Retrofittable Thermal Switches for Dynamic Building Envelopes Integrated with Thermal Energy Storage

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ABSTRACT

Buildings in the United States consume about 40 quadrillion BTU of primary energy annually, which accounts for the nation's 40% of total energy use, 75% of all electricity use, and 35% of the net carbon emissions. Deploying thermal energy storage in the form of phase change material (PCM) in building envelopes is an effective method to reduce space heating/cooling loads, provide load shedding, and shift demand to periods of lower energy cost. However, the full potential of PCM-integrated envelopes can only be realized if the PCM undergoes complete phase change using free ambient heating/cooling, and the stored energy is effectively transferred between the exterior and the interior environments. Conventional thermal insulation (with a fixed thermal resistance) limits PCM utilization, particularly with the increasing emphasis on higher R-value in building envelopes, which negatively affects the energy-saving potential of a PCM-integrated envelope. In contrast, dynamic building envelopes integrated with PCMs provide the option of varying the thermal resistance based on the indoor and outdoor conditions, thereby enhancing utilization of free ambient cooling and heating to charge/discharge the PCM thermal storage, reducing the buildings' heating and cooling load, and shifting the peak energy demand. In this study, we demonstrate innovative retrofittable thermal switches in the form of the insertable plugs inside an insulation to provide variable thermal resistance depending on the operating temperature and direction of temperature gradient, thus allowing preferential directional heat flow. Notably, they are passive in nature, requiring no external power, and work solely based on the ambient temperature.

Introduction

The U.S. building sector accounts for about 40 quadrillion BTU annually, which is around 40% of the nation's total energy consumption and approximately 75% of the nation's electricity consumption (DOE 2015). Additionally, about half of energy consumption in U.S. buildings is related to space heating and cooling applications (EIA 2012, EIA 2015). Recent building codes, such as International Energy Conservation Code 2021 and California Building Standards Code Title 24, call for increased thermal insulation used in building envelopes to minimize heat loss. While increasing thermal insulation reduces the envelope-related thermal losses and thus improves the energy efficiency of the buildings (Perry 2018), it fails to provide thermal energy storage due to the small thermal mass, and therefore load flexibility potential (Wijesuriya, Booten et al. 2022). One effective method to enhance energy efficiency as well as load flexibility capacity of buildings is by using thermal storage in the form of a thin layer of phase change materials (PCMs) integrated into the building envelopes (Kosny, Kossecka et al. 2012 and Kosny, Shukla et al. 2013). PCMs, due to their phase change-related latent heat, store excess energy, typically by melting or freezing, and release stored energy when there is a shortage (Kishore, Bianchi et al. 2020 and Kishore, Booten et al. 2022). In the case of envelope-integrated thermal storage, the heat transfer between indoor and outdoor environmental conditions is crucial to melt or freeze the PCM, as required, thereby utilizing the free ambient cooling and heating to minimize the buildings' space conditioning related to HVAC load.

Conventional thermal insulation having a fixed thermal resistance creates a large thermal barrier between the exterior environment and the PCM, which is typically placed near the interior side of the envelope, thereby limiting the PCM utilization and preventing the energy-saving potential of a PCM-integrated envelope to a small percentage (Kishore, Bianchi et al. 2020, Kishore and Bianchi et al. 2021). One pragmatic solution to enhance the utilization of diurnal temperature variations for energy savings, when outdoor conditions are favorable, while maintaining the large thermal barrier when outdoor conditions are severe, is by using a dynamic envelope. A dynamic envelope employs switchable insulation material that varies the apparent thermal resistance based on the outdoor climate and indoor conditions and utilizes diurnal temperature swings effectively and controllably to charge/discharge the PCM. A few recent papers reported that switchable insulation when used in building envelopes can result in HVAC energy savings up to 42% in residential buildings (Menyhart and Krarti 2017) and up to 17% in commercial buildings (Shekar and Krarti 2017). Additionally, the dynamic envelope integrated with a thin layer of PCM can provide 15–72% reduction in wall-related annual heat gain and 7–38% reduction in wall-related annual heat loss (Kishore, Bianchi et al. 2021).

