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Optimal thickness determination of insulating air layers in building envelopes

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Abstract

In building envelopes, using enclosed air layer becomes a popular way of thermal insulation, since the air has a much lower conductivity coefficient, and is much cheaper than other building materials. The motivation of this research is to investigate the coupled convective and radiative heat transfer in the air layer of building envelopes, in order to find the optimal geometrical parameters of the insulating air layers. Based on CFD technology, a Ra number judgment basis is summarized for flow pattern judge in insulation air layers, and the coupled convective and radiative heat transfer characteristics across the air layer is analyzed. The results indicated that a larger layer height results in a weaker convective heat transfer; when the thickness is below 20mm, an increasing thickness leads to a considerable decrease in the heat transfer; but when thickness exceeds 20mm, the heat transfer is slightly influenced by the thickness. The optimal thickness of the insulation air layer is 20-30mm depending on the climate condition.

Keywords: Building envelopes; insulating air layer; flow and heat transfer; optimal thickness.

1. Introduction

Globally, building energy demand has been identified as the largest energy consumer. As reported, about 23-50% of the global primary energy is consumed by buildings [1]. Moreover, with the acceleration of urbanization, the

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building areas will continue to grow, the building sector will continue to dominate the global energy situation [2]. Although the high energy consumption of building sectors maybe a warning sign, it provides great energy saving potential in the building sector.

For the energy utilization distribution in a typical commercial building, 32% of the building energy consumption is used by HVAC systems [3]. This energy distribution highlights the energy saving potential in HVAC systems. There are mainly two methods for HVAC energy savings. The first is to improve the energy efficiency of indoor HVAC systems, including employing high efficiency HVAC system, optimizing the design, control and operation of the employed system. Using these measures, the efficiency improvement of the HVAC systems will help to reduce the energy consumption in these systems. The other is to reduce the energy load of HVAC systems. As reported, about 20–50% of the cooling and heating energy consumption is caused by the envelope [4]. So improving the thermal performance of building envelopes enjoys a great potential in HVAC energy saving, as the building envelopes are the interface between indoor and the outdoor environment which affect the indoor heat gain and heat loss. There are various methods to improve the thermal performance of exterior building envelopes, including using high-performance building materials, employing insulating materials, improving the structure of external envelopes, etc. Among these methods, using enclosed air layer in exterior building envelopes becomes a popular way, since the air has a much lower conductivity coefficient than other structural materials in building envelopes [5].

The heat transfer process is complicated in air-layer building envelopes. When we concentrated on the internal air layer, the heat transfer includes exterior heat transfer and internal heat transfer. The former consists of the heat radiation between the surface and indoor/outdoor environments, heat convection between the surface and indoor/outdoor environments, and heat conduction in the structural layers; while the latter covers the heat conduction in the air, heat radiation between the inner surfaces, and heat convection between air and surfaces [6]. Thus, the heat transfer across the air layer is a coupled convective and radiative heat transfer problem. Moreover, the heat transfer in the air layer can be influence by the flow pattern, the temperature boundary, the geometrical parameters, external heat transfer condition and some other factors. The motivation for this research is to investigate the coupled convective and radiative heat transfer in air layers, in order to find the optimal thickness for insulation air layers. The objective of this research is to distinguish the flow pattern in the air layer, to investigate the coupled convective and radiative heat transfer characteristics across the air layer, and to determine the optimal air layer thickness for insulation in building envelopes.

2. Methods

Numerical simulation based on CFD technology was processed to model the flow and heat transfer process in the air layers with different channel sizes and different input temperatures. A simplified physical model of the air layer is established in Figure 1.

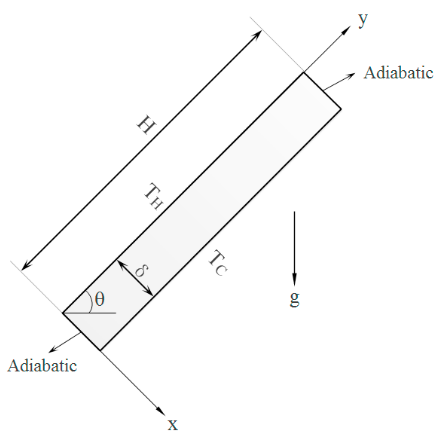

Figure 1. Computational model of insulation air layers

The channel height is H, and the width is δ. The left side is exposed to high temperature T_h, while the right side is exposed to low temperature T_c. The flow and heat transfer process is assumed as steady-state and two-dimensional. The airflow within the air layer is induced by the temperature difference. The air density satisfies the boussinesq approximation, and other property parameters are constant.

A numerical model based on the conservation equations of mass, momentum and energy, is established to simulate the natural convection in this vertical channel [7].

