

CFD Analysis and Energy Simulation Analysis for a New Type of Window

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Question Statement

Prof. Moncef Krarti:

Part 1: CFD Analysis.

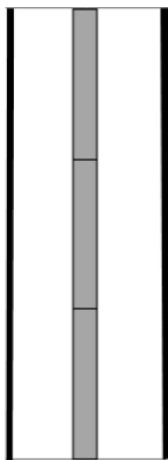
1. State all the assumptions in the CFD analysis;
2. Provide the procedure to estimate R-values based on the CFD analysis;
3. Show the airflow velocity and temperature fields;
4. Summarize the results of the equivalent R-values.

Part 2: Energy Simulation Analysis.

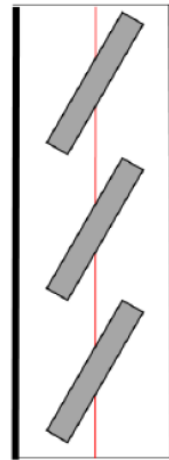
1. Show and summarize the hourly variation of thermal heating and cooling loads (two representative days) for the cases:
 - a. Locations: Boulder, CO; Phoenix, AZ; and Chicago, IL;
 - b. Insulation angles: 0° , 45° , and 90° .

1. CFD Analysis

This section is objective to calculate the equivalent R-values of a simple model for a sealed window with variable thermal properties made up of single layer of glass, rotating insulation layer within an air cavity, and another layer of glass. Figure 1 shows the simplified model.



(a) Closed Insulation Layers (High R-value)



(b) Opened Insulation Layers (Low R-value)

Figure 1. Description of the simple model for a sealed window with variable thermal properties

The height of the window is 10 ft with 10 rotating insulation pieces of 1 ft length each. The R-value of the insulation piece is R-10 (IP unit). Further, the air cavity layer is 1 ft and 2 in wide. The range of rotation angle of insulation piece is from 0° to 90°.

1.1. Assumptions

Based on the description of the model, several reasonable assumptions of the model still need to be made:

1. To simplify the model, the thickness of the two layers of glass is 0 and the R-value is 0;
2. To simplify the boundary condition settings, the temperature of the outside layer of glass is equal to the outdoor temperature and the temperature of the inside layer of glass is equal to the indoor temperature. For both upper and lower boundaries, the heat flux is 0;
3. The thickness of the insulation layer is 2 in and the material of the insulation layer is a hypothetical material, which density is 2,320 kg/m³, specific heat is 1,138 J/kg-K, and thermal conductivity is 0.02884561 W/m-K (The R-value is R-10 when the thickness is 2 in);
4. The air between the glass layers and insulation layer is incompressible ideal gas;
5. The gravity is 9.81 kg/s².

1.2. Procedure to Estimate R-values

To estimate the R-value of the window, Figure 2 shows the key parameters.

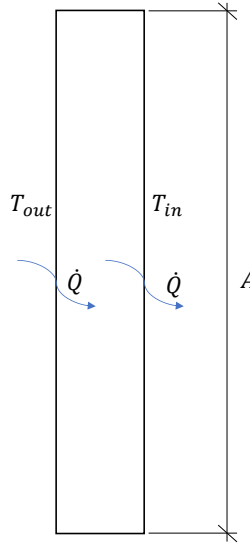


Figure 2. Key parameters of the model to estimate R-values

The T_{out} and T_{in} are the outdoor temperature and indoor temperature respectively. Based on the assumptions, these two parameters also represent the temperatures of the two layers of glass. A is the area of the window. \dot{Q} is the heat flux, which is calculated based on the CFD analysis. As we all know, the equation to calculate the heat flux can be expressed as:

$$\dot{Q} = \frac{A\Delta T}{R} \quad (1)$$

Assuming the direction of the heat flux from outdoor to indoor is positive, the equation to calculate R-value can be rewritten as:

$$R = \frac{A\Delta T}{\dot{Q}} = \frac{A(T_{out} - T_{in})}{\dot{Q}} \quad (2)$$

Thus, we need to identify the value of heat flux based on the CFD analysis. Then, by using Equation (2), we can estimate the R-value of the window.

1.3. Temperature and Airflow Velocity

ANSYS 19.2 is used to simulate the temperature and airflow velocity in the window, and estimate the R-values of the window with different insulation angles. We consider two conditions – winter condition (Outdoor temperature is 272.04 (30 F) and indoor temperature is 294.26 K (70 F)) and summer condition (Outdoor temperature is 308.15 (95 F) and indoor temperature is 294.26 K (70 F)). Before conducting simulation and analysis, we need to conduct the sensitivity analysis to identify the impact of the number of the nodes on the simulation results. The window with 45° insulation angle is used to do the analysis, which is shown in Figure 3. When the number of nodes is larger than 4,000, the estimated R-value becomes constant. Finally, we select 4,637 nodes to do the following simulation and analysis.

