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To cite this article: Emishaw Iffa *et al* 2021 *J. Phys.: Conf. Ser.* **2069** 012092

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Energy performance analysis of smart wall system with switchable insulation and thermal storage capacity

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Abstract. The ever-increasing global energy demand and the issues caused by population growth and unsustainable energy resource usages have several environmental and economic impacts. The on-demand capability of dynamic wall systems with switchable insulation systems can contribute toward energy efficiency and reduced electric cost using “building-as-a-battery.” In this paper, the performance of an exterior envelope system that employs a switchable insulation system is investigated. A COMSOL simulation was used to study the envelope performance under three switchable insulation locations in the wall system. The on and off switching cycle included insulating or conducting the exterior, interior, or both sides of the mass wall system. To validate the simulation work, an experimental test was conducted in climate chamber on a 4 × 8 in. wall system with identical wall components used in the COMSOL simulation. Results show a good agreement between the experiment and simulation results. The wall system with switchable insulation placed on the exterior side provided the highest interior inward heat flux when compared with the interior or split insulation. Also, an exterior switchable insulation system in addition to a thermal mass maintained a positive heat flow for more hours when the outdoor temperature was lower than the interior temperature.

1. Introduction

The residential and commercial building sectors consume around 40% of the primary energy within the United States. Space heating and cooling loads are responsible for 35% of the energy used in buildings [1]. Gowrishankar and Levin [2] reported that energy-efficient residential buildings have the potential as the largest source of CO₂ reduction compared with commercial, industrial, and transportation sectors. According to the report, the residential building energy efficiency can account for as much as 550 million metric tons of CO₂ equivalent emissions reductions annually by 2050.

Climate-responsive buildings can have the ability to consider the building’s surroundings and local climate to behave in an energy-efficient way. One of these methods is to switch an insulation system’s thermal behavior on demand to reduce heating and cooling loads. An active area of research is the application of active (a.k.a. dynamic, smart, or switchable) insulation systems and taking advantage of buildings’ thermal mass as an energy storage system using the building-as-a-battery concept to shift peak load demand and enhance thermal comfort.

Cui and Overend [3] reviewed and classified the existing active insulation technologies. Also, they conducted an assessment of the promising switchable insulation technologies for building envelopes. In this review paper, five types of insulations are selected and discussed: active vacuum thermal insulation, mechanical contact switchable insulation, suspended-particle-based switchable insulation, pipe-

embedded switchable thermal insulation, and phase-change switchable insulation. Several recent experimental [4-6] and simulation [7-9] research works have reported the advantages of switchable insulation toward energy efficiency and peak load demand. Furthermore, some potential innovative solutions to develop effective smart insulation solutions are recommended [10-12].

A typical scenario further investigated in this study is a time in the heating season when solar radiation warms up the exterior cladding of the wall and makes the exterior surface temperature of the wall higher than the interior surface. Switching the insulation from insulating to conducting helps to reduce the heating load or can store the heating load in the building thermal storage system.

In this paper, the thermal performance of a south-facing wall equipped with switchable insulation in a mild (Zone 4A) climate zone is investigated. Weather data from the month of April were used to compute the heat flow variations between a typical wall with passive insulation and a smart wall with switchable insulation that was controlled using logic based on a comparison of the exterior wall surface temperature and indoor temperature. The spring season was selected because of the large temperature difference in the diurnal cycles, and the daily maximum and minimum temperature values are higher and lower than the indoor temperature, respectively.

2. Governing Equations

The transfer of heat through a switchable insulation by conduction can be described by the modified Fourier's equation (Equation. 1),

$$\rho_{h,l} C_{h,l} \frac{\partial T}{\partial t} = -K_{h,l} \nabla T + Q \quad (1)$$

where $\rho_{h,l}$, $C_{h,l}$ and $K_{h,l}$ are the binary values of density, heat capacity, and thermal conductivity when the material property is varied between high and low thermal resistance. T is temperature and Q is an additional heat flux source.

The net radiation at the wall surface can be calculated as (Equation. 2)

$$I = \alpha I_s + \varepsilon I_l - I_e \quad (2)$$

where I , I_s , I_l , and I_e are net radiation on the exterior wall surface, short wave radiation, long-wave radiation, and long-wave counter radiation, respectively. α and ε are short-wave radiation absorptivity and long-wave emissivity, respectively.