The concept of dynamic envelopes was introduced in the 1980s and 1990s by researchers like Anderlind and Johansson (Anderlind and Johansson 1983), Wallentén (Wallentén 1996), and Taylor and Imbabi (Taylor and Imbabi 1998), who proposed a breathing wall that has a controlled movement of air and moisture, providing lower wall-related thermal losses and improved indoor air quality. There were, however, a few practical difficulties in implementing the breathing walls; some of these concerns included operational complexity, increased susceptibility to air infiltration, and poorer thermal comfort of the occupants (Gan 2000). Later, the efforts in developing dynamic envelopes have been focused on simpler material or mechanical systems. Dabbagh and Krarti (Dabbagh and Krarti 2020) proposed a dynamic envelope system comprising movable fins that rotate in the wall cavity, creating and closing air gaps, as required. Depending on the angle of rotation, the thermal resistance of the dynamic envelope varies from 0.38 $m^2 \cdot K/W$ (2.16 $°F \cdot ft^2 \cdot h/BTU$) when fins are in fully open to 2.30 $m^2 \cdot K/W$ (13.1 $°F \cdot ft^2 \cdot h/BTU$) when fins are fully closed. Koenders et al. (Koenders, Loonen et al. 2018) proposed another dynamic envelope design comprising a closed loop air duct with ventilators/fans for forced convection. The thermal resistance of the building envelope changes based on the angular speed and amount of airflow in the duct. When fans are off and there is no airflow, thermal resistance of the wall is high, 5.405 $K \cdot m^2/W$ (30.7 $°F \cdot ft^2 \cdot h/BTU$); however, when the fans are turned on and airflow bypasses the central insulation layer and it allows a significant heat transfer between indoor and outdoor environment, thermal resistance of the wall reduces to 0.603 $K \cdot m^2/W$ (3.4 $°F \cdot ft^2 \cdot h/BTU$).

Previous studies have also shown that dynamic envelopes when integrated with a layer of PCM for thermal storage provide better performance than a dynamic envelope alone. This is because while the dynamic envelopes allow higher utilization of free ambient cooling or heating, PCMs provide thermal storage and allow stored energy to be used when it is needed the most. De Gracia (de Gracia 2019) proposed a dynamic building envelope integrated with a movable PCM layer, allowing its location to vary between interior and exterior side of the building envelope.

When outdoor conditions are conducive, PCM is moved toward the exterior side, thereby allowing PCM to charge (e.g., freeze in nighttime of summer or melt in daytime of winter). Later or as needed, PCM is moved toward the interior side, thereby allowing PCM to discharge using the heat transfer from the indoor air and thus reducing the thermal load of the building. Another concept of dynamic building wall with thermal storage was proposed by Iffa et al. (Iffa, Hun et al. 2022). In this case, the building wall consists of a network of embedded pipes on its interior and exterior sides and a thermal storage layer in the middle. This study was focused on the cooling load reduction; therefore, cold water from a chiller is pumped during the off-peak hours, allowing the dynamic wall to store the thermal energy when electricity price is low, or an excess of renewable energy is available. Later during the peak hours, flow through the inner pipes is used to discharge thermal storage, thereby reducing the building's HVAC energy demand for space conditioning.

To minimize the operational complexity in the dynamic wall, some recent studies have focused the attention on thermal switches. A thermal switch, analogous to an electrical switch, allows the heat flow, when the switch is "on" and stops or lessens the heat transfer when it is "off." One such thermal switch design was proposed by Miao et al. (Miao, Kishore et al. 2022), who demonstrated an voltage-actuated, shape memory alloy (SMA)-based thermal switch. The thermal switch comprises a pair of SMA wires, which are heated in alternating manner to achieve a bi-stable snap-through mechanism of a metallic beam. When one of the two SMA wires is heated, it shrinks and brings two thermal conducting plates to contact and the "on'" position is reached, permitting a high heat transfer rate. Reversibly, when the second SMA wire is heated, it disengages the two conducting plates and the "off" position is achieved, resulting in a very small heat transfer rate. This mechanism provides the thermal switch with a switch ratio of about 12 and an off-state effective thermal conductivity of 0.045 W/m·K (0.026 Btu·ft/h·ft^2·°F), which is comparable to fiberglass insulation. It was estimated that these switches in combination with a PCM layer when used in building envelopes can reduce the wall-related heating load by 9–55% and wall-related cooling load by 17–76%. Another solid-state thermal switch design for dynamic envelope was proposed by Iffa et al. (Iffa, Salonvaara et al. 2022) and Kunwar et al. (Kunwar, Salonvaara et al. 2023). The proposed solid-state thermal switch employed a direct current motor to connect and disengage two metallic U-channels placed between the insulation panels and used a concrete wall as thermal mass. By varying the thermal bridging provided by U-channels, the effective thermal resistance was noted to change from 0.18 m^2·K/W (1 ft^2 ·°F·h/BTU) to 1.23 m^2·K/W (7 ft^2·°F·h/BTU) under a switching time of less than one minute. The simulation results show that these switches can provide energy savings in the range of 980 to 2,290 kWh (3344 to 7813 kBTU) in a single-family home.

Various thermal switches designed for building envelope applications are "active" in nature, i.e., they require electric power to operate. This could be challenging considering the scale of operation in buildings and the need for repairs and replacements for a long-term application. In this paper, we describe a retrofittable thermal switch, developed at the National Renewable Energy Laboratory, which selectively opens and closes the two thermally conductive surfaces in the form of insertable plugs inside an insulation to provide variable thermal resistance depending on the operating temperature and direction of temperature gradient (Kishore, Kommandur et al. 2022). These thermal switches are constructed using readily available materials like aluminum and a temperature-based thermal actuator called wax motor. The preselected wax motor has a mean actuation temperature of ~20°C (transition range: 18-23 °C); therefore, when the operating temperature is higher than the actuation temperature, wax melts and expands, whereas when the operating temperature is less than the actuation temperature, wax solidifies and contracts. This phenomenon is utilized to connect and separate two thermally conducting surfaces, leading to thermal switching. The similar concept of paraffin-actuated thermal switches has been greatly explored for space applications (Sunada, Lankford et al. 2002, Sunada, Pauken et al. 2002). Note that the actuation temperature of wax motor used in this study was selected considering the typical indoor temperature; however, the actuation temperature or the wax motor can be changed based on the applications and use-case scenarios.

