of climate-adaptive building envelopes.

Introduction

A building envelope is the single largest contributor to building heating and cooling energy use. On average, the building envelope directly affects about 50% of the thermal load of a building (Sozer 2010). To be more specific, the opaque building envelope is responsible for 25% of total building energy use, which is equivalent to 10% of total U.S. primary energy use (Langevin, Harris and Renya 2019). Even though the opaque building envelope has a significant potential that not only reduces building energy use but also improves indoor environmental quality, the predominant practice for a building envelope is to isolate the building from exterior climates and neglect the beneficial synergies that could be developed by interacting with the exterior climates (Tsamis, Hwang and Borca 2020).

Recently, a new type of a building envelope that dynamically adapts to outdoor weather conditions is being developed beyond the traditional static envelope approach. More precisely, climate-adaptive building envelopes (CABEs) are actively proposed that deploy either passive or active technologies, or combine both technologies to mitigate impacts from the weather outside (Mohtashami et al. 2022). As a unique feature, this type of envelope actively regulates heat exchange between the interior and exterior environments by controlling heat conduction, convective heat transfer, and radiation exchange through building surfaces. The U.S. Department of Energy (DOE) has recently published a report that addresses state-of-the-art climate-adaptive opaque envelope technology and its significance focusing on energy saving potential with additional benefits such as comfort and well-being (DOE 2020). However, the DOE paper as well as other relevant papers also mention that most opaque building envelope technologies remain as a theoretical or conceptual model at a module-scale prototype relying on physical experiments and analytical methods as well as point out that further explorations of building integration in a feasible manner should be conducted (DOE, 2020; Antretter et al. 2019). This paper explores an alternative building energy modeling and simulation approach using Modelica for a climate-adaptive opaque building envelope with a case study introduced in this paper.

Challenges in modeling and simulation of climate-adaptive opaque building envelope technologies

Insufficient abilities in stand-alone modern building energy modeling tools to implement emerging CABE technologies and control strategies cause the delay in the development of CABEs (Favoino et al. 2018). Most evaluation methodologies of CABEs rely on numerical methods and physical experiments even though examining system performances at a building scale is significant for building and system integration. In comparison to the climate-adaptive opaque building envelope, simulation and control strategies for the transparent envelope technologies have been relatively well-established at the whole building scale with various built-in application-oriented features in modern tools, such as EnergyPlus and IES-VE (Lee, Cho and Jo 2021).

However, in the case of the opaque building technologies, a few adaptive technologies have been implemented in these modern tools. These include phase change materials (Tabares, Christensen and Bianchi 2012) and movable insulation (Antretter et al. 2019), which is suitable for a simplified model assuming only a two-stage thermal resistance value. Especially, hydronic system-based climate-adaptive opaque building technologies requiring the combination of dynamic thermal and fluid exchange cannot be supported in these stand-alone tools. Yu et al. proposed a single hydronic micro-capillary channel embedded opaque wall as an adaptive insulation technology and developed an analytical model to investigate its impacts compared to a conventional multi-layer wall (Yu et al. 2019). However, the analysis is limited to a prototype scale, a 1m x 1m panel, which is not suitable for extending to the building scale analysis. Ibrahim et al. proposed a south-north pipe-embedded closed water loop system as a thermo-activated building wall and investigated its dynamic performance at a room level (Ibrahim et al. 2017). However, both the room and proposed thermo-activated wall are developed as a numerical model because the system cannot be modeled in the modern building energy modeling tools, which do not allow users to add a building technology not pre-defined in the tools.

Emerging simulation technique using Modelica for dynamic building systems and technologies

Modelica is an equation-based object-oriented system modeling language that is emerging as a new alternative for building energy modeling and simulation to expedite the development of advanced building technologies and dynamic simulation while achieving high accuracy and flexibility (Wetter, Bonvoni and Nouidui 2016). Developing a system model in Modelica can provide many benefits, such as extensive libraries available for the conservation of mass and energy and sub-systems, a hierarchical block modeling approach that allows debugging and replacing individual blocks of the model, and a graphical diagram interface (Shultz 2018).