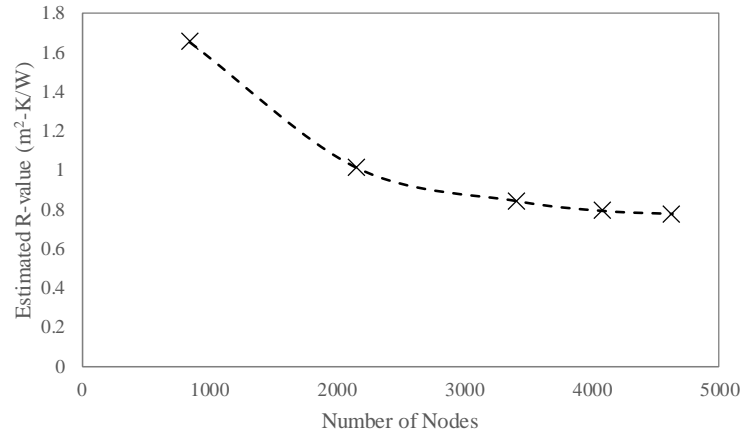
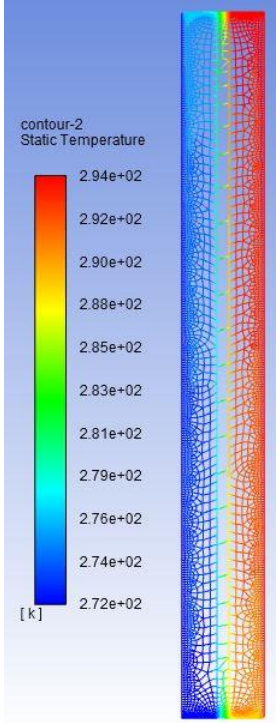
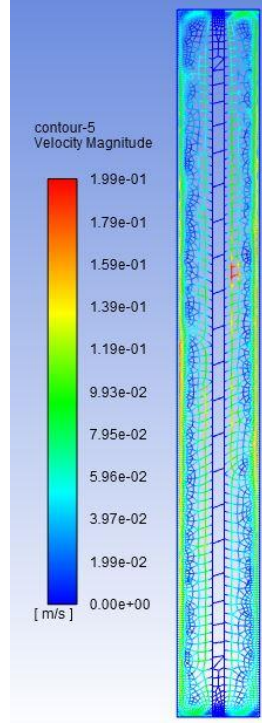


Figure 3. Sensitivity analysis to identify the impact of the number of nodes on estimated R-values

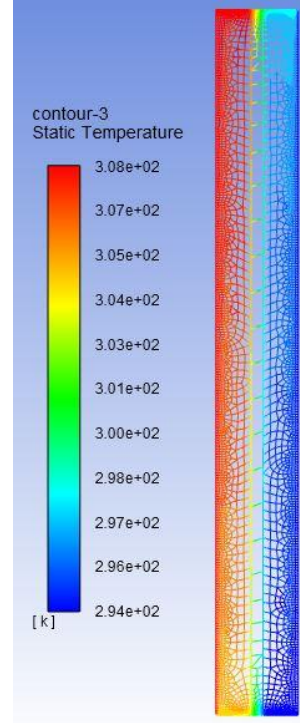
Figure 4 shows the temperatures and airflow velocities of the window with the five typical insulation angles under the two conditions. When the insulation angle is 0°, the air cavity is divided into outside cavity and inside cavity. The mean temperature of the outside cavity is lower in winter and higher in summer by compared with the value of the inside cavity. The airflow is moved in each cavity. The windows with the other four insulation angles have similar distributions of the temperature and airflow velocity. Generally, the temperature of upper air is higher than that of lower air in both winter and summer conditions. The airflow is moved through the whole air cavity. It is noticeable that the airflow velocity is the smallest in the summer condition when the insulation angle is 60°, which is closed to 0 in the whole air cavity. Further, since the gaps between each insulation panel and the two glass layers are all narrow when the insulation angle is 90°, the airflow also tends to be moved in each small air cavity created by two nearby insulation panels and two glass layers.



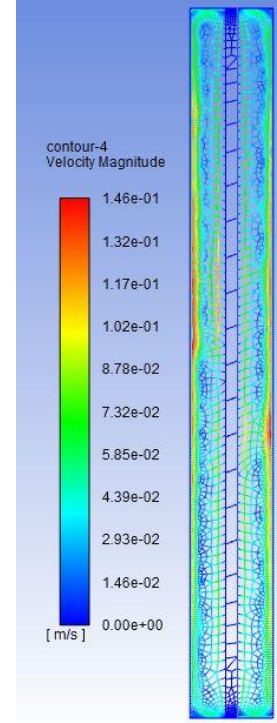
(a) Temperature
(winter, 0°)



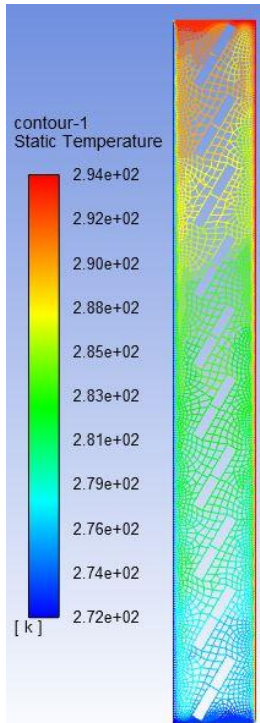
(b) Velocity
(winter, 0°)



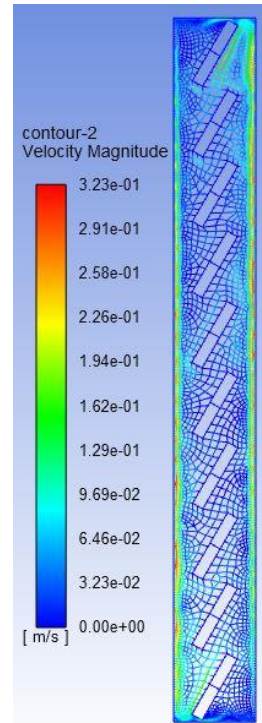
(c) Temperature
(summer, 0°)