Thermal Switch Design and Operation

Figure 1 shows a schematic illustrating the operating principle of the thermal switch. It consists of two thermally conductive aluminum cylinders, concentrically aligned with an insulating polycarbonate cylinder. A thermally conductive connector made up of aluminum slides inside the three cylinders, providing the required switching mechanism. In the low conductance configuration or “off” state, the connector is positioned to only contact the upper aluminum cylinder and the polycarbonate cylinder. The path of least resistance to heat flow consists of the low thermal conductivity polycarbonate, thus resulting in an overall low conductance. In the high conductance configuration or “on” state, the connector is positioned to contact both the aluminum cylinders and the polycarbonate. The path of least resistance to heat flow in this configuration consists of the high thermal conductivity aluminum, thus resulting in an overall high conductance (Kommandur and Kishore 2022).

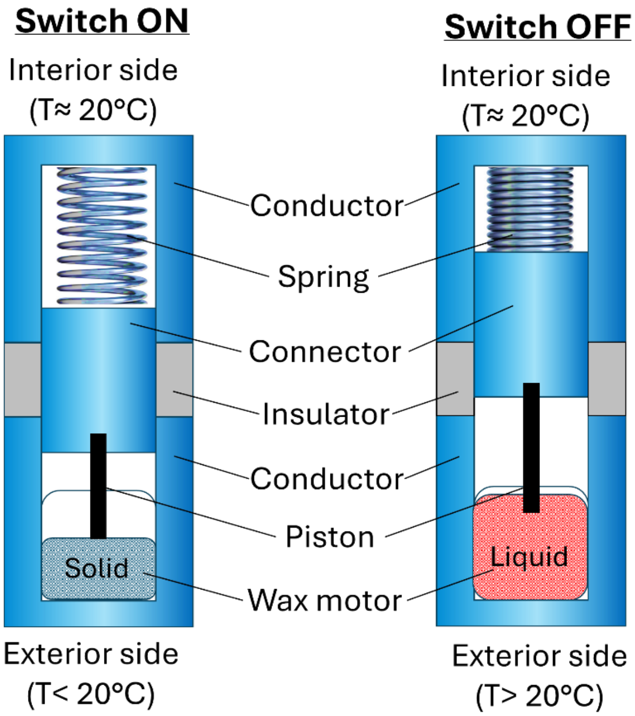

Figure 1. Schematics illustrating the operating principle of thermal switch in on- and off-states

The thermal switch shown in Figure 2**Error! Reference source not found.** is primarily designed for hot climate with large diurnal swings; however, the design can be easily modified for a cold climate. In the shown configuration, when the outdoor is cold, i.e., in the nighttime, the thermal switch shifts to the on-state, allowing free ambient cooling to transfer into the indoor environment, thereby providing passive cooling and reducing the building's air-conditioning load. In contrast, when the outdoor is hot during the daytime, the thermal switch configures to the off-state, thereby blocking the heat flow, like an insulation material. The benefits of thermal switch can be greatly enhanced if it is used in combination with a thermal storage system, e.g., a layer of PCM. As shown in Figure 2, thermal storage allows ambient cooling to be stored when it is available in the nighttime and use the stored energy during the daytime to provide passive cooling.