Modelica is currently being used for various building energy-related research areas requiring a dynamic simulation environment. For instance, at a building component scale, a triple-glazed supply-air window contributing to both heat recovery and ventilation was examined in Modelica with a simplified CFD model (Gloriant et al. 2015). At a building scale, the thermal impact of a trombe wall incorporating phase change materials on a single house was investigated in Modelica (Leang et al. 2020). At a system level, an integrated energy system based on a solar-assisted ground source heat pump was proposed and tested in Modelica (Chen et al. 2021). All these recent studies deployed the Modelica Buildings library developed by Lawrence Berkeley National Laboratory (Wetter et al. 2014) which can significantly reduce the load for developing the models with pre-constructed library components.

Modelica has also been used to develop a climate-adaptive opaque building envelope. A ceramic-based envelope module that can heat and cool water using the ambient exterior environment through precisely designed module geometries to maximize both conductive and convective heat transfer to provide pre-heated or cooled water for building radiant heating and cooling systems (Gindlesparger et al. 2018). The proposed ceramic module was implemented in Modelica with simplified thermo-fluid library components in the Modelica Standard Library and then coupled with a building model developed in EnergyPlus through a co-simulation interface to examine its energy support for the building radiant heating and cooling system (Shultz 2018).

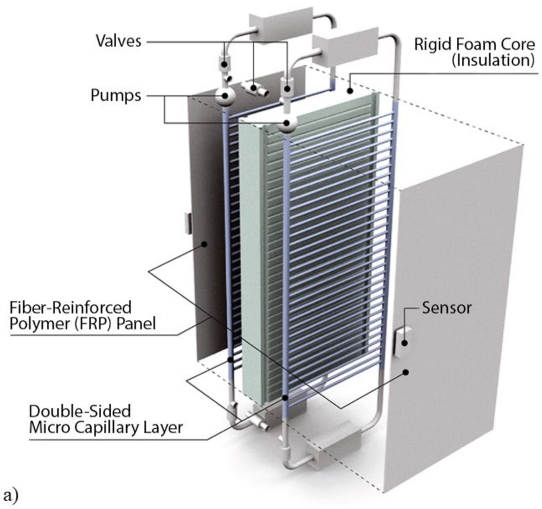
Case Study: Methodology to Model an Adaptive Opaque Building Envelope

The authors introduce the Modelica-based modeling and simulation approach with a case study, which is a hydronic-based climate-adaptive building envelope developed by the authors. The paper illustrates detailed processes of the simulation model development of the proposed fluidic-thermal adaptive system in the Modelica environment and its preliminary simulation results. The simulation focuses on surface heat flux changes depending on dynamic operational scenarios of the proposed system with different climate conditions. Also, the study describes challenges to using Modelica for building energy modeling and future research scopes to develop the proposed climate-adaptive opaque building envelope.

An integrated, climate-adaptive structural building energy module

An integrated, climate-adaptive heating and cooling structural building component, called FROG, which can be applied to various opaque building components, including wall, floor and roof, is being developed. Its concept and associated technologies were introduced previously by the authors (Tsamis, Hwang and Borca 2020). This climate-adaptive building technology aims to actively manage thermal resistance and store ambient energy simultaneously. As shown in Figure 1, FROG has a unique double-sided micro-capillary hydronic layer that is embedded in a composite structural insulated panel as a dynamic heating and cooling system.

An integrated computational module including sensors is embedded in the FROG module to monitor the changes in the indoor and outdoor environment, occupant's thermal demands, and available ambient renewable energy sources, such as solar, geothermal, or low-temperature waste heat. Monitored data is used in real-time to control the dynamic thermal behaviors of the double-sided heating and cooling layer as well as the thermal networks between the FROG modules to distribute thermal energy intelligently.