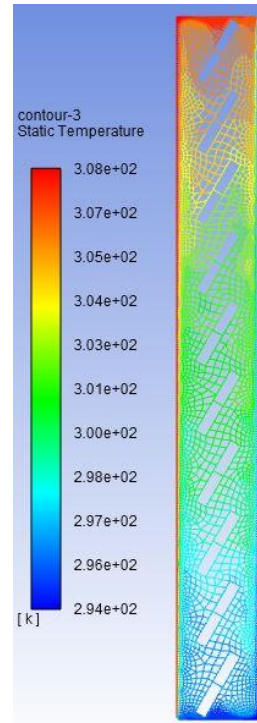
(d) Velocity
(summer, 0°)



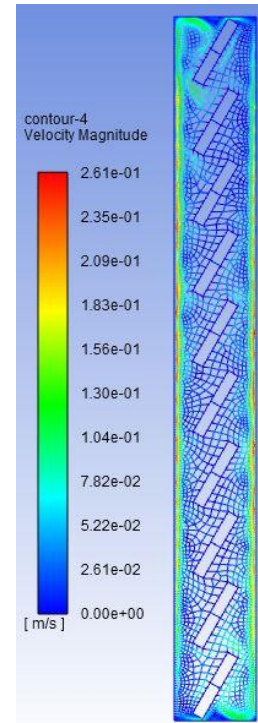
(e) Temperature
(winter, 30°)



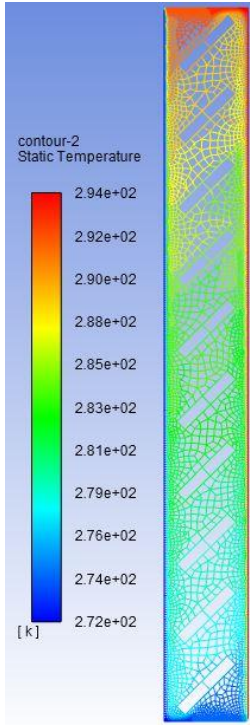
(f) Velocity
(winter, 30°)



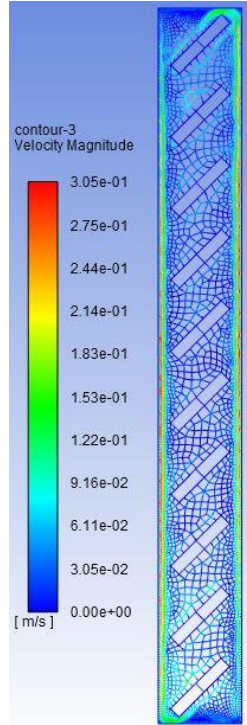
(g) Temperature
(summer, 30°)



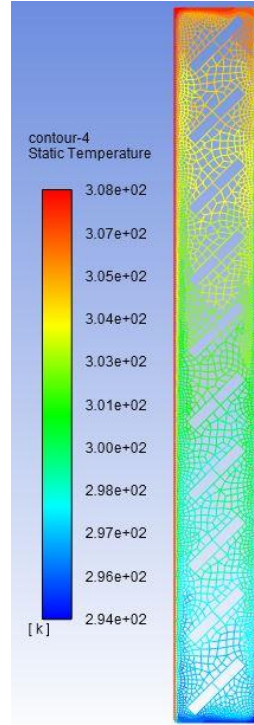
(h) Velocity
(summer, 30°)



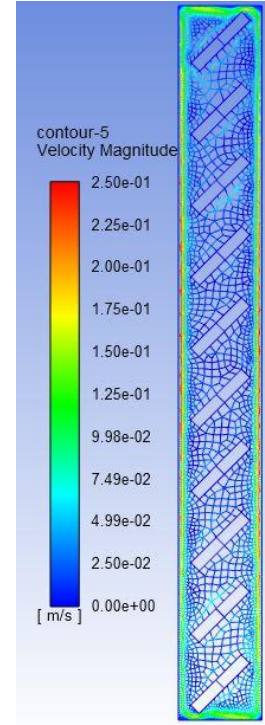
(i) Temperature
(winter, 45°)



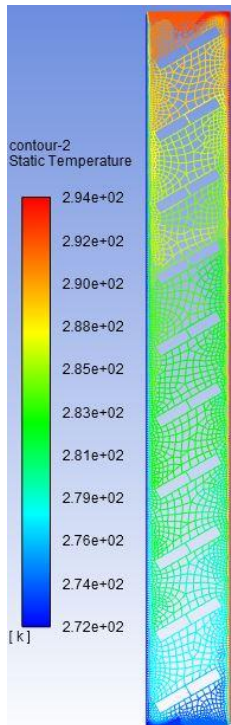
(j) Velocity
(winter, 45°)



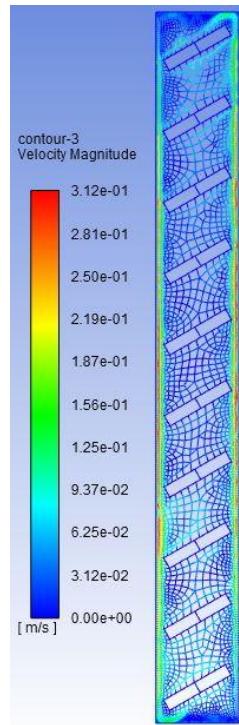
(k) Temperature
(summer, 45°)