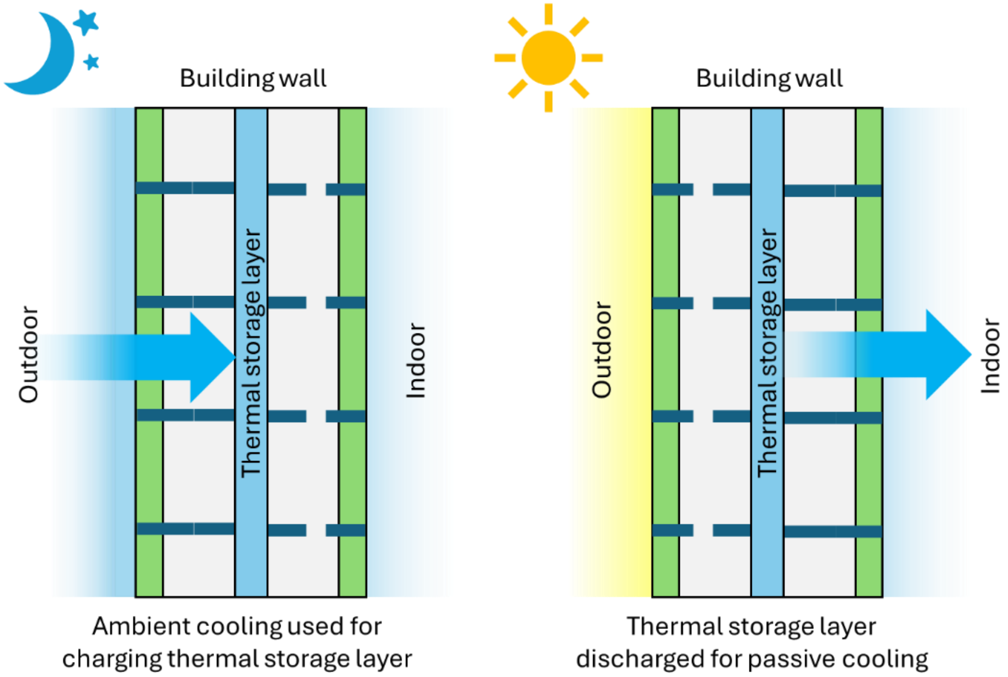

Figure 2. Operation of the thermal switches integrated with a thermal storage layer into the building wall in a hot climate

Numerical Model and Design Optimization

Model and Methods

For our design optimization and parametric study, we used a commercial finite element code, COMSOL Multiphysics. Thermal modeling is based on well-established fundamental principles of heat transfer and heat diffusion equations. Since the device is cylindrical, a two-dimensional axis-symmetric model was used to minimize computational resources. Some of the main geometrical parameters that affect the thermal switch performance are inner radius, outer radius, and connector contact length. Figure 3 shows the model geometry and all the relevant parameters used for the design optimization. Table 1 shows the range of parameters considered for parametric analysis. The height of the switch in this study is fixed to 3.0 inch (76.2 mm).

Table 1. Range of parameters considered for parametric analysis

	Range (mm) [in]
Inner radius (R_{in})	2.54 – 20.32 [0.1 – 0.8]
Outer radius (R_{out})	7.62 – 25.4 [0.3 – 1.0]
Connector contact length	1.27 – 16.51 [0.05 – 0.65]
Insulation radius	143.51 [5.65]

Modeling Assumptions

For all the simulations in this study, we considered thermal conductivity of aluminum cylinders as 238 W/m·K (137.6 BTU/h·ft·°F) and polycarbonate cylinder as 0.2 W/m·K (0.12 BTU/h·ft·°F). The insulation panel around the thermal switch was assumed to be extruded polystyrene board (XPS) board with thermal conductivity of 0.041 W/m·K (0.024 BTU/h·ft·°F). Thermal bridging because of the air and wax motor was not accounted for in the model. All simulations were performed assuming a steady state condition.

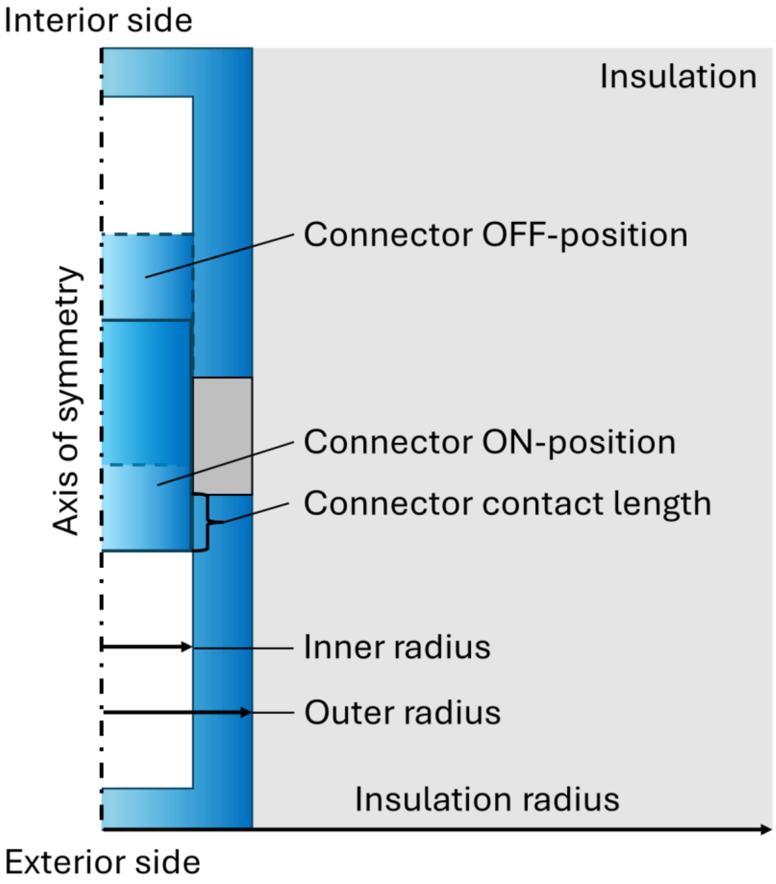

Figure 3. Two-dimensional axis-symmetric model used for design optimization and parametric analysis