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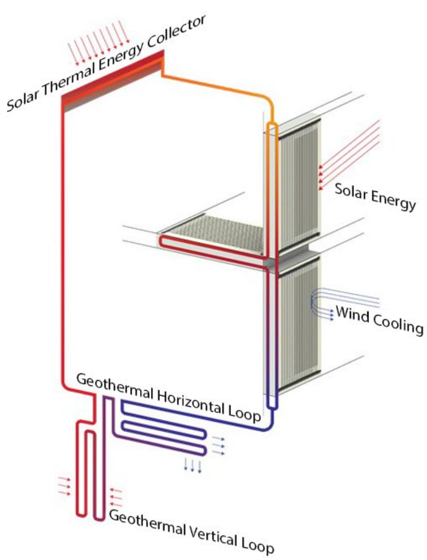

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Figure 1 (a) The FROG model and (b) thermal network of the FROG system and its target renewable energy sources

As the FROG system is based on the hydronic heating and cooling system, it can also be coupled with conventional hydronic-based renewable energy systems, including a solar thermal panel and a geothermal loop. In this paper, the model assumes that the proposed system is connected to an ideal geothermal heating and cooling loop, and the geothermal system provides heated and cooled water to the FROG module when it is needed to regulate heat exchange between the indoor and outdoor environment.

Simulation model

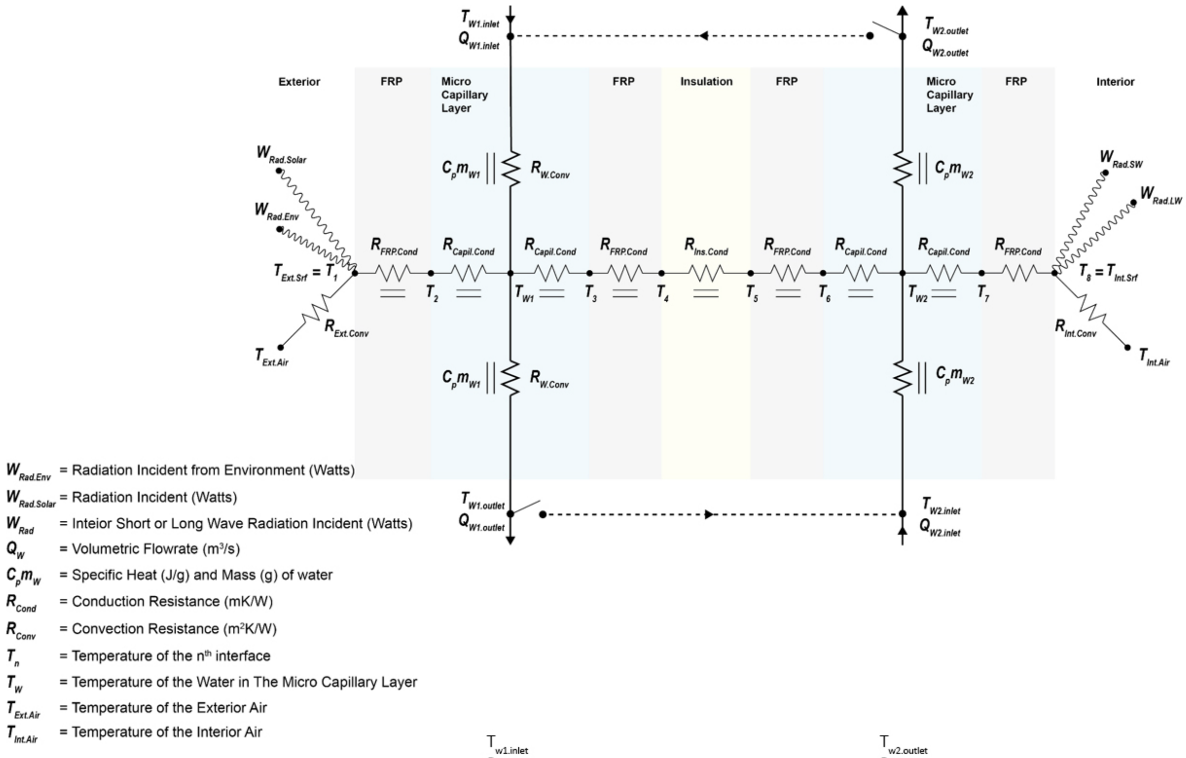
A preliminary simulation model of the FROG system is developed in Modelica. For the development of the FROG system, the Modelica Standard Library and the Buildings Library were used to present heat transfer and boundary conditions with weather data exclusively developed for building energy modeling.