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\rho\beta g(T-T_0)\cos\theta \tag{2}$$

$$\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial y}=-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho\beta g(T-T_0)\sin\theta \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\lambda}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The radiative heat transfer can be calculated by the following equation.

$$J_i=\varepsilon_i\sigma T_i^4+\left(1-\varepsilon_i\right)\sum_{i=1}^{N}J_jX_{i,j} \tag{5}$$

Boundary conditions:

$$\begin{cases} x=0,T=T_H;x=\delta,T=T_C; \\ y=0,\dfrac{\partial T}{\partial y}=0;y=H,\dfrac{\partial T}{\partial y}=0 \end{cases} \tag{6}$$

Rayleigh number (Ra) and the Aspect ratio (AR) are defined to summarize the simulation results:

$$\mathrm{Ra}=g\Delta T\beta\delta^3/\left(\upsilon a\right) \tag{7}$$

$$\mathrm{AR}=H/\delta \tag{8}$$

The problem was solved in FLUENT software. The simulation results were compared to the experimental results reported in an existing literature and a heat flux test results from our experiment. Figure 2 shows the comparison results. For the average Nu number, the relative error between the predicted values and the test results ranges between 0.4%-5.44%. For the total heat flux, the changing tendencies of the simulation and experimental results are consistent. The maximal errors of the temperature differences are 6.47% and 4.02%, respectively for 7.48℃ and 12.17℃. The relative errors are acceptable. Thus, this model can be used to predict the flow and heat transfer process in the air layer. Moreover, by changing the geometrical parameters of the physical model, the flow pattern characteristic can be summarized, and the effect of layer height, width and other factors could be evaluated.

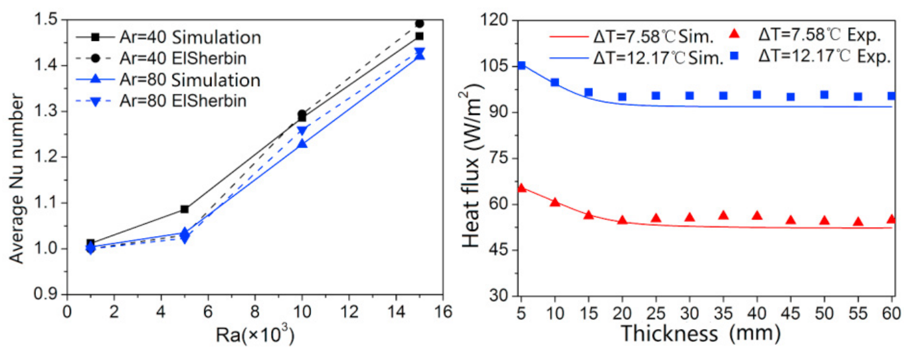

Figure 2. Comparison of average Nu number and heat flux between simulation and experimental results.

3. Results and discussions

Figure 3 illustrates the streamlines and isotherms under different Ra values with AR of 50. As the figure shows, under the effect of the temperature difference act on the sidewalls, air movement is induced. Air moves upward along the left hot wall, and downward along the right cold wall. When Ra is 10^2, the streamlines and the isotherms show parallel distributions, indicating that the flow is negligible. When Ra is 10^3, the isotherm slightly bends at the top and bottom of the air layer, showing that convection occurs in the layer, but still can be ignored. When Ra is 10^4, some local circulations occur in the streamlines, and the isotherms become more bending, the convection effect cannot be neglected in this case. When Ra grows to 10^5, the small circulations become a large circulation, indicating that the convection grows much stronger. At Ra lower than 10^5, the streamlines and isotherms are orderly distributed, which means that the flow belongs to the laminar flow state. However, when Ra grows bigger than 10^6, irregular vortexes occurs in the streamlines, and the isotherms become disordered, indicating that the flow becomes turbulent. Similar results can be found in the streamlines and isotherms for the air layer with AR of 20 and 10. Seen from the changing tendencies of the streamlines and the isotherms, it can be concluded that there may be two critical points of the Ra for natural convection in air layers. One is the critical point of conduction and convection, which may fall in the region of 10^3-10^4. The other is the critical point of laminar flow and turbulent flow, falling between 10^5 and 10^6.