3. Simulation design

The simulation was designed to represent a mild climate zone of the United States and study a mass wall's thermal performance with a switchable insulation system. A simple control strategy was implemented to vary the insulation values to high and low based on the exterior wall surface and indoor temperature comparison. Based on the control strategy, the COMSOL Multiphysics 5.6 variable material property feature was used to vary the insulation's material properties (density, heat capacity, and thermal conductivity) in an hourly manner. To study the effect of the insulation location in the wall, the switchable insulation was located in three positions: exterior, interior, and in both exterior and interior sides (split insulation). The following sections discuss the weather data, control strategy, wall type, material properties, and simulation assumptions.

3.1. Weather data

As a representative of a mild climate zone, weather data of Washington Dulles International Airport from April 1 to 30 was used. The spring season was selected because it is predominantly neither a heating nor cooling season, in addition to the high diurnal cycle of outdoor temperature. The solar radiation and the outdoor temperature are shown in Figure 1. The indoor temperature was kept at 21°C throughout the study.

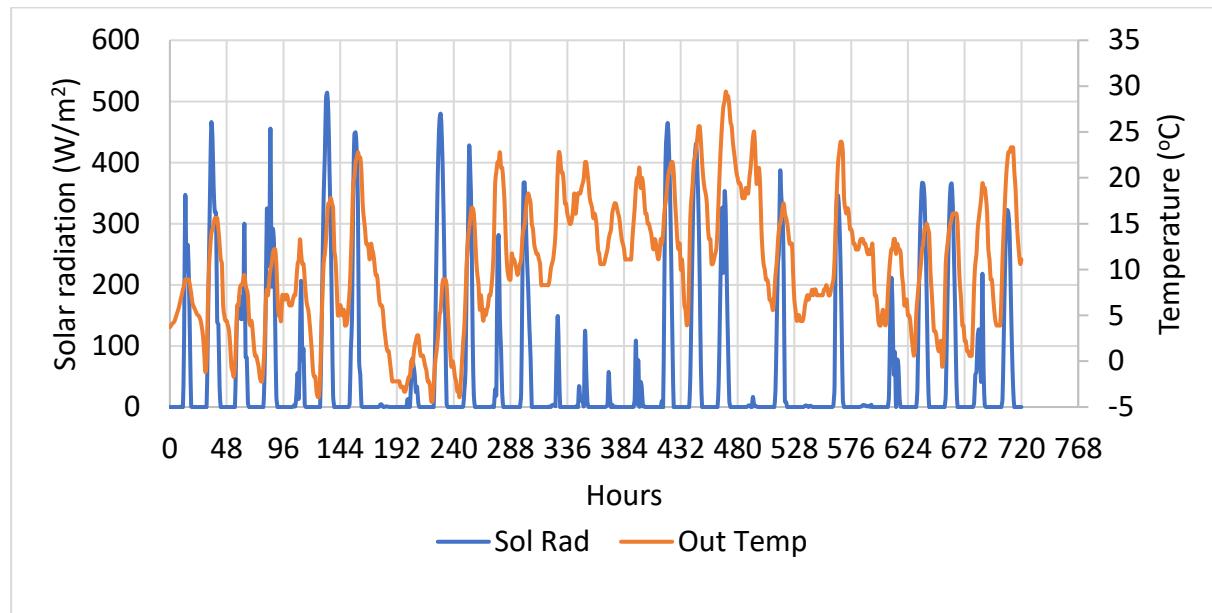


Figure 1. Hourly data of solar radiation outdoor temperature.

3.2. Control strategy

The simple control strategy used in this study was to change the insulation's thermal resistance to high (R-high) and low (R-low) based on the exterior surface temperature and indoor temperature difference. This strategy was selected because it focuses on maximizing the heat flux toward the inside of the building during heating hours by taking advantage of the heated exterior surface temperature and storing the thermal energy in the grouted concrete, which was used as thermal storage. An outdoor temperature (T_{out}) of 24°C was selected to differentiate the cooling and heating periods. Because the outdoor temperature was below 24°C for 97% of the time during the simulation period, the simulation period was only treated as a heating period. As shown in Table 1, the selected control strategy has two options.

During hours when the exterior surface temperature (T_{surf}) was higher than the indoor temperature, low thermal resistance (R-low) was activated in the insulation. In other heating periods, the state of switchable insulation remained at the high R-value (R-high).

Table 1. Control strategy.