In order to develop the FROG system as a block-based network model, detailed mass and energy transfer between the FROG module and climates were examined and illustrated as a thermal resistance diagram, as shown in Figure 2, to discretize the system into individual models. Each node in the resistance diagram was replaced with an appropriate individual module from the libraries mentioned above to present each phenomenon. For the double-sided micro-capillary layer, a customized Modelica model was developed. At the interior and exterior surfaces of the FROG panel, as per the boundary conditions, the heat transfer due to conduction in the FROG panel is equal to the heat transfer due to convection and that due to radiation (Equations 1 and 2).

$$W_{Cond} = W_{Int.Conv} + W_{Rad.SW} + W_{Rad.LW}$$
$$\frac{(T_{W2} - T_{Int.Srf})}{R_{Cond}} = \frac{(T_{Int.Srf} - T_{Int.Air})}{R_{Int.Conv}} + \epsilon\sigma A_{wall}(T_{Int.Srf}^4 - T_{Int.Air}^4) \quad (1)$$

$$W_{Cond} = W_{Ext.Conv} + W_{Rad.Solar} + W_{Rad.Env}$$
$$\frac{(T_{Ext.Srf} - T_{W1})}{R_{Cond}} = \frac{(T_{Ext.Air} - T_{Ext.Srf})}{R_{Ext.Conv}} + W_{Rad.Solar} + \epsilon\sigma A_{wall}(T_{Sky}^4 - T_{Ext.Srf}^4) + \epsilon\sigma A_{wall}(T_{Ext.Air}^4 - T_{Ext.Srf}^4) \quad (2)$$

In Equations 1 and 2, $T_{Int.Air}$ is the temperature of the room air, T_{ExtAir} is the temperature of the outside air, T_{Sky} is the temperature of the sky and $W_{Rad.Solar}$ is the total solar heat gain on the panel of surface area A_{wall} and emissivity ϵ. For the purpose of calculation, longwave radiation in the room is neglected ($W_{Rad.LW}$ = 0W) as the model doesn't count radiant heat exchange between indoor room surfaces and radiant heat gains from equipment. The emissivity of the panel surface is assumed to be $\epsilon = 0.8$ with southern orientation, and the convective heat transfer coefficient between the interior wall surface and the room air is assumed to be $h_{Int.Air} =$ 3.076 W/m^{2}K, which is a simplified constant natural convective coefficient (Walton 1983). This value is also



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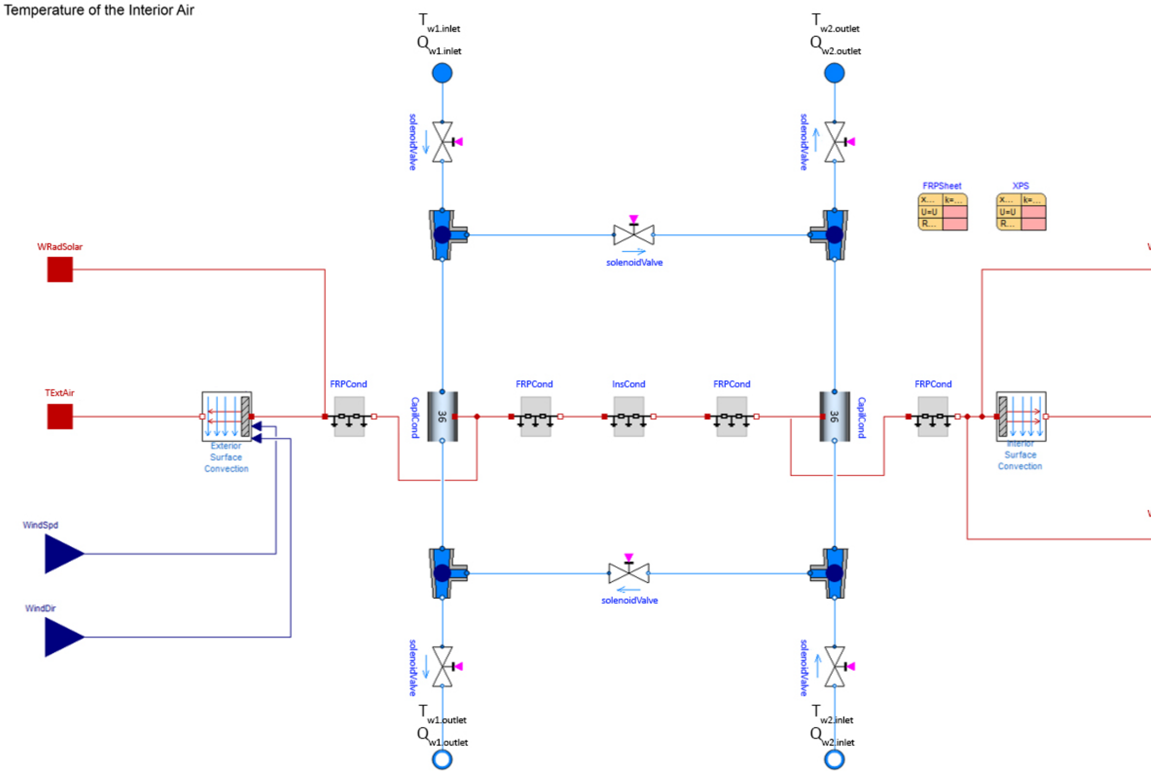

