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Heat transfer pattern judgment and thermal performance enhancement of insulation air layers in building envelopes[1]

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Abstract

Building envelopes act as the thermal interfaces between the indoor and outdoor environments, thus can greatly influence the indoor thermal condition and the energy consumption of air-conditioning systems. The development of high-performance exterior envelopes is anticipated to be the most effective way to guarantee both low energy consumption and high indoor thermal comfort for a building. Recently, designing and structuring intermediate enclosed air layers have become a popular way to improve the thermal insulation property of building envelopes. Based on the establishment of a dimensionless model, this study numerically investigates the flow and heat transfer characteristics of the insulation air layers with different geometrical sizes and temperature boundary conditions. By analyzing the variation tendencies of the streamlines, isotherms and temperature profiles, a simplified Rayleigh number (Ra) based judgment basis is summarized for the heat transfer pattern of the insulation air layers. Simultaneously, the critical thicknesses of the heat transfer pattern are determined under different temperature boundary conditions. Furthermore, the coupled convective and radiative heat transfer characteristics and the influencing

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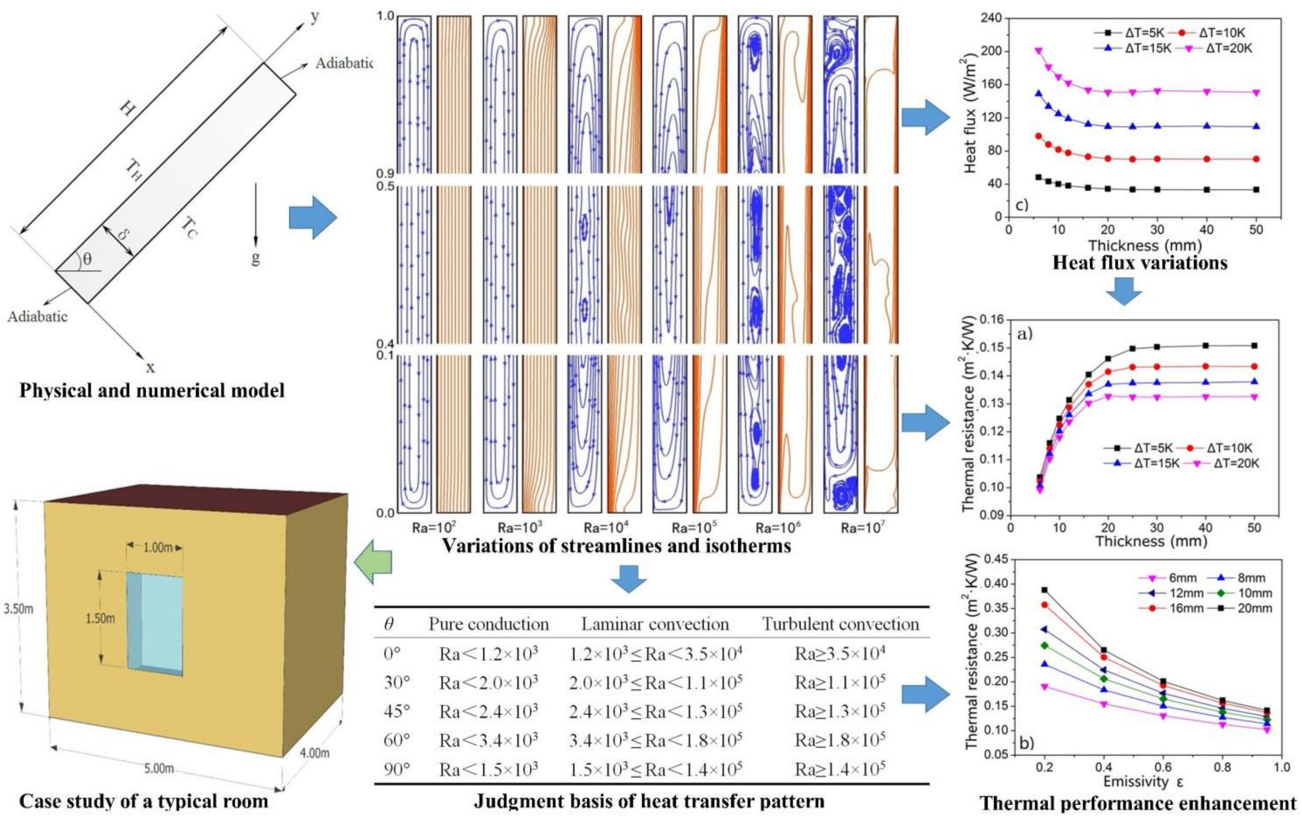
factors of the heat transfer through the air layer are examined. Finally, two measures are proposed to enhance the air layer's thermal insulation performance. The optimal air layer thickness is determined to be 20-30mm depending on the temperature boundary conditions. Reducing the surface emissivity enjoys a great potential for the thermal performance improvement of insulation air layers. When the emissivity decreases from 0.95 to 0.2, the thermal resistance of the air layer can be improved by 87.15%-172.73%. A case study indicates that using the air layer as insulation helps to reduce the annual heat transfer through the building envelopes by 10.54%-39.23% depending on the climate condition.