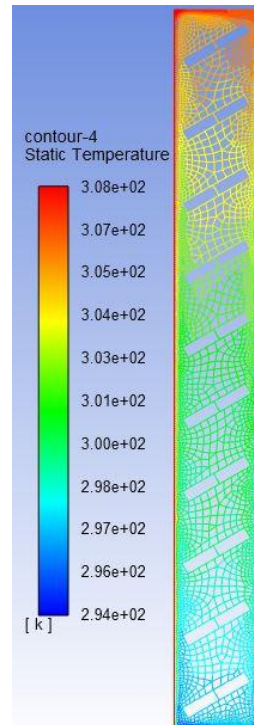
(l) Velocity
(summer, 45°)



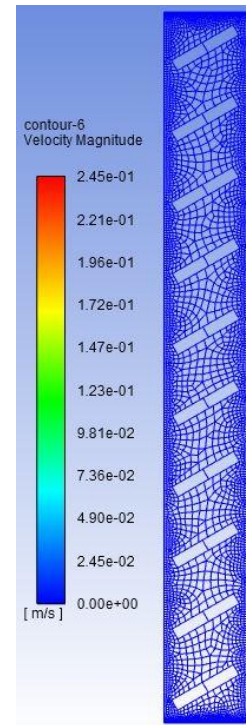
(m) Temperature
(winter, 60°)



(n) Velocity
(winter, 60°)



(o) Temperature
(summer, 60°)



(p) Velocity
(summer, 60°)

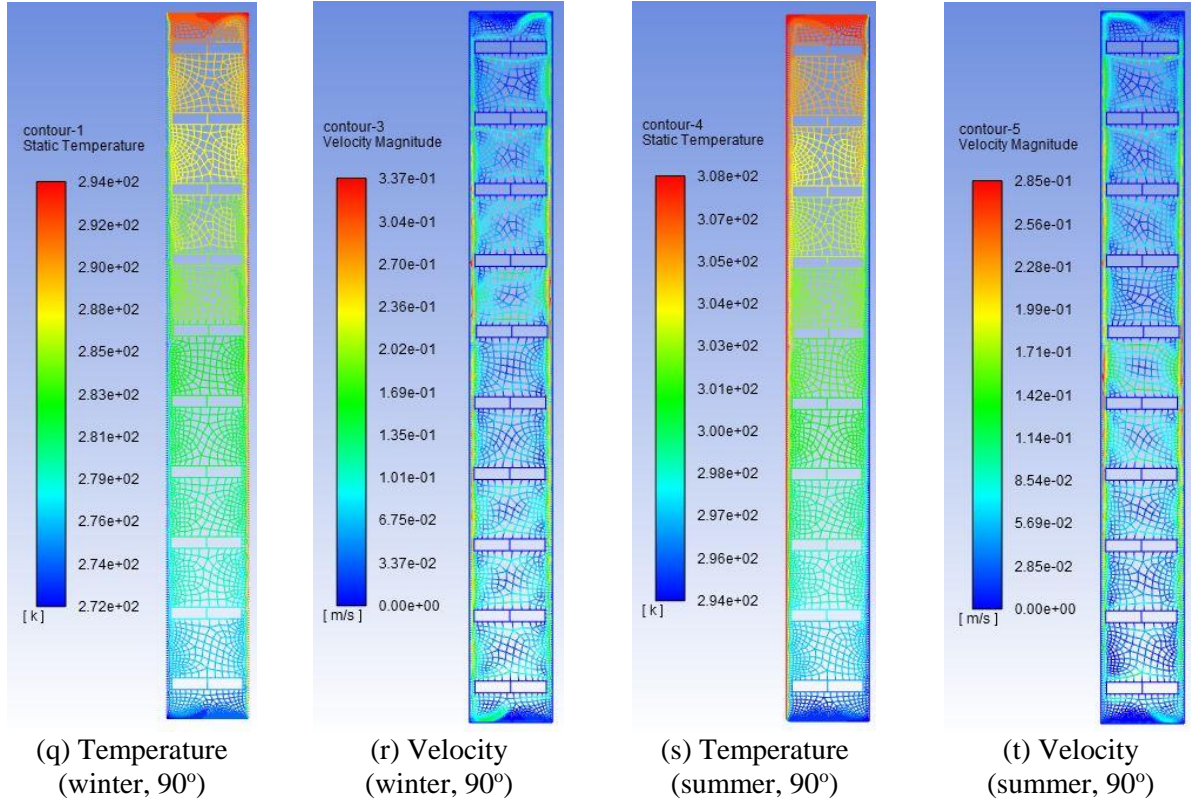


Figure 4. Temperature and airflow velocity in winter and summer (Insulation angle: 0°, 30°, 45°, 60°, and 90°)

1.4. Estimated R-values

After analyzing the temperature and airflow velocity in each situation, we need to estimate the R-values of the window with different insulation angles based on the method mentioned in Section 1.2. Table 1 shows the results of the estimated R-values of the window with the 0°, 30°, 45°, 60°, and 90° insulation angles. Two R-values can be calculated based on the winter and summer conditions for each insulation angle. Since the difference between the two R-values is not significant, we use the average value as the estimated R-value.