b)

Figure 2 (a) Thermal resistance diagram of the proposed system and (b) a computational module of the proposed system by using Modelica used for the simple natural convection algorithm in EnergyPlus. Similarly, at the surface of the micro-capillary, as per the boundary conditions, the heat transfer due to conduction in the thermal panel is equal to the heat transfer due to flowing water (Equations 3 and 4).

$$\frac{(T_{W1.outlet} - T_{W1.inlet})}{R_{W.Conv}} = \frac{(T_{Ext.Srf} - T_{W1})}{R_{Cond}} - \frac{(T_{W1} - T_{W2})}{R_{Int.Cond}} \quad (3)$$

$$\frac{(T_{W2.inlet} - T_{W2.outlet})}{R_{W.Conv}} = \frac{(T_{W2} - T_{Int.Srf})}{R_{Cond}} - \frac{(T_{W1} - T_{W2})}{R_{Int.Cond}} \quad (4)$$

A single micro-capillary was modeled using a one-dimensional steady-state heat conduction assuming uniform surface temperature. The water properties such as density, specific heat capacity, and the convective heat transfer coefficient remain constant while traveling through the micro-capillaries. The uniform micro-capillary wall temperatures T_{W1} and T_{W2} are defined by Equation 5.

$$T_{Wi} = \frac{T_{Wi.inlet} - T_{Wi.outlet} exp\left(\frac{h_i A_{MC_{wall}}}{\dot{m}_i c_{p_i}}\right)}{1 - exp\left(\frac{h_i A_{MC_{wall}}}{\dot{m}_i c_{p_i}}\right)} \quad (5)$$

Here, $T_{Wi.inlet}$ is the water inlet temperature, $T_{Wi.outlet}$ is the water outlet temperature, h_i is the convective heat transfer coefficient of water flowing in the micro-capillary channel, A_{MCwall} is the inner surface area of the micro-capillary channel, $\dot{m}_i$ is the mass flow rate of water and c_{pi} is the specific heat capacity of the water. The mass flow rate of the water $\dot{m}_i$ relates to the pressure drop (ΔP) across the micro-capillary channel of length (L) and diameter (D_{in}) with Equation 6 as –

$$\Delta P = \frac{8\dot{m}^2 f L}{\pi^2 D_{in}^5 \rho} \quad (6)$$

Where, ρ is the density of the water flowing in the micro-capillary channel and f is the Darcy friction factor. In a system with multiple micro-capillary channels, the total heat transfer rate can be obtained by multiplying the heat transfer rate of the single micro-capillary with the number of micro-capillary channels (n), i.e., $\dot{Q}_{tot} = \dot{m}\, c_p\, n\, (T_{inlet} - T_{outlet})$.