Graphical abstract:



Keywords: building envelopes; insulation air layer; heat transfer pattern; performance improvement

Nomenclature		**Greek symbols**	
AR	aspect ratio (H/δ)	δ	air layer thickness (m)
H	height of the air layer (m)	β	thermal expansion coefficient of air
C_p	specific heat capacity of air (J kg^{-1}K^{-1})	α	thermal diffusivity (m^2/s)
g	gravitational acceleration (m/s^2)	ρ	density (kg/m^3)

H	channel height (m)	ε	surface emissivity
Nu	Nusselt number ($h\delta/\lambda$)	λ	thermal conductivity ($Wm^{-1}K^{-1}$)
p	pressure (N/m^2)	μ	dynamic viscosity coefficient (Pa s)
P	dimensionless pressure ($p/\rho V_0^2$)	θ	inclination angle
Ra	Rayleigh number ($g\beta\Delta T\delta^3$)	φ	dimensionless temperature
Pr	Prandtl number	**Abbreviations**	
T	temperature (K)	HVAC	heating, ventilation and air-conditioning
T_H, T_C	Temperature boundaries (K)	PV	photovoltaic
u, v	velocity components in the x and y directions respectively (m/s)	COP	coefficient of performance
U,V	dimensionless velocities		
V_0	dimensionless reference velocity		
x, y	Cartesian coordinates (m)		
X,Y	dimensionless coordinates		

1. Introduction

In buildings, exterior envelopes act as the thermal interfaces between the indoor and outdoor environments, thus can greatly influence the indoor thermal condition and the overall energy consumption of air-conditioning systems [1]. As reported, approximately 20%-50% of indoor heating, ventilation and air-conditioning (HVAC) energy consumption is resulted from the heat gain or loss through building envelopes [2]. Actually, buildings' energy demand is closely linked to exterior envelopes' thermal performances. If the thermal property of a building's envelope is poor and unreasonably designed, excessive heat gain and heat loss will occur in these structure, resulting in a significant increase in the energy requirement of indoor air-conditioning systems. Therefore, it is essential to develop high-performance exterior envelopes to guarantee both low energy consumption and high indoor thermal comfort for buildings.

Various measures can be taken to enhance the thermal performance of exterior building envelopes, such as employing advanced building materials, adding insulation layers, improving the envelope structure, etc. [3]. Currently, reserving intermediate air layers has become a popular way, since the air layer can bring multiple benefits to building envelopes [4]. Nowadays, various air layer envelope components can be found in existing buildings, such as hollow wall [5, 6], double/multiple glazed window [7, 8], Trombe walls [9, 10], solar wall/chimney [11, 12], double-skin façades [13, 14], ventilated PV façades [15, 16], etc. The air layers in these components can achieve different operate modes in accordance with their configurations and regulation measures. On one hand, the air layer can also work in an open-ended mode by reserving ventilation vents to the air layer, for instance, the air layer involved Trombe walls, solar wall/chimney, double-skin façades, ventilated PV façades. In this case, multiple functions could be achieved, such as fresh air preheating and supplying, space heating, natural ventilating, and passive cooling [4], etc. On the other hand, the air layer can operate in a closed mode to serve as an extra insulation layer for exterior envelopes, such as the air layer applied in hollow wall or multiple glazed windows. Since the thermal conductivity of air is much lower than other building materials, the thermal insulation property of the envelope can be considerably improved by the air layer. This study focus on the closed working mode of the air layers in building envelopes.

A large number of previously available literatures can be found focusing on with the thermal performance of the air layer building envelopes including hollow walls and multiple glazed windows. To investigate the thermal performance of a hollow wall, Majed [5] numerically studied the coupled heat transfer of conduction and convection in a hollow brick to find the optimal insulation configuration. The results showed that the air movement inside air layers greatly influenced the heat transfer rate. A 36% reduction can be achieved in the heat transfer rate by filling the air cavities with polystyrene bars. Boukendil et al. [6] established a 2-D steady state model to study the coupled conductive, convective and radiative heat transfer through a honeycomb wall and air layer system. The simulation results indicated that the total heat flux through this wall varies almost linearly with the temperature difference. They also concluded the overall heat exchange coefficients for the thermal behavior prediction of this wall system. Later in 2017, Boukendil et al. [17] numerically investigated the combined heat transfer through an air layer in a hollow wall. They concluded the heat transfer coefficients and the thermal resistance of the intermediate air layer based on the numerical results. The influences of the surface emissivity and the mortar thickness on the total heat transfer were also examined. Zhang et al. [18] investigated the influences of the boundary condition, the material thermo-physical property, and the wall configuration on the heat transfer condition of a hollow wall through numerical simulations.

Many research results indicated that increasing the glazing number and introducing more air layers in a window is helpful for better sealing and insulation performances [19]. Consequently, double triple and glazed windows have replaced single glazed windows in recent years, regarding to its better thermal insulation performance, especially in cold regions [20]. The study on the multiple glazed window mainly focused on the thermal performance evaluation and layer thickness optimization. Xaman et al. [21] carried out a simulation study to evaluate the convective heat transfer coefficient of the air layer in double glazed windows. Nu formula was established for both the laminar and turbulent regime. Aydın [22] optimized the air layer thickness for double glazed windows applied in Turkey, based on the simulations of conjugate heat transfer in the whole window area. The optimal thickness was determined to be 12mm-21mm depending on the climates [23]. Arıcı and Karabay [7] also carried out a study to find the optimal thickness of the air layer employed in the double glazed windows, from the energy saving and initial investment point of view. In accordance with the climate conditions and some other factors, the air layer with the thickness of 12-15mm performed better in their study. Using the optimal thickness, an energy saving of 60% could be achieved.