Table 1. Estimated R-values (Insulation angle: 0°, 30°, 45°, 60°, and 90°)

- Indoor temperature: 294.26 K (70 F);
- Area of the window: 3.048 m².

Insulation Angle	Outdoor Temperature (K)	Heat Flux (W)	Estimated R-value (m ² -K/W)
0°	272.04 (30 F)	-18.07	3.85
	308.15 (95 F)	10.7	
30°	272.04 (30 F)	-94.43	0.76
	308.15 (95 F)	52.57	
45°	272.04 (30 F)	-93.29	0.78
	308.15 (95 F)	51.09	
60°	272.04 (30 F)	-95.14	0.76
	308.15 (95 F)	52.83	
90°	272.04 (30 F)	-94.99	0.75
	308.15 (95 F)	53.14	

Based on the estimated R-values, we draw a plot and try to identify the regression line, which can be used in the range of 0° to 90° . Figure 5 shows the results of the estimated R-values by using the regression model.

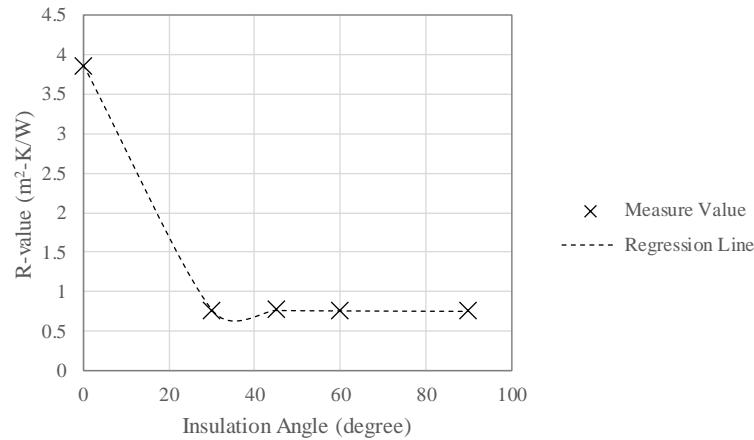


Figure 5. Plot of the estimated R-values by using regression model

Based on the results shown in Figure 5, it seems that the window with the insulation angles between 0° ~ 30° do not have the accurate estimation. Thus, we add the four situations (5° , 10° , 15° , and 20°) to address the issue. The results shown in Figure 6.

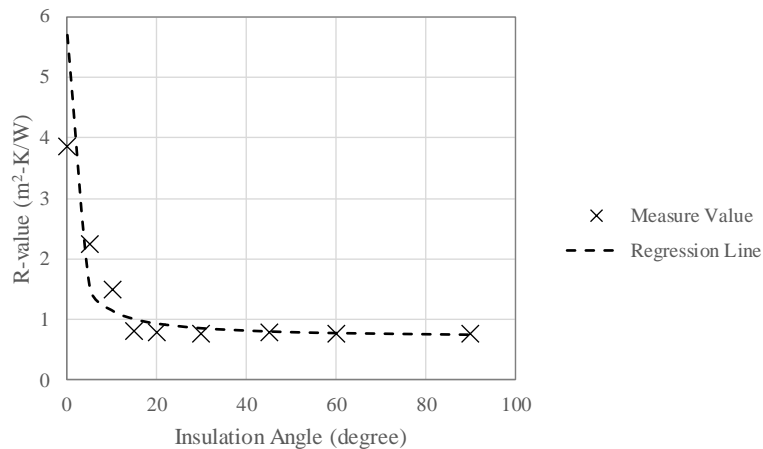


Figure 6. Plot of the estimated R-values by using regression model (Updated)

Since the insulation panels have 2in thickness, when the angle is lower than 9.5° , the air flow is 0; when the angle is around 10° , heat conductivity is still the main method to transfer heat; when the angle is much larger than 10° , the heat convection becomes the dominant method to transfer heat and the angle seems to only have minor impacts on the R-value of the window.

When the insulation angle is small, the insulation panels can be a layer, which blocks the air to flow in the whole air cavity. Thus, the heat conduction is the dominant method to transfer heat. However, when the insulation angle is large, the heat convection becomes the dominant method to transfer heat. The impact of

the insulation panels is only to control the direction of the airflow. The R-value of the window is constant and is approximately $0.76 \text{ m}^2\text{-K/W}$.

2. Energy Simulation Analysis

This report conducts energy simulation analysis by using small office building models from DOE Commercial Prototype building Models (Ye et al. 2019; Thornton et al. 2011; DOE 2015).

2.1. Description of the Building Models

The baseline models consist of 3 small office buildings, which are located in Boulder, CO; Phoenix, AZ; and Chicago, IL. Figure 7 shows the geometry and thermal zones of the baseline small office building models. Each small office building model has one floor and is rectangle shape. There are five thermal zones in each model, including four perimeter zones and one core zone.