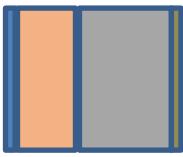
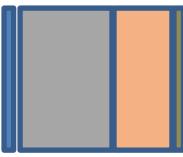
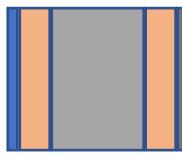
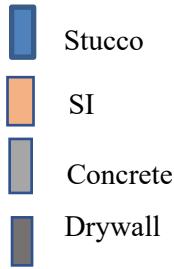
Cooling/heating periods	Switchable insulation state	
Surface to interior temperature comparison	$T_{surf} > T_{int}$	$T_{surf} < T_{int}$
Insulation state	R-low	R-high

3.3. Wall types and material properties

A concrete mass wall with switchable insulation on the interior, exterior, or split on both sides was used in this study. According to the 2015 International Energy Conservation Code, Section R402 Building Thermal Envelope [13], the minimum required R-value for climate zone 4A is R-8. This R-value changes to R-13 if more than 50% of the insulation is on the wall's interior side. In this study, the insulation locations varied as 100% on the interior, 100% on the exterior, and 50%/50% split between the interior and exterior. The code required minimum R-values were used as the switchable insulation high-R-value

state (R-high), and the low-R-value state (R-low) was set as an air layer. Table 2 shows the insulation locations in the wall and their respective R-high and R-low values.

Table 2. Switchable insulation locations and R-high and R-low values.

R-high/R-low values			
Exterior insulation	Interior insulation	Split insulation (50%/50%)	Legend
			
R-high/R-low	R-8/R-1	R-13/R-1	R-4+R-4/R1

The wall system used in the simulation had stucco as cladding, switchable insulation, an 8 in. (203.2 mm) thick concrete wall, and gypsum board drywall. A grey exterior wall with short-wave absorptivity of 0.6 and long-wave emissivity of 0.9 was used. The thickness and the thermal properties of the materials are shown in Table 3.

Table 3. Material properties.

Material	Thickness (mm)	Density (Kg/m ³)	Thermal conductivity (W/m.K)	Heat capacity (J/kg.K)
Stucco	12.50	1,795	0.37	840
Switchable insulation	R-low	1.3	0.28	1,000
	R-high	34	0.03	1,400
Concrete	203.2	2,300	1.8	880
Gypsum board	12.5	850	0.20	850

4. Results and discussion

This section discusses the experimental validation done to calibrate the model, the number of hours the insulation was switched, and the wall performance as a function of heat flux transport variation. The sign convention used for heat flux was positive when the heat flux was directed toward the interior and negative when the flow direction was toward the exterior side.

4.1. Model Validation

To validate the COMSOL model, data from an active insulation experimental test at Oak Ridge National Laboratory's heat, air, and moisture climate chamber were used to test a wall system with an active insulation system that was switched on (insulating) and off (conductive) based on a control schedule. The wall system comprised vinyl siding on oriented strand board as exterior cladding, 2 in. (51 mm) extruded polystyrene or 2 in. (51 mm) air as switchable insulation on either side of the mass wall, 8 in. (203 mm) fully grouted concrete masonry unit, and a gypsum board. 24-h outdoor temperature weather data of a warm climate were in the climate chamber.

The schedule used in this validation study is as follows. While the interior insulation was kept as R-low (air), the exterior insulation schedule was R-low from 12:00 a.m. to 10:00 a.m. and from 4:30 p.m.

to 12:00 a.m. The R-value was set to R-high from 10:00 a.m. to 4:30 p.m. Figure 2 shows the picture of the wall setup, the control schedule and the heat flux on the interior side obtained by measurement and simulation. As shown in the figure the ‘door’ setup is used to manually switch the insulation ON and OFF by removing and installing the XPS insulation in the cavity respectively.



(a)