Through the above literature review, the majority of these studies focused on the overall thermal performance of the air layer building envelopes like the hollow wall and multiple glazed windows. The influencing factors of thermal performances of these two air-layer envelopes have been extensively studied. It was found that the air layer thickness is an important factor that determines the overall thermal performance. Consequently, another hotspot was the thickness optimization of the air layer in these envelopes. So far, due to the extensive research work and practical applications of air layer insulation, the use of air layer in building envelopes has been commonly accepted as a regular thermal insulation method. Moreover, the thermal resistance of the air layer can be directly obtained in some design handbooks.

However, there are still some limitations on the researches of air layer insulation. Firstly, the obtained results on the optimal thickness show a great diversity from each other. Therefore, presently, there is not any universally applicable optimization criteria for determine the air layer thickness, since most of the previous results were obtained from comparisons between repeated tests or simulations. Secondly, for the heat transfer through the air layer, when the temperature difference imposed on the air layer is limited, and the layer thickness is small, the air movement is so weak that can be neglected. The heat transfer through the air layer tends to be pure heat conduction coupled with surface radiation. When the temperature difference and the layer thickness increase, convection effect occurs and becomes increasingly stronger, and the heat transfer pattern would possibly translate from heat conduction to laminar convection, and further to turbulent convection, coupled with radiation. Therefore, theoretically, there are three types of heat transfer patterns (pure conduction, laminar convection, turbulent convection) and two possible dividing points for the heat transfer in these air layers: one divides the conduction and convection and the other divides laminar regime and turbulent regime. If the dividing points of the heat transfer pattern could be determined, it is possible to find an optimization criterion for the thickness of the insulation air layers. Unfortunately, no such research results can be found in previous literatures.

This work aims to find these two dividing points in the air layer thickness, and to establish a simplified method for the judgment of the heat transfer pattern in insulation air layers. Based on CFD simulation, the changing tendencies of the streamlines, isotherms and temperature fields under different boundary conditions and air layer sizes are analyzed to establish a simplified judgment basis for the heat transfer pattern in the air layers. Moreover, the changing tendencies of the convective, radiative and total heat fluxes and the influencing factors of the thermal property of the air layer will also be examined. Some possible measures will be proposed to enhance the air layer's thermal insulation performance. Finally, a simplified case study will be performed to investigate the performance of using insulation air layers in real buildings.

2. Numerical methods of this study

2.1 Physical and numerical model establishment

This study focuses on the coupled heat transfer through the insulation air layers with different geometrical sizes and boundary conditions. The physical model is established, as illustrated in Fig. 1. The length of the air channel is H, and the width of the air channel is δ. The aspect ratio is defined as: $\mathrm{AR} = H / \delta$. The left and right sides of the channel are exposed to constant temperature T_H and T_c respectively. Exposed to the temperature boundaries, buoyancy driven natural convection occurs in the air layer. Some assumptions are made in this paper. The simulation focuses on the steady state stage, and the model is simplified as two-dimensional. The air in the layer is assumed as non-participating to radiation. The physical parameters of the air are assumed constant, except that the density satisfies the boussinesq approximation.

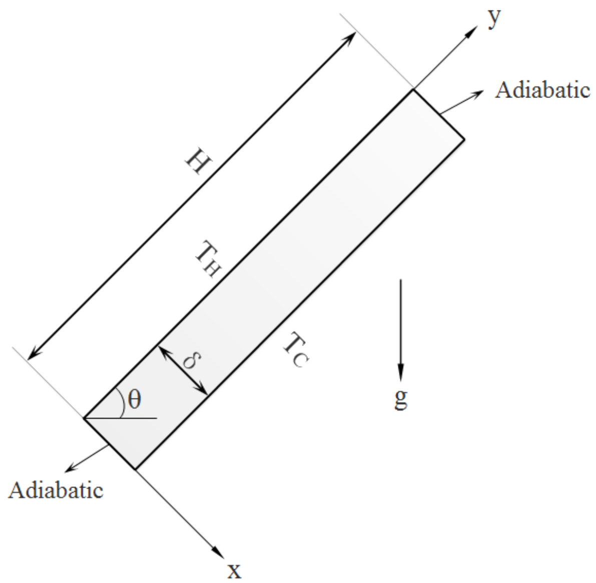


Fig.1. Computational model

For this hear transfer problem, a dimensionless model is established [24]:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\mathrm{Pr}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)-\mathrm{Ra}{\bullet}\mathrm{Pr}{\bullet}\phi{\bullet}\cos\theta \tag{2}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\mathrm{Pr}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\mathrm{Ra}{\bullet}\mathrm{Pr}{\bullet}\phi{\bullet}\sin\theta \tag{3}$$

$$U\frac{\partial \phi}{\partial X}+V\frac{\partial \phi}{\partial Y}=\frac{\partial^2 \phi}{\partial X^2}+\frac{\partial^2 \phi}{\partial Y^2} \tag{4}$$