Table 2 Characteristics of the FROG module

Part	Value
Panel width	600 mm (23.62 in)
Panel height	900 mm (35.43 in)
Panel thickness	102 mm (4 in)
Micro-capillary inner diameter	6.4 mm (0.25 in)
Micro-capillary outer diameter	9.6 mm (0.38 in)
Micro-capillary channel length	600 mm (23.62 in)
Spacing between channels	15 mm (0.59 in)
Total number of a single channel	36 ea
Thermal conductivity of the channel material	0.6 W/Mk (0.35 Btu/ hr.ft°F)

Table 3 Material properties of the FROG module

	FRP panel	Insulation foam
Thickness (mm [in])	2 (0.08)	86 (3.38)
Thermal conductivity (W/Mk [Btu/hr.ft°F])	0.35 (0.20)	0.035 (0.02)
Specific heat capacity (J/kgK [Btu/lb°F])	1200 (0.286)	1500 (0.358)
Density (kg/m^3 [lb/ft^3])	1600 (99.88)	45 (2.80)

Table 2 shows the dimensions and material properties of the FROG module and the micro-capillary channel applied to this study, and Table 3 describes the material properties of other layers of the FROG module.

Control Logistic

The integrated computational module operates the double-sided micro-capillary layer to regulate its thermal behavior by controlling on/off solenoid valves installed in the FROG module, as illustrated in Figure 2. Air and water temperature sensors monitor distinct environments and provide data to the computer to determine whether the valves are activated or not. Depending on the valve activation, this double-sided layer is either connected to transfer heat directly from one side to the other, as heat exchange mode, or disconnected to operate individually, as an isolating (insulating) mode, as shown in Figure 3.

Due to this high operational flexibility, various climate-adaptive isolating modes can be achieved to control the indoor thermal environment depending on the relationship between the indoor and the outdoor environment. The FROG system can operate both micro-capillaries simultaneously for severely hot and cold weather for a better isolating mode. The system's thermal resistance can also be regulated by using one side of the micro-capillary upon the change of climate for efficiency.

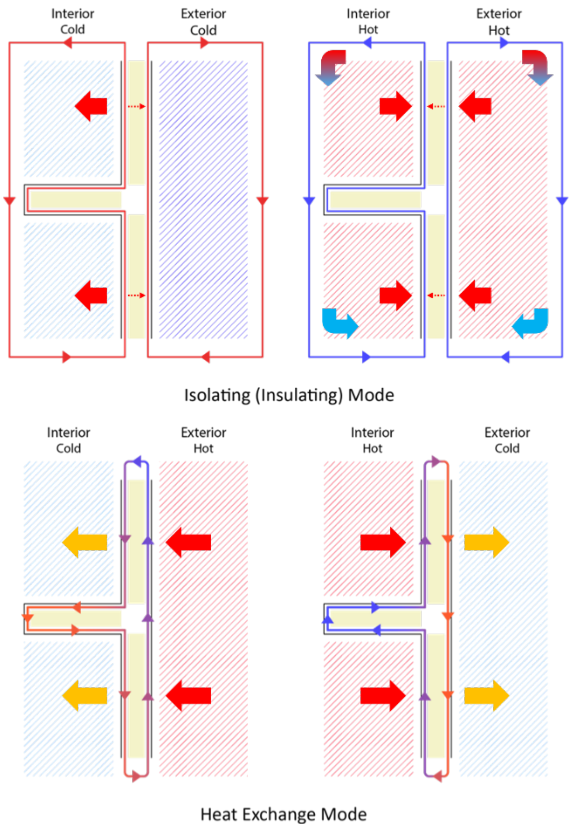

Figure 3 Climate-adaptive thermal behaviors of the proposed system

Simulation Results

As a preliminary study, this paper shows simulation results of the following two isolating modes and one heat exchange mode scenario to examine energy benefits achieved by the proposed system for various climate conditions, as shown in Figure 4:

1. Isolating mode for cooling: The indoor temperature T_{in} is 28°C (82.4°F), and the outdoor temperature T_{out} is 32°C (89.6°F), and 264 Wh/m^2 (83.69 Btu/ft^{2}hr) solar incident on the exterior surface exists; therefore, the isolating mode for cooling is required to reduce the heat flux from the panel to the room.
2. Isolating mode for heating: T_{in} is 18°C (64.4°F), and T_{out} is 0°C (32°F) without solar incident on the surface; therefore, the isolating mode for heating is required to increase the heat flux from the panel to the room.
3. Heat exchange mode: the indoor temperature is 28°C (82.4°F), and the outdoor temperature is 22°C (71.6°F) without solar incident of the surface; therefore, the heat exchange mode is required to accelerate heat transfer from the indoor to the outdoor environment.