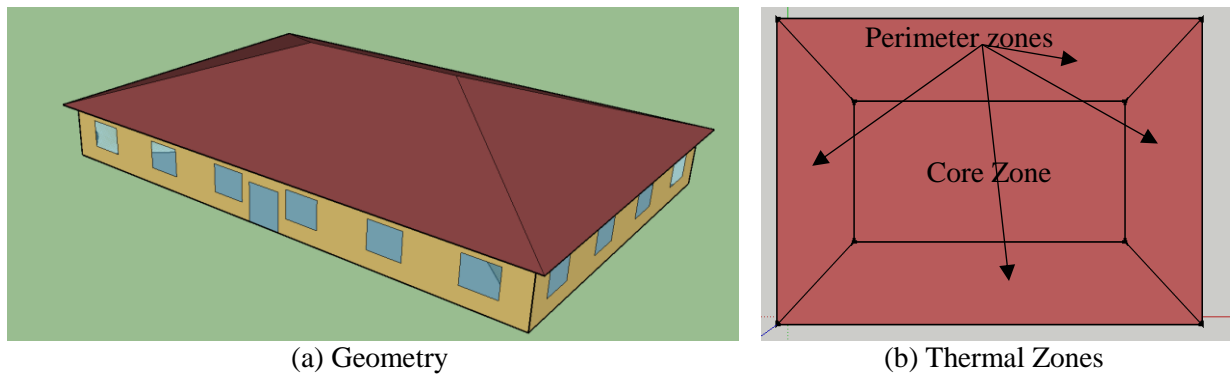


Figure 7. Geometry and thermal zones of the baseline small office building models

Table 2 summarizes the key parameters of the baseline small office building models. The total floor area of each model is 510 m^2 and window-to-wall ratio is approximately 20%. The wood-frame walls and attic roof are used in the models. Further, the models use air-source heat pumps for both heating and cooling.

Table 2. Key parameters of the baseline small office building models

Parameter Name	Value		
Location (Climate Zone: Typical City)	5B: Boulder, CO	2B: Phoenix, AZ	5A: Chicago, IL
Total Floor Area	510 m^2 ($27.7 \text{ m} \times 18.4 \text{ m}$)		
Aspect Ratio	1.5		
Number of Floors	1		
Window-to-Wall Ratio	24.4% for South and 19.8% for the Other Three Orientations		
Floor-to-Floor Height	3.048 m		
Envelope	Exterior Walls: Wood-Frame Walls Roof: Attic Roof with Wood Joist Windows: Hypothetical Windows		
Lighting Power Density	10.76 W/m^2		
Plug Load Density	6.78 W/m^2		
HVAC System	Heating: Air-source Heat Pump with Gas Furnace as Back Up Cooling: Air-source Heat Pump Terminal Units: Single Zone, Constant Air Volume Air Distribution		

Parameter Name	Value
Service Water Heating	Tank-type, Electric Water Heater

2.2. Results of Energy Simulation Analysis

By using EnergyPlus, we run the simulations for the baseline models and the new models. We use Object, “WindowMaterial:SimpleGlazingSystem”, to replace the window materials in the baseline models to generate the new models. Then we calculate the hourly thermal heating and cooling loads. January 20th and July 21st are selected as two representative days to analysis the impacts of the new windows to the building loads in the winter and summer. The results of building loads in the winter and summer for the three locations are shown in Figure 8~Figure 13.

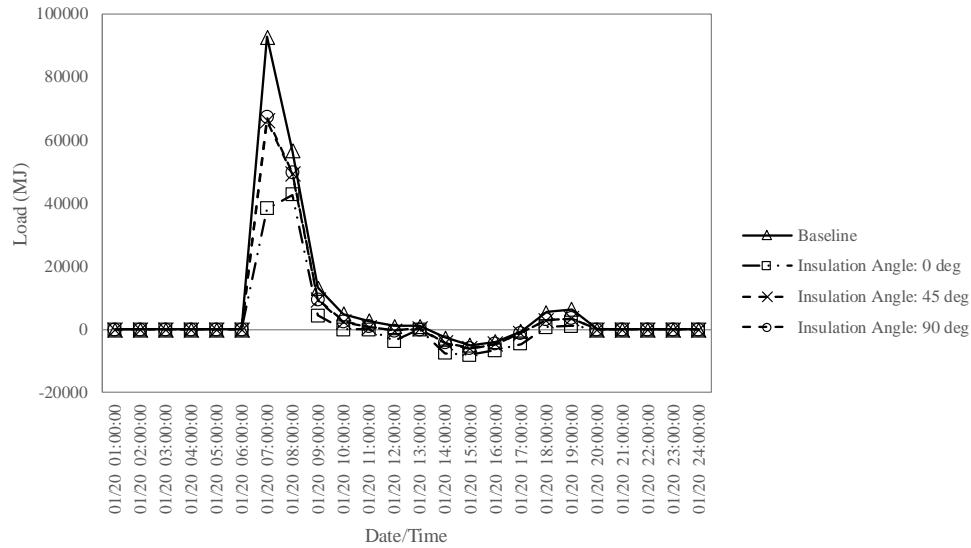


Figure 8. Hourly variation of thermal heating and cooling loads (Boulder, CO; January 20th)