where X and Y are dimensionless coordinates, $X=x/\delta$, $Y=y/\delta$; U and V are dimensionless velocities, $U=u\delta/a$, $V=v\delta/a$, a is thermal diffusivity; P is dimensionless pressure , $P=p/\rho V_0^2$; V_0 is dimensionless reference velocity, $V_0=\sqrt{g\beta\Delta T\delta}$, $\Delta T=T_H-T_C$; ϕ is dimensionless temperature, $\phi=(T-T_C)/(T_H-T_C)$; Ra is the Rayleigh number, Pr is the Prandtl number:

$$\mathrm{Ra}=g\Delta T\beta\delta^3/(\upsilon a) \tag{5}$$

$$\mathrm{Pr}=\nu/a \tag{6}$$

The boundary conditions are:

$$\begin{cases} X=0,\phi=1; X=1,\phi=0; \\ Y=0,\dfrac{\partial\phi}{\partial Y}=0; Y=1,\dfrac{\partial\phi}{\partial Y}=0 \end{cases} \tag{7}$$

Using this dimensionless model, the flow and heat transfer characteristics and their variation tendencies can be easily summarized by dimensionless parameters, and the judgment basis of the heat transfer pattern can be developed based on these dimensionless parameters.

2.2 Grid independence test and model validation

The finite volume method is employed to discretize the governing equations, and the second-order upwind scheme is adopted to solve the discretized equations. The SIMPLE algorithm is employed to couple the velocity and pressure during the solution. Enhanced wall function is employed to deal with the large gradients in temperature and velocity in the near-wall regions. All the discretization and solution are performed in the Fluent 6.3 software.

A grid independence test was conducted before the case studies to find out suitable grid sizes that would be applicable for solving the flow and heat transfer problems in vertical air channels. For the air layer with the size of 50mm×1000mm, this test was performed by employing mesh numbers of 8000, 12500 and 25000. Nonuniform structured meshes were made with clustering near the sidewall regions. When the Ra was set as 1×10^4, the results show that the grid number of 12500 and 25000 gave similar results on the temperature and velocity profiles. The difference between the results was only 3.86%. Therefore, these two grid numbers are applicable for this problem. To save computational time, the grid number of 12500 is the most suitable mesh scheme. Furthermore, for air layers with other sizes, similar mesh scheme can be employed.

To evaluate the model reliability and accuracy, the modeling results were directly compared to the measured data that is available in literature [25] and [26]. Fig. 2 presents the comparisons between the average Nu number and the local heat fluxes. The changing tendencies of the average Nu number with the Ra are similar between the predicted results from the simulation and the calculated results from the test. The relative effort is only 0.4%-5.44%. Therefore, the modeling results on the average are considered satisfactory. The variation tendencies of the predicted heat flux and the measure heat flux are very close to each other. The maximal errors are 6.47% and 4.02%, respectively for the temperature differences of 7.48℃ and 12.17℃ [26]. Considering both the changing tendencies and the relative errors, the established model can provide satisfactory predictions for coupled heat transfer problems in the air layers of building envelopes.

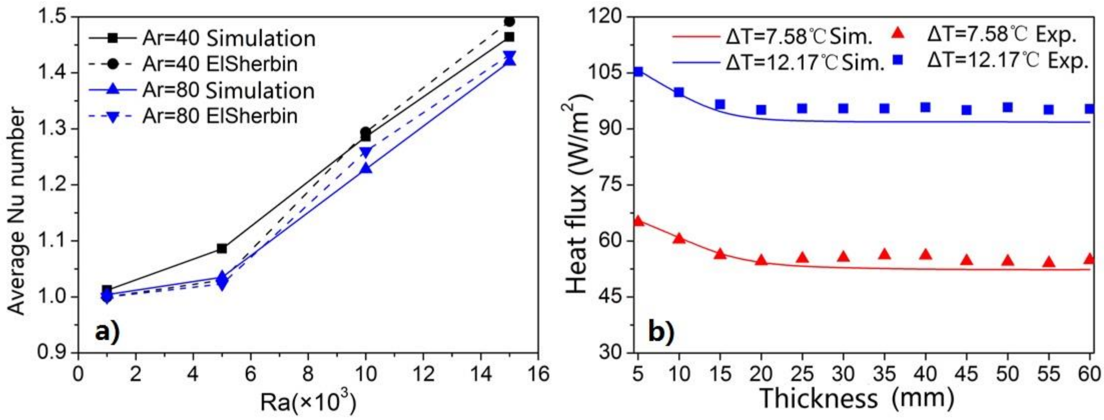


Fig. 2 Model validation on the a) average Nu number and b) heat flux.

3. Results and discussions

3.1 The flow and heat transfer in vertical air layers

Using the established dimensionless model, numerical simulations were performed for the air layers with the height of 1m, the thickness of 20mm-100mm (ARs of 10-50). In the simulation, Pr=0.71, Ra=10^2-10^7, the inclination angle θ=0-90°. The reference density of air is ρ_0=1.205kg/m^3; the coefficient of thermal expansion of the air is β=3.356×10^{-5}K^{-1}; the heat conductivity of air is λ=0.0259W/(m·K); the specific heat capacity of air is c_p=1005.43J/(kg·K); the air dynamic viscosity is μ=1.81×10^{-5}kg/(m·s). T_H and T_C were kept unchanged to be 20℃ and 0℃, to make sure that the temperature difference between the sidewalls was 20℃. The height was remained at 1m, while the thickness varied between 20mm and 100mm to achieve different AR values. Additionally, the acceleration of gravity was set to be various values to realize different Ra values. During the simulation process, when the Ra exceeds 10^5 and the iterative failed to converge, the model was switched into the realizable k-ε in the Fluent software, since the convection in the air layer became turbulent in the given boundary and gravity condition.