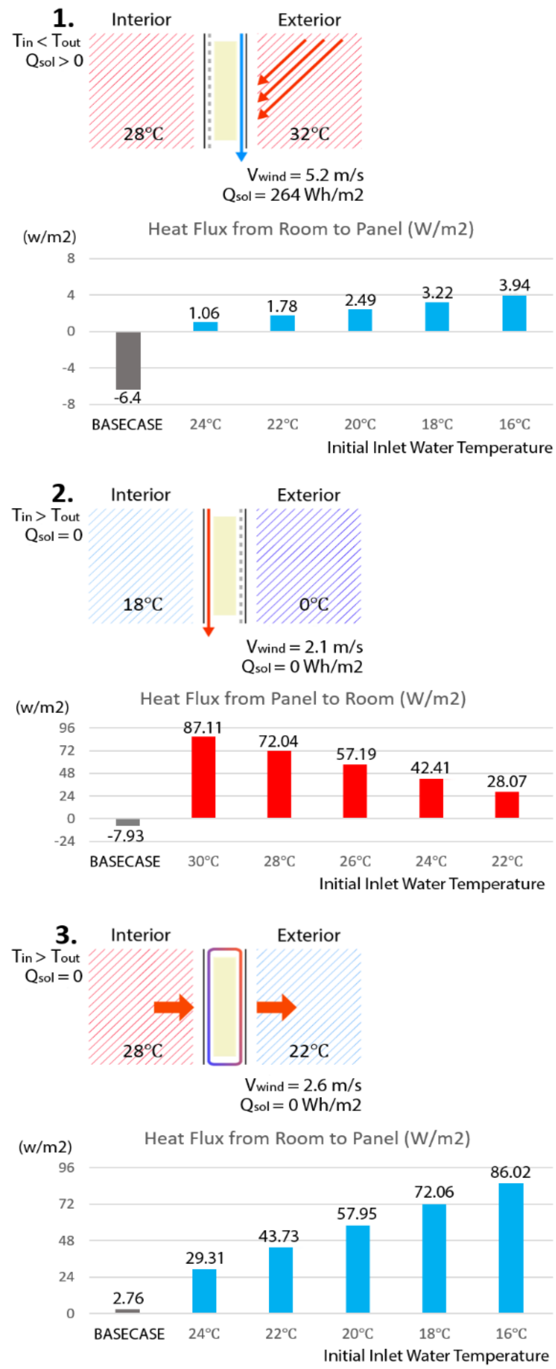

Figure 4 Simulation scenarios and results

For the purpose of simulation, the mass flow rate $\dot{m}$ was calculated and chosen to be 10^{-3}kg/s (0.0022lb/s), as it is theoretically estimated to provide the optimum heat transfer rate for the scenarios selected for this paper. The range of the inlet water temperature T_{inlet} is from 16°C (60.8°F) to 30°C (86°F) that is easily achievable from a geothermal loop and a solar thermal energy collector. Therefore, the simulation assumes that the proposed system uses geothermal energy for heating and cooling in the case of the isolating mode. As this study focuses on the development of the proposed climate-adaptive building module, energy used to circulate water through a pump and energy used for a heat exchanger coupled with the geothermal loop to achieve the target water temperature are not modeled and calculated in this study. Specific outdoor wind velocity was applied to all cases for natural convective heat transfer on the exterior surface. All tests were compared with a baseline that is a static building envelope without the proposed system.