Modeling Results

Figure 4 depicts the modeling results, illustrating the effective thermal conductivity in “on” and “off” states of the insulation and thermal switch integrated system. It can be noted that both “on” and “off” state effective thermal conductivity increases with an increase in the outer radius (R_{out}). This is because of the increase in the area fraction occupied by metallic conductor used in the thermal switch. Likewise, at a fixed R_{out}, increasing inner radius (R_{in}) increases the on-state thermal conductivity (k_{on}) but decreases off-state thermal conductivity (k_{off}). While higher on-state thermal conductivity is desired, higher off-state thermal conductivity leads to thermal bridging when outdoor conditions are not favorable. Therefore, we ideally like to maximize k_{on} but minimize k_{off}, which is practically challenging given the nature of the thermal switches. Additionally, with an increase in R_{out}, k_{off} increases at higher rate than k_{on}, leading to decrease in switching ratio (k_{on}/k_{off}). In this study, we selected an off-state thermal conductivity of around 0.05 W/m·K, which is achieved when R_{in}= 7.62 mm (0.3 in) and R_{out}=12.7 mm (0.5 in), providing an effective switching ratio of ~6.0.

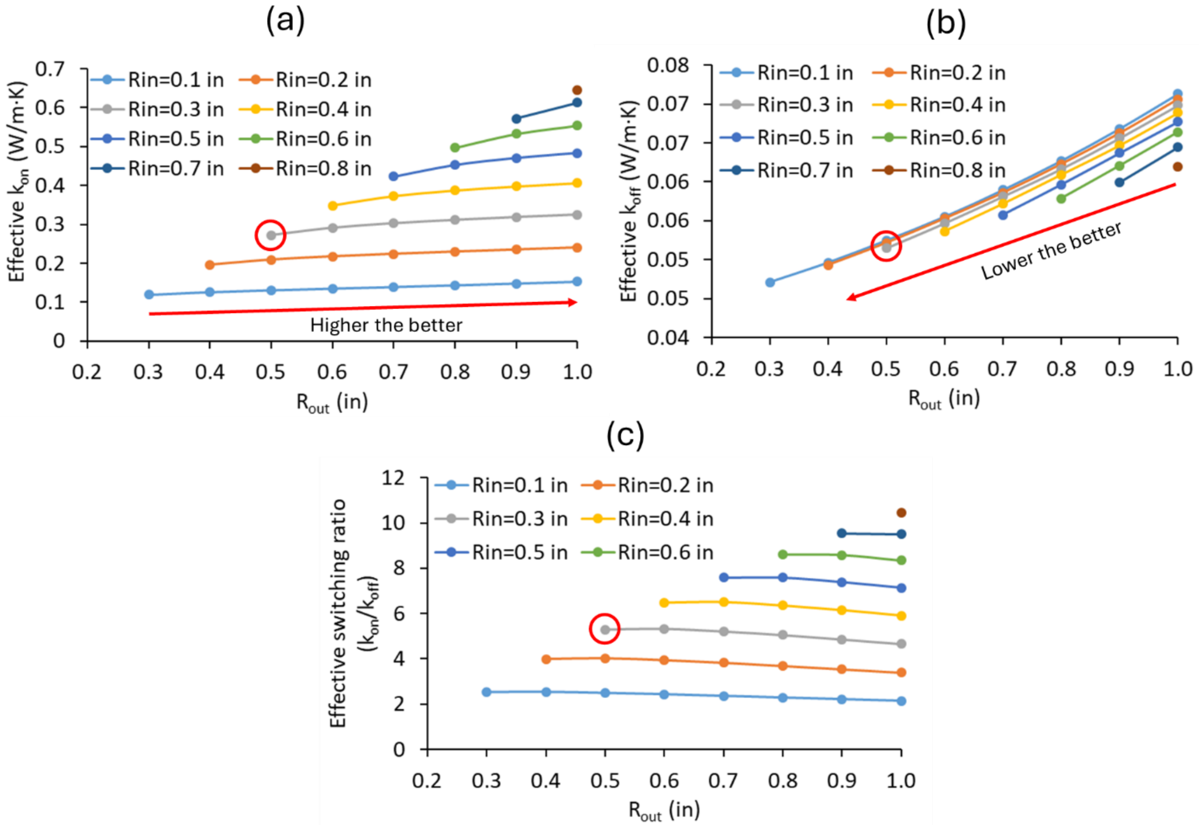

Figure 4. Effect of inner (R_{in}) and outer (R_{out}) radius (in inches) on the effective thermal conductivity in (a) on-state (b) off-state and (c) the effective switching ratio

Figure 5 shows the effect of connector contact length on the effective thermal conductivity and the effective switching ratio. Since the contact length is a parameter related to on-state configuration only, it has nearly no impact on the off-state thermal conductivity. Interestingly, k_{on} increases with an increase in the contact length first, reaches a highest value, and then reduces with further increase in the contact length. The highest k_{on} as well as switching ratio occurs when the connector contacts both lower and upper aluminum cylinders equally (contact length of 0.3 in (7.62 mm)). Compared to the optimal value, when the contact length is lower on the one side and higher on the other side, the heat transfer is lower due to less contact on one of the two sides, leading to reducing in k_{on}.