Fig.3 illustrates the streamlines and isotherms in the vertical air layers. Induced by the buoyancy force, the air moves upward and downward along the left and right wall, respectively. When the Ra is 10^2, the isotherms and the streamlines are parallel and uniformly distributed, and the isotherms are almost straight lines. Therefore, the natural convection of the air is very weak and can be ignored. When the Ra increases to 10^3, the isotherms bend slightly at the top and bottom, which means that convection occurs in the layer, but the intensity of the convection can still be negligible. When the Ra grows to 10^4, in the streamlines, local circulations occur. The isotherms bend dramatically at the top and bottom, and show a wavy distribution in the middle, indicating that many local air circulations are induced in the layer. Therefore, the convection intensity increases, and the convective heat transfer cannot be ignored. When the Ra comes to 10^5, the natural convection becomes a global circulation throughout the whole air layer, thus, the convection grows much stronger. When the Ra exceeds 10^6, the distributions of both the streamlines and the isotherms become seriously disordered, and some irregular vortexes occur in the streamlines. At this stage, the natural convection translates from laminar to turbulent. For air layers with other AR values, similar results can be observed.

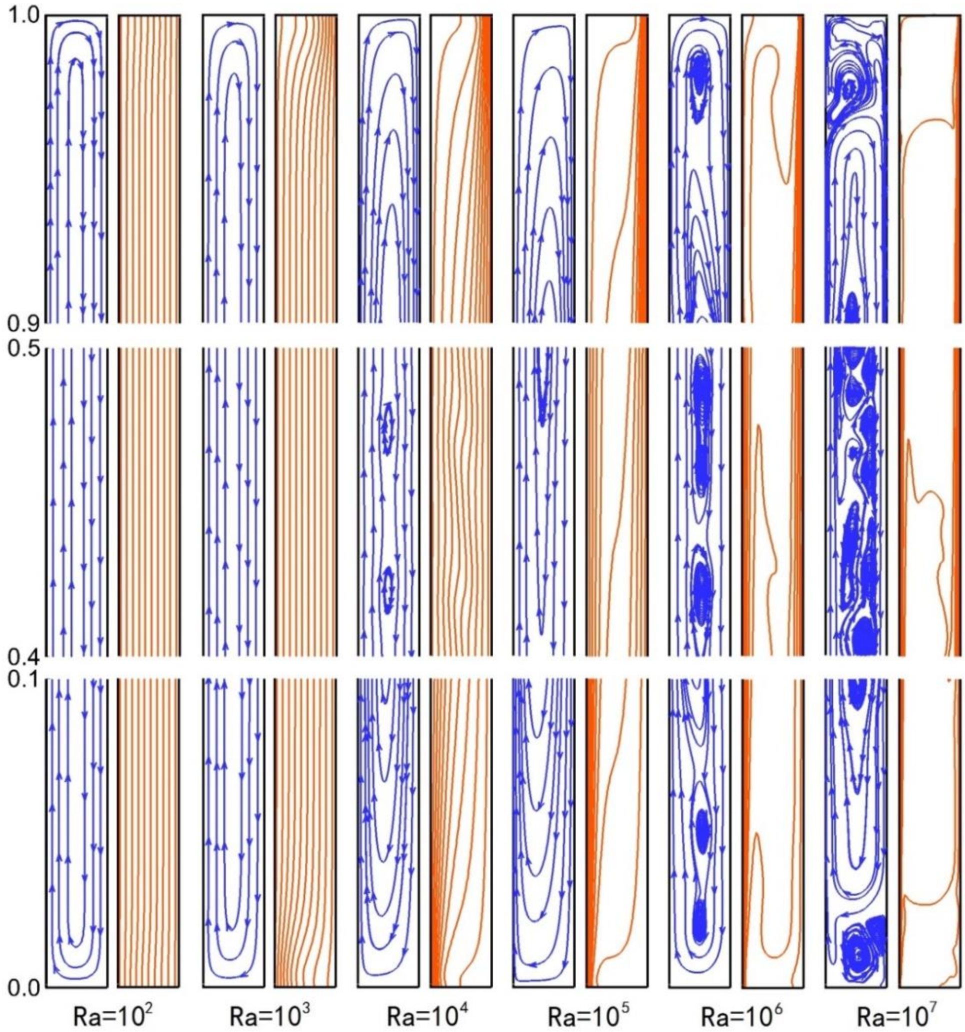


Fig.3. Streamlines and isotherms in vertical air layers with the AR of 50

When the Ra increases, the intensity of the natural convection gradually strengthens in the air layer. When the Ra is below 10^5, the natural convection belongs to the laminar regime. Moreover, in the laminar region, when the Ra is lower than 10^3, the convection effect is so weak that can be ignored. Consequently, the heat transfer can be assumed as pure heat conduction of the air, as the longitudinal movement is very weak. When the Ra is larger than 10^4, the convection becomes considerable, and the heat transfer through the air layer is a combination of heat convection and conduction, i.e. a convective heat transfer. When the Ra further grows to 10^6, the convection becomes turbulent, and the heat transfer grows to turbulent convective heat transfer.