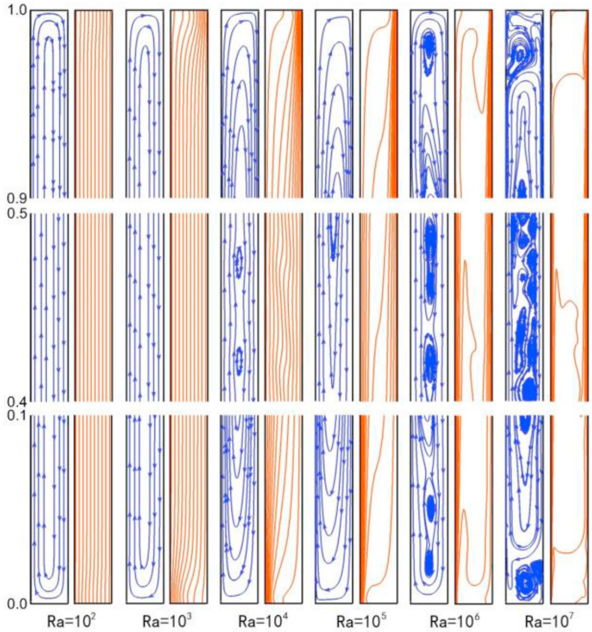

Figure 3. Streamlines and isotherms with AR of 50

To figure out the critical Ra values, a detailed simulation was performed on the convective heat transfer with different Ra and AR values, and different inclined angles. Based on the results, a table is summarized for the flow pattern judgment in the insulation air layers. For a given air layer with certain geometrical parameters and temperature boundaries, if the Ra number falls in the first column, the heat transfer can be treated as pure conduction. If it falls in the second column, the flow is laminar with convective heat transfer. When Ra falls in the last column, turbulent natural convection occurs.

Table 1. Judgment of airflow pattern in insulation air layers

θ	Pure conduction	Laminar flow	Turbulent flow
0°	$Ra < 1.2\times10^3$	$1.2\times10^3 \leq Ra < 3.5\times10^4$	$Ra \geq 3.5\times10^4$
30°	$Ra < 2.0\times10^3$	$2.0\times10^3 \leq Ra < 1.1\times10^5$	$Ra \geq 1.1\times10^5$
45°	$Ra < 2.4\times10^3$	$2.4\times10^3 \leq Ra < 1.3\times10^5$	$Ra \geq 1.3\times10^5$
60°	$Ra < 3.4\times10^3$	$3.4\times10^3 \leq Ra < 1.8\times10^5$	$Ra \geq 1.8\times10^5$
90°	$Ra < 1.5\times10^3$	$1.5\times10^3 \leq Ra < 1.4\times10^5$	$Ra \geq 1.4\times10^5$

Figure 4 presents the convective, radiative and total heat flux variations with the thickness. Seen from the left figure, when the thickness is less than 20mm, increasing the thickness will result in significant decreases in the convective heat flux, but the reduction rate becomes lower and lower. When the thickness exceeds 20mm, the influence of the thickness is quite limited. The overall tendency of the convective heat transfer is that, the convective heat flux decreases with the increasing thickness, but when the thickness passes 30mm, the heat flux remains almost consistent, even when the thickness is further increased. From the middle figure, the radiative heat flux reduces slightly with the increase in thickness. For the temperature differences of 5K, 10K, 15K and 20K, when the thickness increases from 6mm to 50mm, the heat flux reductions are 2.41%, 2.60%, 2.73%, and 2.76%, respectively. The effect of thickness on the radiative heat transfer is very weak and can be ignored. For the total heat flux variations, the changing tendency is the same with that of the convective heat flux. For the ratios, when the thickness increases from 6mm to 50mm, the convection ratio decreases from 40% to about 20%, and the radiation ratio increases from 60% to 80%. Thus, the radiation plays a dominant role in the coupled heat transfer.