Figure 6 depicts the model and experimental results comparison using a preliminary experiment. While more details about the experiments are provided in the subsequent section, model and experimental values were noted to be in good agreement.

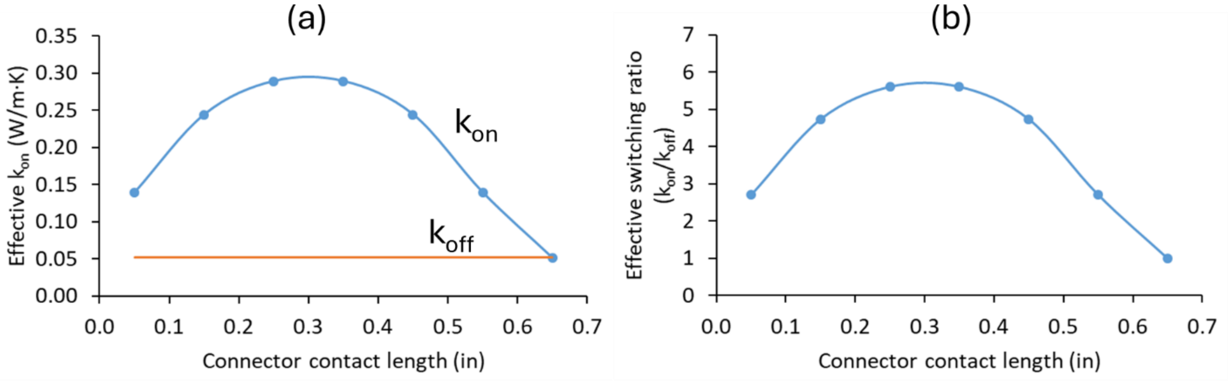

Figure 5. Effect of connector contact length (in inches) on (a) the effective thermal conductivity in “on” and “off” states and (b) the effective switching ratio

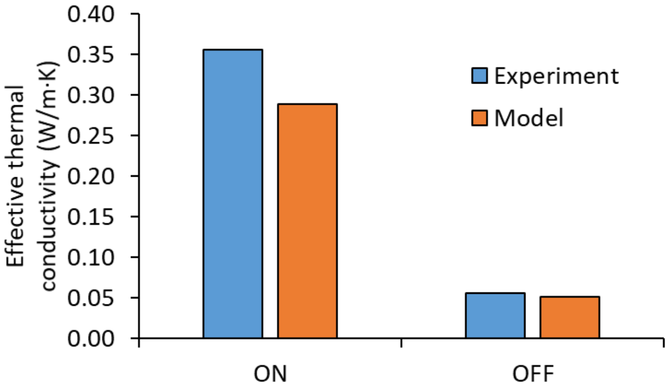

Figure 6. Comparison depicting model and experimental results for the effective thermal conductivity in “on” and “off” states

Experiments

Figure 7 shows the actual prototype, along with the “on” and “off” states of the thermal switch. As described above, the optimized thermal switch prototype is very easy to fabricate using regular machining and assemble using threaded joints. To minimize the wear and tear due to continuous movement of the connector over a long time, we used pump oil as lubricant. While long-term life cycle analysis and cyclability tests are still underway, initial results show that proper lubrication helps in reducing the mechanical contact resistances while maintaining a good thermal contact, leading to consistent performance over various operating cycles.

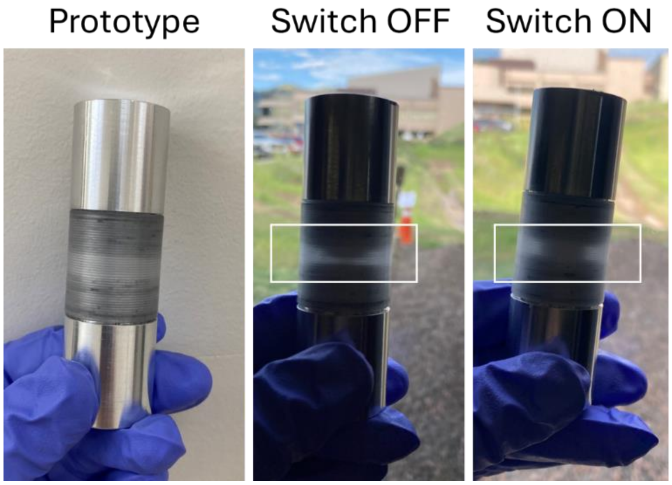

Figure 7. Actual prototype depicting the off and on states of the thermal switch

Figure 8 shows the heat flow meter test setup along with the experimental sample containing a thermal switch. To achieve the off-state configuration of the thermal switch, the two sides of the test sample were maintained at 35°C (exterior) and 20°C (interior), respectively. Likewise, to achieve the on-state configuration of the thermal switch, the two sides of the test sample were maintained at 10°C (exterior) and 20°C (interior), respectively. While the size of the insulation sample used for the test was 60.96 cm x 60.96 cm (24 in x 24 in), the measurement area was only 25.4 cm x 25.4 cm (10 in x 10 in). All the effective thermal properties reported here are for 25.4 cm x 25.4 cm (10 in x 10 in) insulation integrated with one thermal switch.