Fig. 4 illustrates the velocity profiles at y/H=0.5 of the air layer under different Ra values and different ARs.

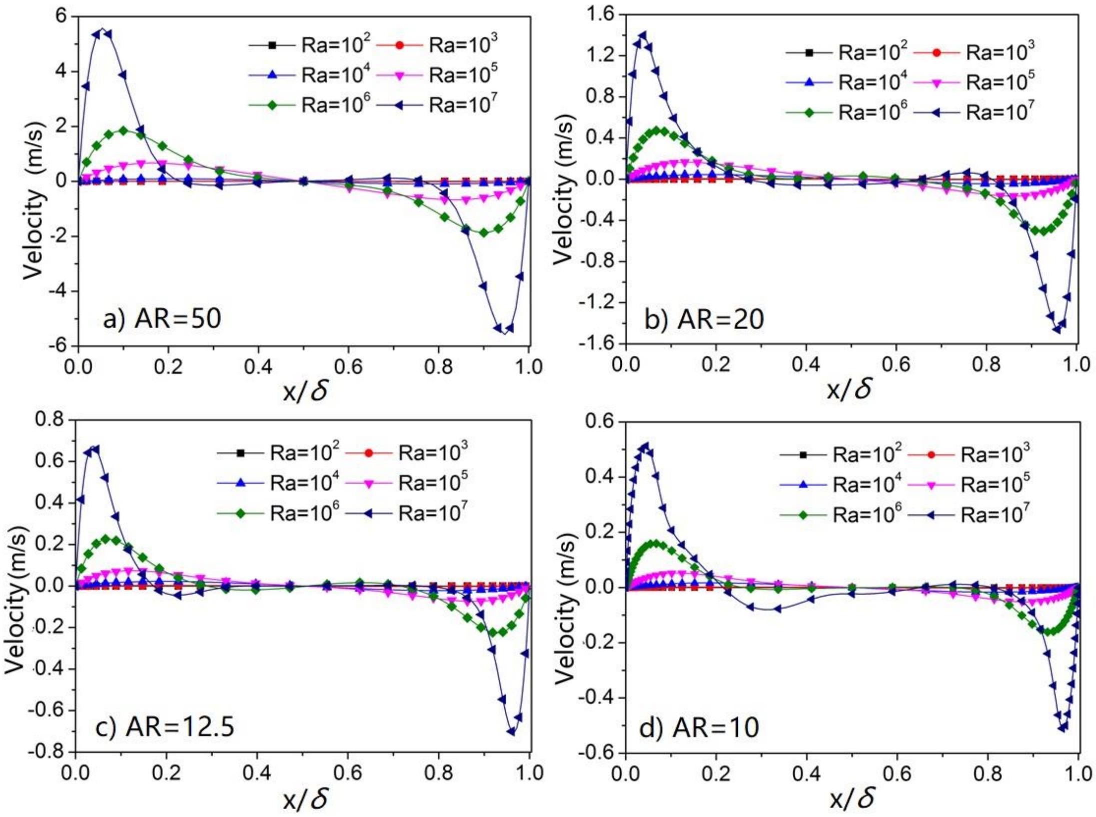


Fig.4 Velocity profiles at y/H=0.5 under different Ra values and under a) AR=50; b) AR=20; c) AR=12.5; d) AR=10

Seen from the velocity profiles, in an air layer with a given AR, the longitudinal velocity increases as the Ra increases, i.e. the air movement grows stronger when the Ra increases. When the Ra is below 10^4, the velocity curves are almost coincident with x-axis. Therefore, the air movement induced by the natural convection is weak enough to be neglected. Consequently, the heat transfer through the air layer can be treated as pure heat conduction of the air. When the Ra grows to 10^7, the temperature curves become irregular. In the left side, some of the velocities fall below zero, showing that the air movement in this region become disordered and turbulent.

For the air layers with the AR of 10-50, when the Ra is lower than 10^3, the heat transfer through the air layer can be treated as pure conduction. When the Ra exceeds 10^4, the convection dominates the heat transfer process. Moreover, the natural convection is laminar when the Ra is below 10^5, while turbulent flow occurs when the Ra exceeds 10^6. Therefore, there are two possible critical Ra values for the heat transfer in these air layers: one divides the conduction and convection ($10^3 \leqslant Ra \leqslant 10^4$) and the other divides laminar regime and turbulent regime ($10^5 \leqslant Ra \leqslant 10^6$).

3.2 Heat transfer pattern judgment and critical values of the layer thickness

To identify the critical Ra numbers, simulations were conducted for air layers with different inclination angles and ARs, under the Ra values of 10^3-10^4 and 10^5-10^6, the simulation interval was further divided into 0.1×10^3. The Ra values at which the local circulations or the irregular vortexes occur were recorded as the two critical points. Taking the vertical air layer as an example, local circulations occur at the Ra of 1.5×10^3, and irregular vortexes occur when the Ra is 1.4×10^5. Therefore, Ra=1.5×10^3 and Ra=1.4×10^5 are the dividing points for three heat transfer pattern. When Ra is below 1.5×10^3, the heat transfer is pure heat conduction; when Ra lies between 1.5×10^3 and 1.4×10^5, the heat transfer is laminar convection; when Ra is bigger than 1.4×10^5, the heat transfer is turbulent convection.