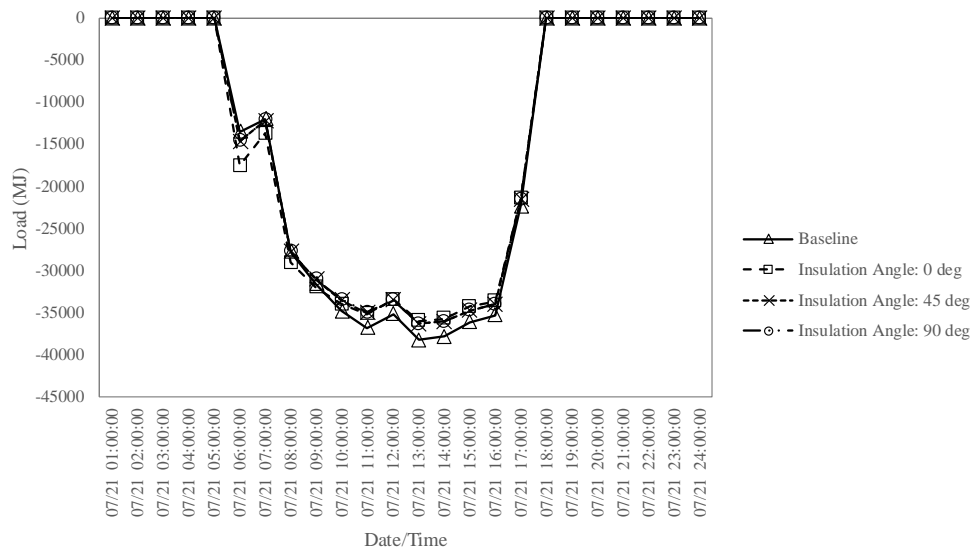


Figure 9. Hourly variation of thermal heating and cooling loads (Boulder, CO; July 21st)

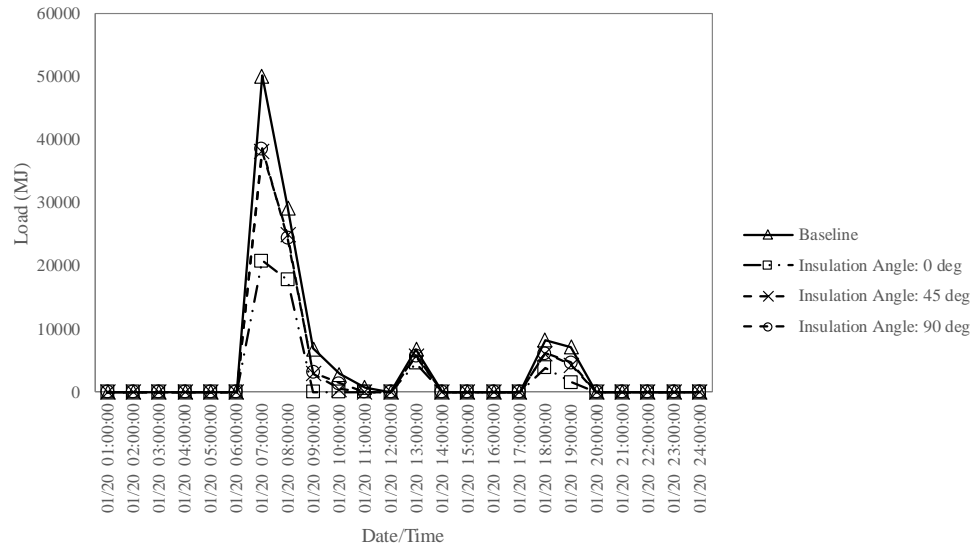


Figure 10. Hourly variation of thermal heating and cooling loads (Chicago, IL; January 20th)

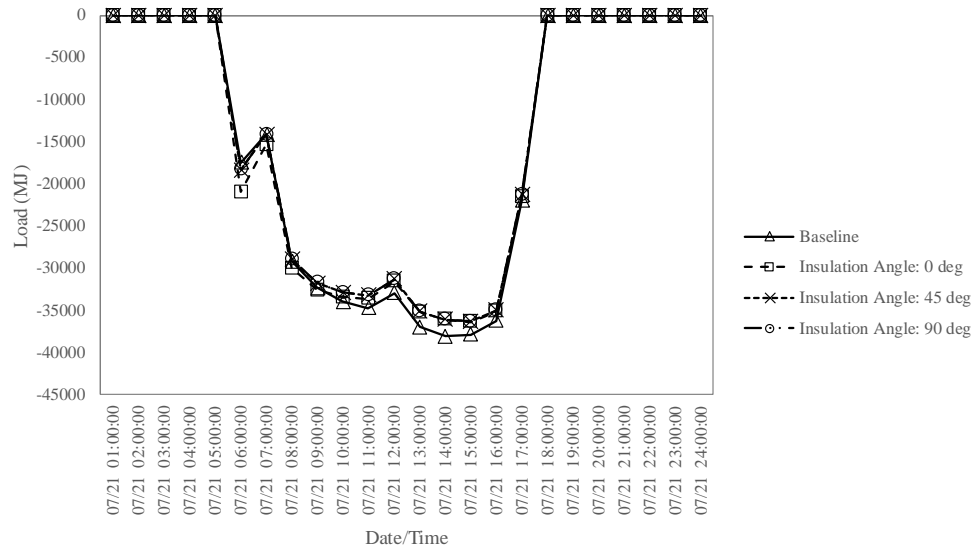


Figure 11. Hourly variation of thermal heating and cooling loads (Chicago, IL; July 21st)