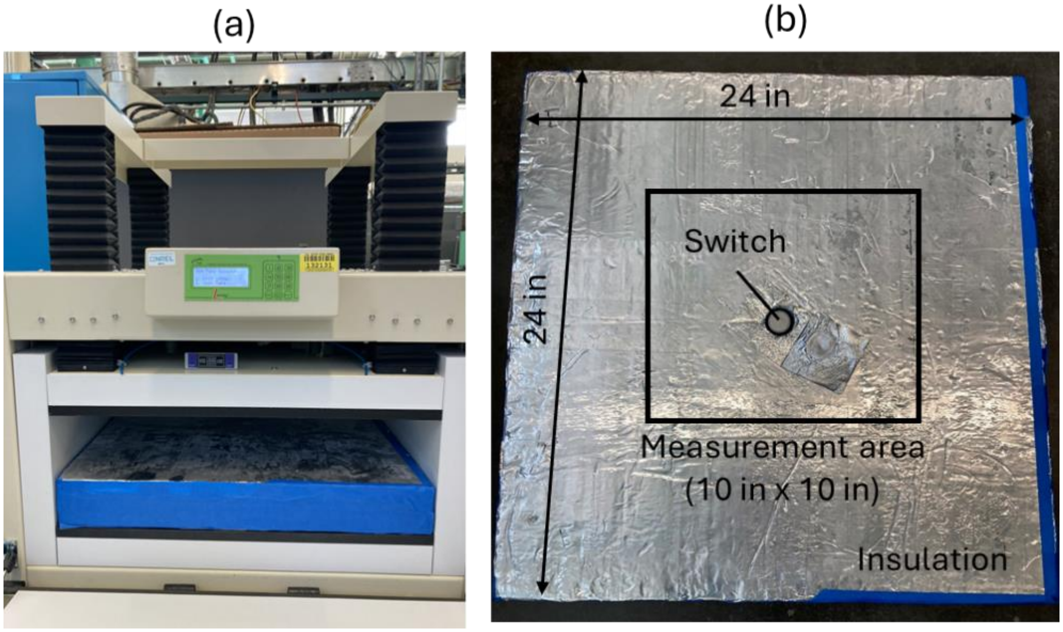

Figure 8. Heat flow meter used to assess the thermal switch operation under hot and cold climatic conditions and measure the effective thermal conductivity in “on” and “off” states

Figure 9 depicts the measured effective thermal properties of the insulation integrated with one thermal switch. The on-state thermal conductivity of ~0.350 W/m·K (0.20 BTU/h·ft·°F), off-state thermal conductivity of ~0.055 W/m·K (0.032 BTU/h·ft·°F), and switching ratio of ~6.3 were found consist over a few cycles performed. The detailed cyclability tests are being performed and will be reported in the future study.

Note that while the experiments were performed at 35°C and 10°C, the wax motor used on the current thermal switch transitions at 18-23 °C; therefore, as long as wax motor experiences the required temperature change, the on- and off-state thermal conductivities should not change. Additionally, one of the essential features of switchable insulation technologies is the activation time, which is the time required to transition between the on- and off-states. The current thermal switch, being passive in nature, is solely dependent on the available thermal gradient between the wax motor and the operating environment; therefore, its activation time is expected to be lower when higher temperature difference is available, and vice versa. None-the-less, once the wax motor reaches its transition temperature, the activation time needed to switch from off- to on-state is just a few minutes. In addition, while passive nature provides powerless operation particularly during power outage situations; it results in some limitations related to lack of user's control to manage the switch operation. The thermal switch design, however, can be modified by employing an electrically powered linear motor to enhance the controllability.