Based on the simulation results of the air layer with different inclination angles, Table 1 is summarized for the Ra judgment for this heat transfer pattern. For air layers applied in building envelopes, under a typical heat transfer condition, the Ra value can be calculated by the actual parameters. The flow and heat transfer pattern can be judged according to Table1.

Table 1. Ra judgment of heat transfer pattern in insulation air layers (AR=10~50)

θ	Pure conduction	Laminar convection	Turbulent convection
0°	$Ra<1.2\times10^3$	$1.2\times10^3\le Ra<3.5\times10^4$	$Ra\ge3.5\times10^4$
30°	$Ra<2.0\times10^3$	$2.0\times10^3\le Ra<1.1\times10^5$	$Ra\ge1.1\times10^5$
45°	$Ra<2.4\times10^3$	$2.4\times10^3\le Ra<1.3\times10^5$	$Ra\ge1.3\times10^5$
60°	$Ra<3.4\times10^3$	$3.4\times10^3\le Ra<1.8\times10^5$	$Ra\ge1.8\times10^5$
90°	$Ra<1.5\times10^3$	$1.5\times10^3\le Ra<1.4\times10^5$	$Ra\ge1.4\times10^5$

In the insulation air layers, the Ra value is determined by the temperature boundaries on the sidewalls and the layer thickness. In daily operation of the building envelopes, different temperature conditions may occur, producing various Ra values, which further leads to different heat transfer patterns including pure conduction, laminar convection and turbulent natural convection. Table 2 can be a judgment basis for the heat transfer pattern of the heat transfer through air layers. Moreover, according to

Equation 10, when the temperature difference of the sidewalls is given, the critical layer thickness (δ_1) between the heat conduction and heat convection, and the critical layer thickness (δ_2) between the laminar convection and turbulent convection can be identified based on Table 1. Table 2 summarizes the critical layer thicknesses of the air layer under different temperature difference.

Table 2 Critical layer thicknesses of air layers under different temperature differences

θ	ΔT=5K		ΔT=10K		ΔT=15K		ΔT=20K		ΔT=25K		ΔT=30K	
	δ_1	δ_2	δ_1	δ_2	δ_1	δ_2	δ_1	δ_2	δ_1	δ_2	δ_1	δ_2
0°	14.0	43.2	11.1	34.3	9.7	29.9	8.8	27.2	8.2	25.2	7.7	23.8
30°	16.6	63.2	13.2	50.2	11.5	43.8	10.5	39.8	9.7	37.0	9.2	34.8
45°	17.7	66.9	14.0	53.1	12.3	46.4	11.1	42.1	10.3	39.1	9.7	36.8
60°	19.8	74.5	15.8	59.1	13.8	51.7	12.5	46.9	11.6	43.6	10.9	41.0
90°	15.1	68.5	12.0	54.4	10.5	47.5	9.5	43.2	8.8	40.1	8.3	37.7

For an air layer under a given temperature difference, the heat transfer pattern through the air layer could be judged according to the following equation and Table 2.

$$\begin{cases} \delta < \delta_1 & \text{Pure conduction} \\ \delta_1 \leqslant \delta < \delta_2 & \text{Laminar convection} \\ \delta \geqslant \delta_2 & \text{Turbulent convection} \end{cases} \tag{12}$$

When air layers used in building envelopes as insulation, there are mainly two application scenarios: one is to serve as insulation layer in transparent windows, the other is to serve as insulation layer in opaque walls or roofs. Taking the application in window as an instance, assume the window is used in severe cold regions of China, the temperature difference between the layer-sides can be up to 30℃, and the air layer thickness is usually 9-25mm. In this case, the Ra value is 1.90×10^3-4.70×10^4. According to Table 1, the airflow is laminar, and the heat transfer is a laminar natural convection. Table 2 can also be used for this judgment. According to Table 2, when the temperature difference is 30℃, δ_1=8.3mm, δ_2=37.7mm. Therefore, the air layer with the thickness of 9-25mm lies between in the laminar convection region.

The identification of the Ra judgment and the critical layer thicknesses provide a new reference for the structure optimization of insulation air layers in building envelopes. Since the turbulent natural convection produces a stronger heat transfer effect than the laminar natural convection. Therefore, when designing and constructing an insulation air layer, the layer thickness should be lower than δ_2 in Table 2. When the layer thickness is below δ_1, the thermal resistance of an air layer increases as the thickness increases. Therefore, the thickness of an insulation air layer should be larger than δ_1 to maximize the thermal resistance of the air layer. In the region between δ_1 and δ_2, when the thickness increases, the heat conduction intensity gradually declines, while the convection intensity strengthens. Consequently, the optimal thickness should be larger than δ_1 and lower than δ_2, but the exact value should be further investigated according to the changing rates of the conduction intensity and convection intensity with the thickness.