In the first scenario, the base case result shows that the heat flows from the outdoor to the indoor space due to a temperature difference and a solar incident on the surface. However, when the outer micro-capillary layer is activated with T_{inlet} from 16°C (60.8°F) to 24°C (75.2°F), the outer micro-capillary layer offsets the thermal load from the solar energy and even provides a cooling impact to the indoor space because the system lowers the wall temperature relative to the indoor air temperature. In the second scenario, the indoor space loses heat as the outdoor temperature is 18°C (64.4°F) lower than that of the indoor space. A geothermal loop can provide low-temperature heated water to the inner micro-capillary layer for heating, and the results show that even 22°C (71.6°F) inlet water temperature, which is close to 18°C (64.4°F) indoor air temperature, can provide 28.07 W/m^2 (8.89 Btu/ft^{2}hr) heat flux to the indoor space. The last scenario shows the heat exchange performance between the indoor and outdoor spaces. This scenario can be seen on summer nights. The activation of the proposed system can dramatically accelerate heat transfer from the indoor to the outdoor space for cooling through the use of temperature differences between distinct environments solely without the consumption of any energy sources.

The simulation results for various climate conditions showed that the FROG system could dynamically adapt to the fluctuating exterior and interior environments and occupant comfort need in real-time. It can also be more energy efficient than conventional building systems because it enables maximizing the direct use of ambient low-grade renewable energy resources to thermoregulate a building.

Conclusion

This paper introduces a modeling approach using the Modelica language for a climate-adaptive opaque building envelope with a case study. This approach can be an effective method to overcome insufficient abilities in measuring the benefits of climate-adaptive opaque building envelope technologies in modern stand-alone building energy modeling tools. However, the development of a simulation model in Modelica is challenging. It requires a high level of knowledge in physics and system modeling language, that would not be suitable for most architects in the industry. Moreover, as a model developed in Modelica is a customized simulation model developed by a user, it requires rigorous validation processes. The model introduced in this paper was preliminarily validated with a numerical model developed separately and will be further validated with physical experiments in the future. Despite these challenges, it is highly valuable, especially for unprecedented dynamic building technology.

For the case study, the preliminary simulation results showed that the proposed system could work with various climates and provide heating and cooling to a building effectively. Therefore, this study showed a significant potential that the proposed envelope system could reduce the reliance on conventional heating and cooling systems, and the envelope could become a heating and cooling system itself. However, the current simulation model was developed based on a steady-state fluidic model and assumed some initial parameters as fixed values, such as the mass flow rate, interior convective coefficient, and the inlet water temperature, to simplify the initialization. Also, this study doesn't calculate the energy used for sub-equipment of the proposed system, such as a pump and a heat exchanger. In order to investigate actual energy benefits compared to a conventional heating and cooling system, these sub-models will be implemented in the model for future research. However, the current study provides the first step toward fully understanding how the proposed system can be modeled and how to measure its climate-adaptive benefits. Further, robust dynamic control logistics should be further developed for both short-term and long-term simulations.

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Nomenclature

$T_{Int.Air}$ = Temperature of the room air,

T_{ExtAir} = Temperature of the outside air,

T_{Sky} = Temperature of the sky,

A_{wall} = Surface area of the panel,

$W_{Rad.Solar}$ = Total solar heat gain on the panel of surface area A_{wall},

ϵ = Emissivity of the panel surface,

$W_{Rad.LW}$ = Longwave radiation heat on the indoor surface of the panel,

$h_{Int.Air}$ = Indoor convective heat transfer coefficient,

T_{W1} = Uniform micro-capillary left wall temperature,

T_{W2} = Uniform micro-capillary right wall temperature,

$T_{Wi.inlet}$ = Water inlet temperature,

$T_{Wi.outlet}$ = Water outlet temperature,

h_i = Convective heat transfer coefficient of water,

A_{MCwall} = Inner surface area of the micro-capillary channel,

$\dot{m}_i$ = Mass water flow rate of water,

c_{pi} = Specific heat capacity of water,

ΔP = Pressure drop across the micro-capillary channel,

L = Length of the micro-capillary channel,

D_{in} = Diameter of the micro-capillary channel,

ρ = Density of water,

f = Darcy friction factor,

$\dot{Q}_{tot}$ = Total heat transfer rate of the micro-capillary layer.

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