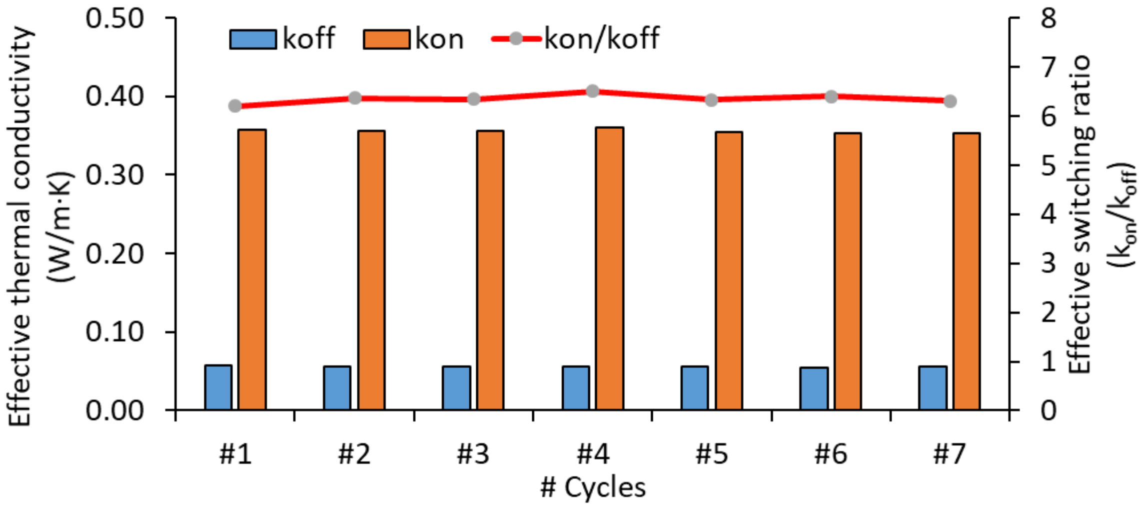

Figure 9. Measured thermal performance of the thermal switch integrated into a rigid insulation: effective on-state thermal conductivity, off-state thermal conductivity, and switching ratio

Potential Impact

Managing thermal load in the building and thus reducing HVAC-related energy bills and enhancing thermal comfort, without need for any major infrastructure upgrades or occupants' disruption, has a direct impact on buildings' decarbonization efforts particularly focused towards equity, affordability, and resilience. Innovative approaches like the retrofittable thermal switches presented in this study are crucial for thermal management in buildings, particularly due to growing mismatch between energy demand and supply as well as increasing occurrences of extreme weather events. Unpredictable power surges due to electrification and extreme weather events, like heat waves, make the power grid struggle to maintain an even supply of electricity that often lead to unplanned power outage. While such events are becoming more frequent and prolonged, they disproportionately affect vulnerable communities such as elderly populations, people with preexisting health conditions, or low-income communities living in older less insulated homes. Our thermal switches in combination with PCM-based thermal storage not only provide passive solutions for thermal management but also enhance the thermal resilience of the building envelopes, for instance, by providing cooling during nighttime and overheating protection during daytime.

The potential impact of our thermal switch technology can be realized by looking at the data reported in the prior literature. Previous studies reported that switchable envelopes, having variable resistance, can provide HVAC energy savings by up to 42% in residential buildings (Shekar and Krarti 2017) and up to 17% in commercial buildings (Menyhart and Krarti 2017). Another study demonstrated that compared to PCM-integrated static walls, PCM-integrated dynamic walls can provide up to 60% to 70% reduction in wall-related heat gain in a residential building. Increasing the switching ratio above 5, however, shows diminishing return (Kishore, Bianchi et al. 2021). Our current thermal switch exhibits an effective switching ratio of ~6, which is well within the range of the desired values. Additionally, another study on techno-economic analysis of dynamic walls shows that the payback period and the incremental cost of the technology is higher when switchable insulation occupies a lesser area fraction of the wall (Kishore, Booten et al. 2022). In the current design, the thermal switch occupies less than 1% area fraction of the total insulation (one thermal switch per 25.4 cm x 25.4 cm (10 in x 10 in) of thermal insulation), making it more economically viable technology than other similar approaches where entire insulation needs to be replaced with a switchable insulation material. More importantly, our thermal switch being passive in nature provides an efficient and cost-effective solution to achieve dynamic envelopes, which can potentially support underrepresented and disadvantaged communities by reducing their energy-related cost burdens and enhancing occupants' thermal comfort in the built environment.

Conclusions

This study presents the design, model, and experiments related to the development of an innovative thermal switch that has been targeted for retrofittable applications in building envelopes. The thermal switch can be inserted into the existing building envelopes by using very simple processes like drilling, plugging, sealing. It is passive in nature, requiring no external power, and works solely based on ambient temperature. Some of the key observations and findings of this study are summarized below.

- PCM-integrated building envelopes can reduce space heating/cooling loads and provide load shedding and shifting capacity; however, increasing insulation level in envelopes reduces PCM utilization and thus its benefits.
- Our thermal switches provide a cost-effective solution to achieve dynamic envelopes, which permit adjustable thermal resistance based on the indoor and outdoor conditions, thereby enhancing utilization of free ambient cooling and heating to charge/discharge the PCM thermal storage, and thus manage buildings' thermal load.

- Thermal switches are constructed using readily available material aluminum and a wax motor, which is utilized to connect and separate two thermally conducting surfaces, leading to thermal switching.
- Modeling as well as experimental testing demonstrates that a single switch integrated into a 100 in^2 (0.065 m^2) rigid insulation board provides an off-state effective thermal conductivity of ~0.055 W/m·K (0.032 BTU/h·ft·°F) and a switching ratio over 6.0, which is well within the desired value reported in the prior studies.

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