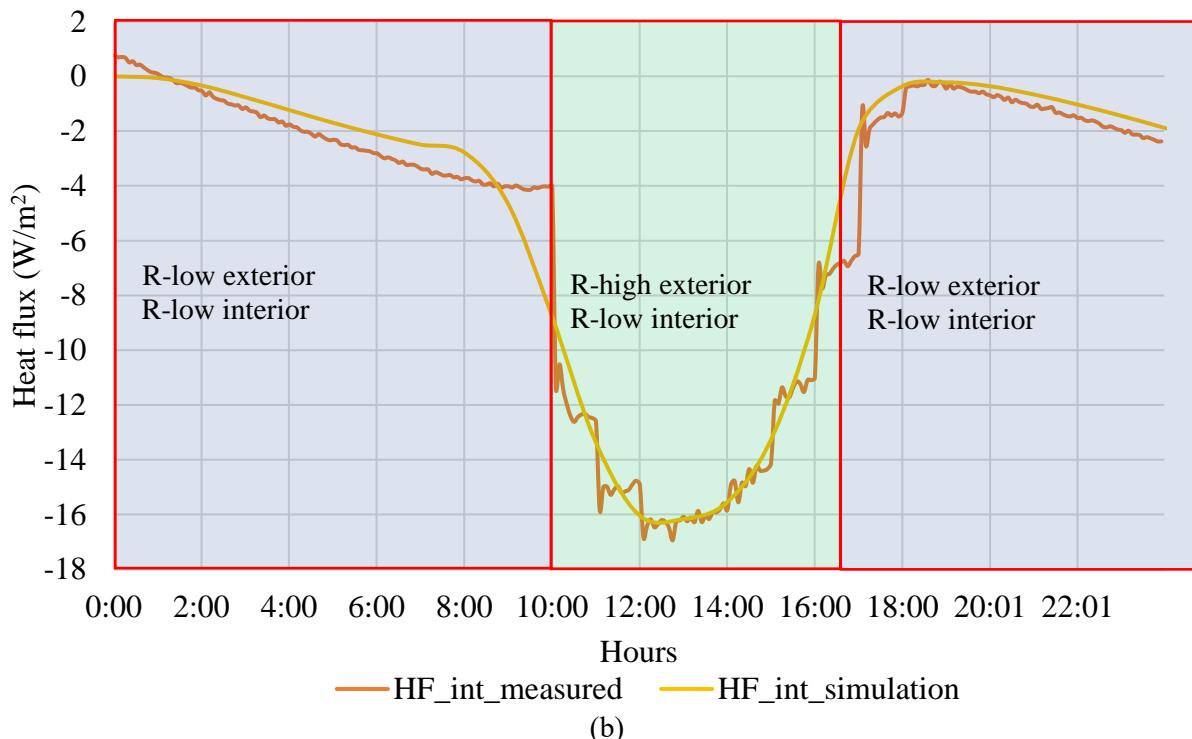


Figure 2. (a) Picture of the wall setup with manually switchable insulation (b) Heat flux values of the wall measured and simulated as a function of the R-value control schedule.

A percentage error of 6.26% was observed between the measured and the simulated data. As shown in Figure 2, a good agreement was obtained between the measured (HF_int_measured) and simulated (HF_int_simulation) heat flux in the wall’s interior side except around the switching time at 10:00 a.m. This could arise from some time difference between the test and simulation R-value switching times.

4.2. Effect of insulation location and comparison between switchable and passive insulations
 The insulation locations were varied as the exterior, interior, and a split of 50%/50% between the interior and exterior. Figure 3 shows the computed heat flux behind the drywall (the interior side of the wall). The weather data used were Washington, DC’s April outdoor temperature and solar radiation.

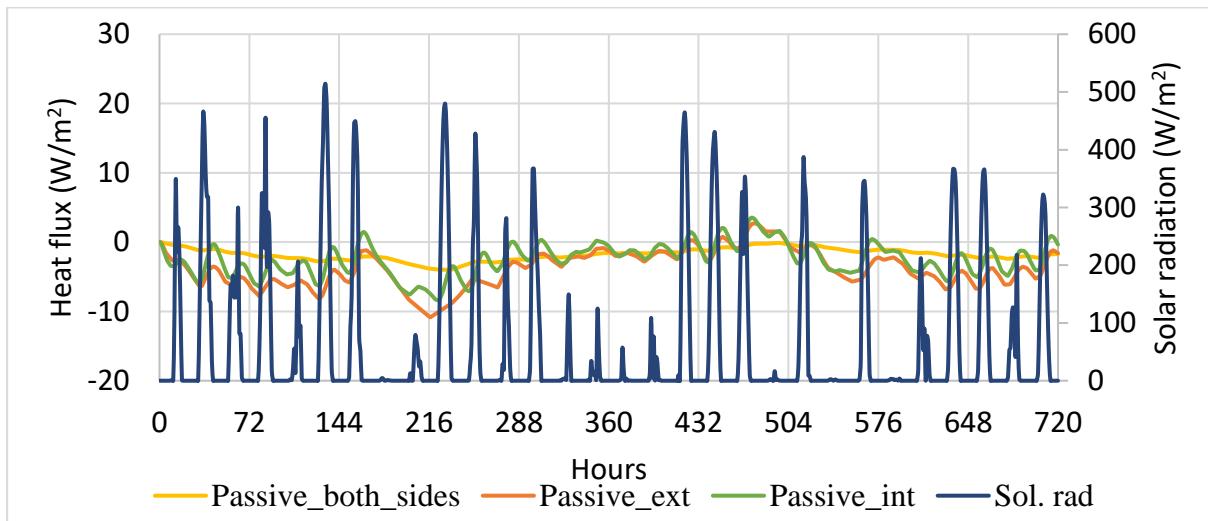


Figure 3. Hourly heat flux values of passive insulation and solar radiation.