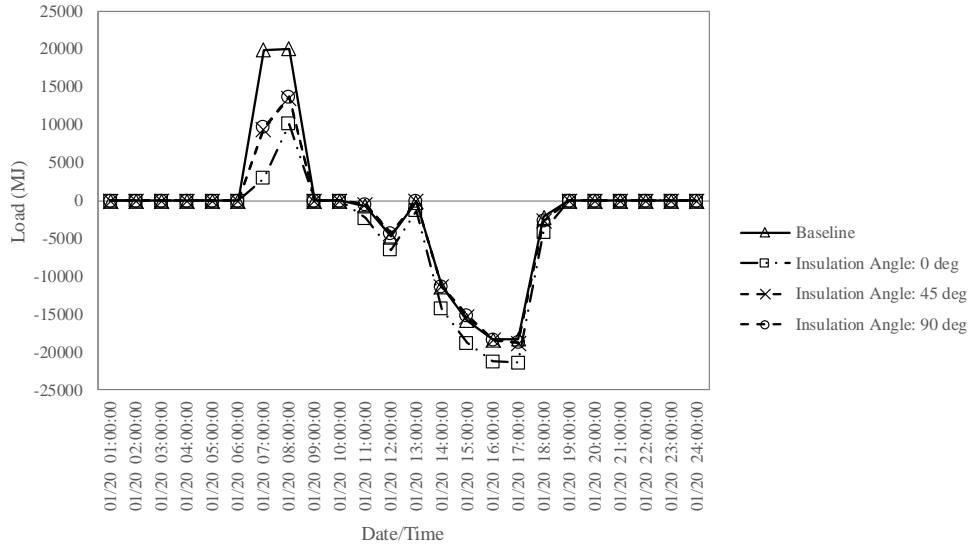


Figure 12. Hourly variation of thermal heating and cooling loads (Phoenix, AZ; January 20th)

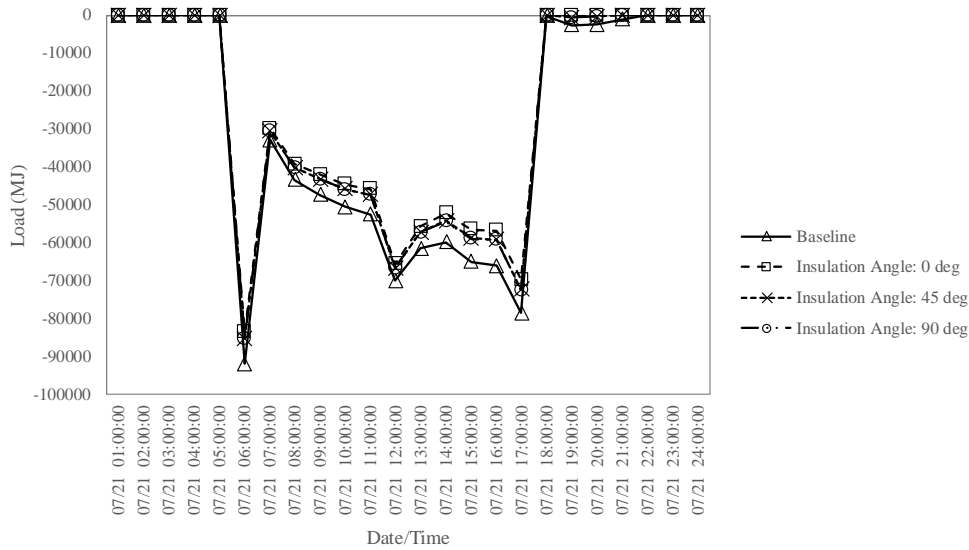


Figure 13. Hourly variation of thermal heating and cooling loads (Phoenix, AZ; July 21st)

The results show that the new window, especially the window with 0° insulation angle, can help to significantly reduce the building heating loads in winter in all the three locations. However, it does not have significant performance to reduce the cooling loads in summer. Further, some peaks of the cooling loads are possible to be higher by using the new window. For example, by using the window with 0° insulation angle, the peak cooling loads at 6:00 am in both Boulder, CO and Chicago, IL are higher than the values in the baseline models. The new window in Phoenix, AZ still has a good performance in summer. Thus, the window is suitable to be used in the location having the hot summer and cold winter, but it is not suitable to be used in the mild environment. Further, since it is difficult to open the new windows, we need to think

about ventilation, especially during the spring and fall. Moreover, it is difficult to clean the air cavity, which could be another issue.

3. Conclusion

This report designs a method to calculate the equivalent R-values of a simple model for a sealed window with variable thermal properties made up of single layer of glass, rotating insulation layer within an air cavity, and another layer of glass. Then the equivalent R-values of the window with different insulation angles are calculated. After that, we evaluate the energy performance of the window by using prototypical small office building models in the three locations. The results show that:

1. The window is suitable to be used in the location having the hot summer and cold winter, but it is not suitable to be used in the mild environment;
2. If using the windows, we need to take more efforts on the ventilation;
3. We need to design a method to maintain the windows, such as cleaning the air cavity.

Reference

- DOE. "Commercial Prototype Building Models." <https://www.energycodes.gov/commercial-prototype-building-models>.
- Thornton, B., M. Rosenberg, E. Richman, W. Wang, Y. Xie, J. Zhang, H. Cho, V. Mendon, R. Athalye, and B. Liu. 2011. Achieving the 30% Goal: Energy and Cost Savings Analysis of Ashrae Standard 90.1-2010. *Pacific Northwest National Laboratory (PNNL), Richland, WA (US)*.
- Ye, Y., W. Zuo, and G. Wang. 2019. A Comprehensive Review of Energy-Related Data for U.S. Commercial Buildings. *Energy and Buildings*, 186:126-37.