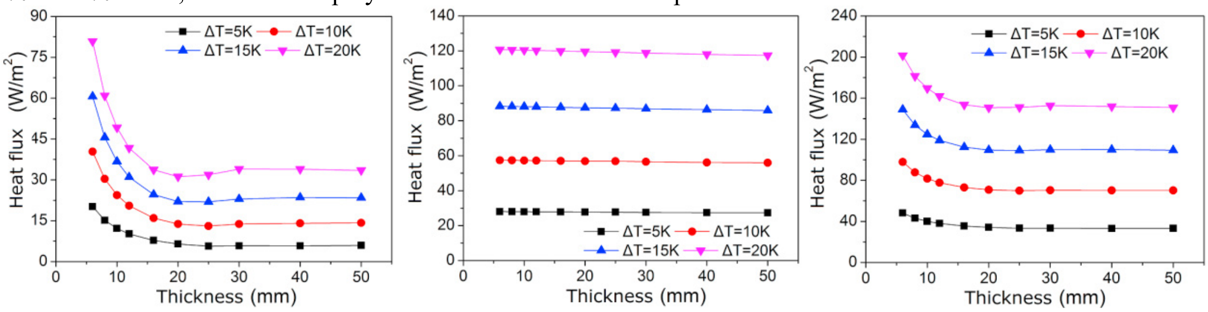

Figure 4. Variations of the convective, radiative and total heat transfer fluxes

Figure 5 shows the influence of the height, thickness and inclination on the total heat flux variations. For the influence of the thickness, in the region of 6mm to 25mm, the fluxes decrease considerably when the thickness increases; while when the thickness exceeds 25mm, the heat fluxes remains almost constant when thickness increases. A larger layer height produces a weaker convective heat transfer, thus a weaker overall heat transfer. For the effect of the inclined angle on the total heat flux, when the thickness is below 12mm, the heat flux curves are nearly coincident, since the heat transfer is pure conduction. In this region, the inclined angle has little effect on the heat transfer in the air layer. When the thickness passes 12mm, the larger the inclined angle, the larger the heat flux is. Every 30-degree increase in the inclination leads to a heat flux increase of 0.29W-0.73W/m^2. From an overall point of view, the effect of inclination on the internal heat transfer of an air layer is quite limited.

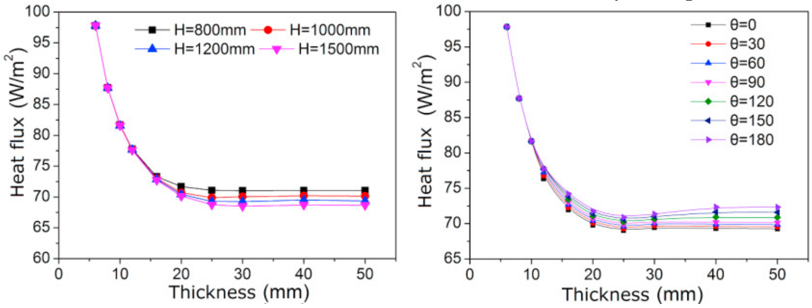

Figure 5. Effect of height, width and inclination on total heat transfer flux

Through the aforementioned analysis, we can find that when using an air layer for thermal insulation, larger layer height is profitable for weakening the heat transfer. In addition, an optimized thickness will be beneficial. Figure 6 presents the thermal resistance variations with the thickness, when the air layer height is 1.0m and 1.5m. When the thickness is lower than 20mm, the resistance increases significantly with the increasing thickness, but the increasing rate gradually declines. The variations of the thermal resistance in the thickness range of 20-30 depend on the temperature difference. In this region, the effect of thickness on the resistance is limited. When the thickness exceeds 30mm, the thermal resistance remains almost stable regarding the thickness. When the thickness increase from 10mm to 20mm, the thermal resistance can be increased by 14.77%; when the thickness is further increased from 20mm to 30mm, the increase is 1.42%. Thus, when the thickness is below 20mm, increasing the thickness is effective for thermal performance improvement. Nevertheless, when the thickness exceeds 20mm, the effect is limited. The optimal thickness lies between 20mm and 30mm, depending on the temperature difference, thus on the climate condition.

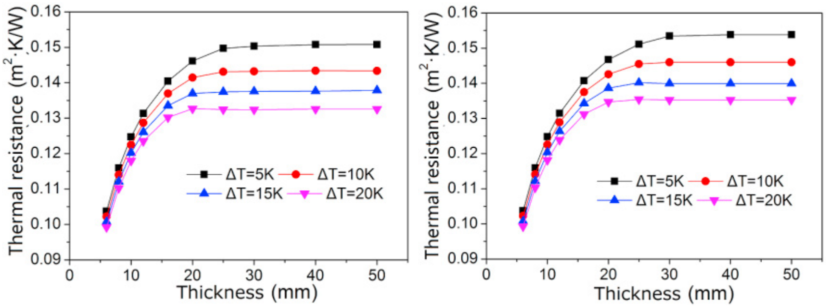

Figure 6. Effect of height and width on thermal resistance

4. conclusions

The study examines the coupled convective and radiative heat transfer in interior insulation air layers of building envelopes. The following conclusions have been drawn:

- 1）The Ra number judgment basis of the flow pattern and heat transfer in an insulation air layer is summarized based on numerical simulation.
- 2）With the thickness increase from 6mm to 50mm, the convective heat transfer ratio declines from 40% to 20%; while the radiative heat transfer ratio grows from 60% to 80%. Radiation dominates the heat transfer of the insulation air layer.
- 3）A larger layer height results in a weaker convective heat transfer; when layer thickness is lower than 20mm, a increasing thickness will lead to a considerable decrease in the heat transfer; but when thickness exceeds 20mm, the heat transfer is slightly influenced by the thickness.
- 4）An thickness increase from 10mm to 20mm results in a 14.77% increase of the thermal resistance; while the increase from 20mm to 30mm only produces a 1.42% increase. The optimal thickness of the insulation air layer is 20-30mm, depending on the climate condition.

Acknowledgements

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