The performances of the passive insulations with no switching at the three different positions are compared in Figure 3. The heat flux values on the interior side of the wall for April remained mostly negative for all three locations. Although the split insulation gave a relatively constant heat transfer throughout, the walls with exterior and interior insulation locations tended to be affected by solar radiation. Throughout the simulation period, the wall with interior insulation was more responsive to solar radiation than the wall system with exterior insulation.

The application of a switchable insulation system was applied using a simple control logic based on comparing the exterior surface temperature to the indoor temperature as shown in Table 1. The insulation was varied from R-high to R-low for a total of 166 h, which is 23% of the simulation hours in a month. These hours were usually accompanied by solar radiation. Figure 4 shows hourly data of the computed heat flux and the solar radiation. Similar to in Figure 3, the peak heat flux values reached peak values between 2 and 4 h after the solar radiation peak because of a thermal lag caused by the mass wall. According to the performance comparison of the three types of walls based on the heat transport on the wall's interior side, the wall system with exterior insulation had a higher transport followed by the split insulation between the interior and exterior.

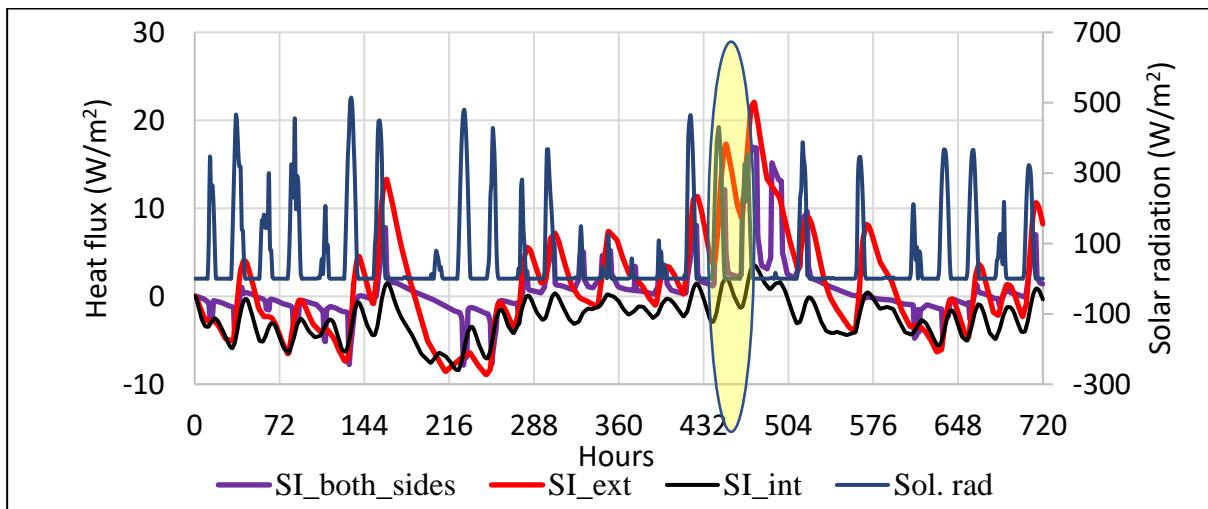


Figure 4. Hourly heat flux values of switchable insulation and solar radiation.

For detailed analysis, 24-h data between hours 432 and 456 (shown in the yellow oval in Figure 4) are plotted in Figure 5. The blue box in Figure 5 represents hours when the insulation was switched to R-low. The thermal switching from R-high to R-low initially had the opposite effect for the wall with interior insulation from the other two locations. The heat flux value at the 11th hour (1st hour of R-high) decreased for the wall with interior insulation, whereas the heat flux values increased in the walls with split and exterior insulations. This scenario was observed throughout the monthly data.

When the switchable insulation performances are compared to the passive insulation, the wall with interior insulation has 62.5% of the time had a higher inward heat transport. The other two walls always had a higher inward flux than their passive counterparts.

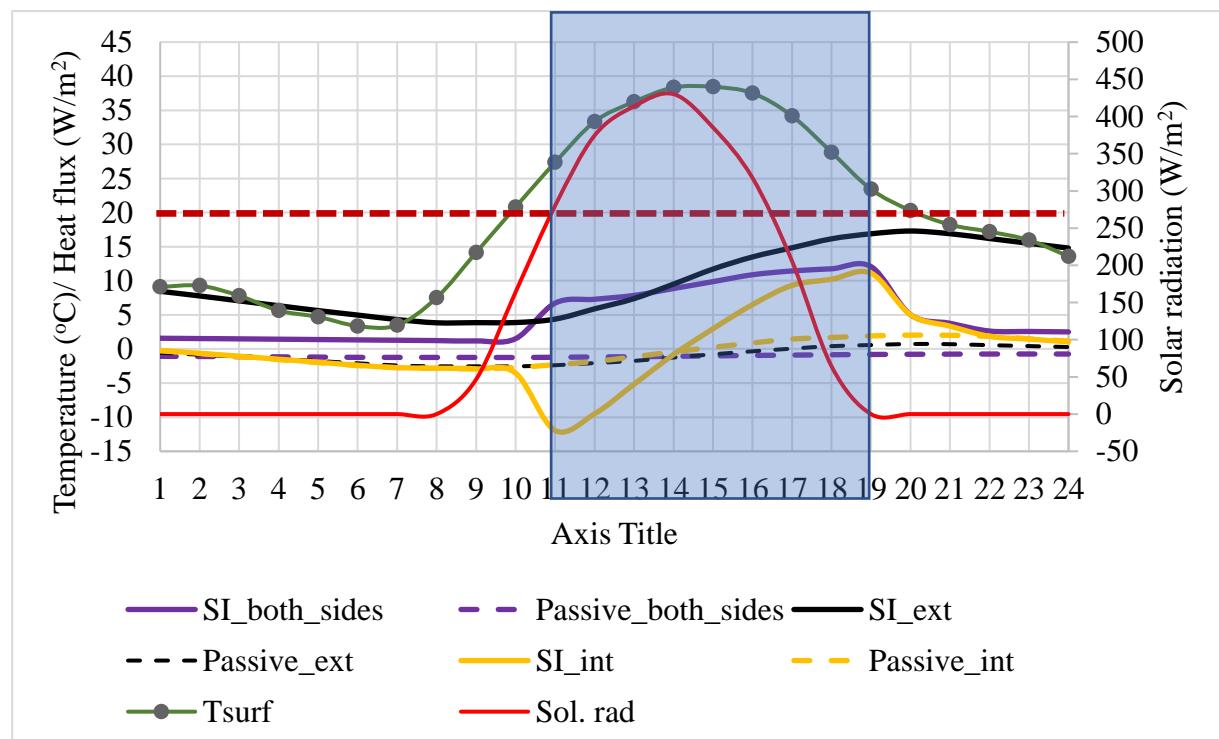


Figure 5. 24-h heat flux data of the passive and active insulations, solar radiation (Sol. rad), and exterior surface temperature (Tsurf).

The split switchable insulation was the fastest to react to the positive change of heat flux when a change of R-value state occurred compared with the other insulation setups. The exterior switchable insulation had a 37% higher heat transfer rate than the split insulation when R-high was activated. The heat flux rates at their peak for switchable insulations were higher by 14.98W/m², 11.31 W/m², and 9.18 W/m² for wall systems with the exterior, split, and interior insulation, respectively, than their passive counterparts.

The other distinct property of the wall with exterior insulation had higher inward heat transfer for more hours than the other wall systems, even when the insulation was in an R-low state.

5. Conclusion

The energy performance of a mass wall equipped with switchable insulation was evaluated. In this simulation work validated by experimental data, a mild climate zone's spring season was selected to study how the mass wall interacts with switchable insulations located at various positions in the wall system. Switchable insulation system location was varied among interior, exterior, and both sides of the grouted concrete. The switching state was dictated by the temperature difference between the exterior surface temperature and indoor temperature. During this simulation period, results showed that about

23% of the time, the R-value was in the R-low state. A wall system with the exterior insulation system provided the highest heat influx to the indoors and took advantage of the grouted concrete's thermal storage capacity and maintained a positive heat flux toward the interior. The heat flux rates at their peak for walls with switchable insulation were higher by 14.98W/m², 11.31 W/m², and 9.18 W/m² than passive wall systems with the exterior, split, and interior insulation, respectively.

6. Acknowledgement

This manuscript has been authored in part by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

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