3.3 Variations of the convective and radiative heat transfer rate

To observe the characteristics of the coupled convective and radiative heat transfer in the insulation air layer, numerical simulations were performed for the air layers with the height of 0.8m, 1.0m, 1.2m and 1.5m, the thickness of 6mm-50mm. The left sidewall temperature was set to be 15℃ according to the space heating condition, and the right sidewall temperature was set as 10℃, 5℃, 0℃ and -5℃. The radiation heat transfer can be directly calculated based on the temperature boundary conditions. The surface emissivity was 0.95, and the Stefan-Boltzmann constant was 5.67×10^{-8}W/(m^2·K^4).

Fig.5 presents the variations of the convective flux, the radiative heat flux, the total heat flux and the proportions of convection and radiation with the thickness in vertical air layers with the height of 1m. The convective heat flux and the total heat flux show similar changing tendencies. Within the region of 6-20mm, the heat fluxes drop quickly, but the degree of declining becomes lower with the increasing thickness. In the range of 20mm-30mm, the convective and total heat fluxes slightly changes with the increasing thickness, but the changing tendencies are different due to the temperature difference. The thickness no longer affects the convective and radiative heat fluxes just as the thickness grows bigger than30mm. For the radiative heat flux, a slightly reduction occurs when the thickness increase, as presented in Fig.5b. For all of the four curves, when the thickness changes from 6mm to 50mm, the average radiative heat flux reduction is only 2.63%. Therefore, the thickness just has s very weak influence on the radiation.

For the changing tendencies of the proportions of convection and radiation in the total heat flux, in the calculation region of 6-50mm, the convection proportion reduces from 43% to 22%, while the radiation proportion improves from 57% to 78%. The radiation proportion is generally larger than 60%, indicating that the radiative heat transfer occupies a dominant role, when compared with the convective heat transfer.

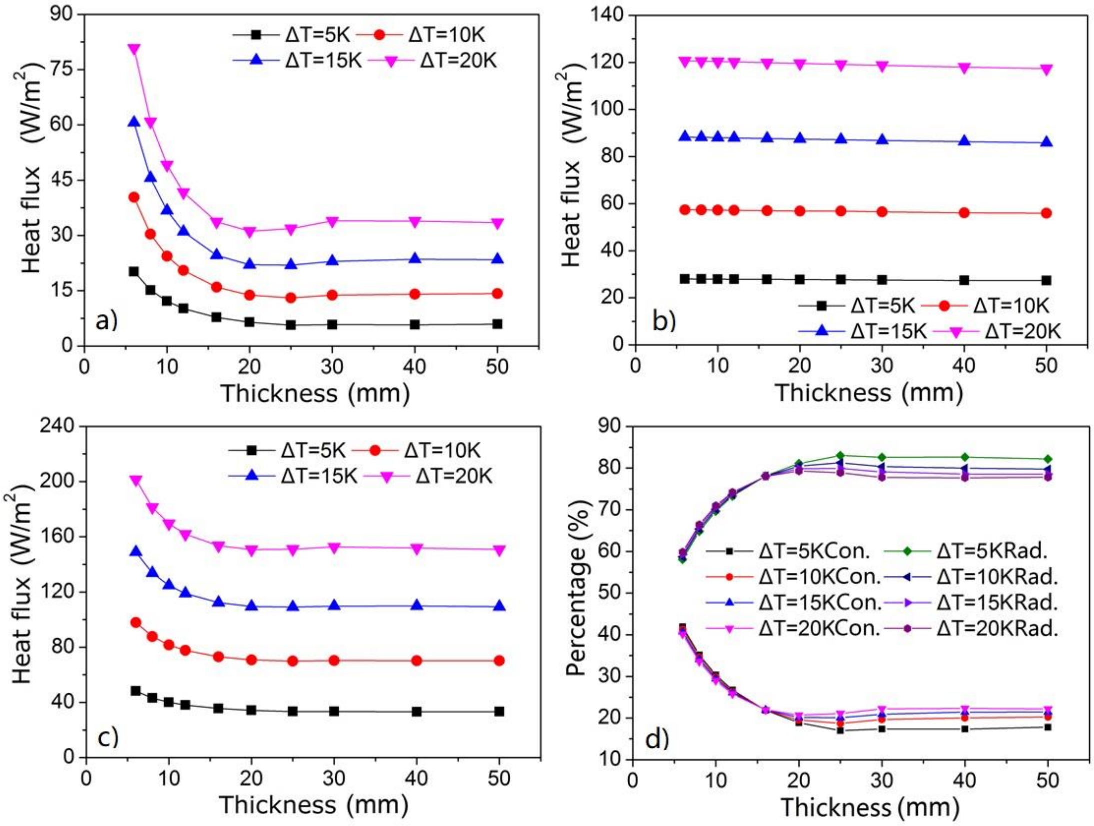


Fig. 5 Variations of a) the convective flux, b) the radiative heat flux, c) the total heat flux and d) the proportions of convection and radiation with the thickness in vertical air layers

3.4 Influential factors of the heat transfer

3.4.1 Layer height, thickness and inclination angle

The AR value of the air layer determines the confinement degree of the sidewalls on the air movement, thus influencing the natural convection and heat transfer. Fig.6

shows the effect of layer height and thickness on the convective heat flux, radiative heat flux, total heat flux, and the effect of the inclination angle on total heat flux, when ΔT=10K.

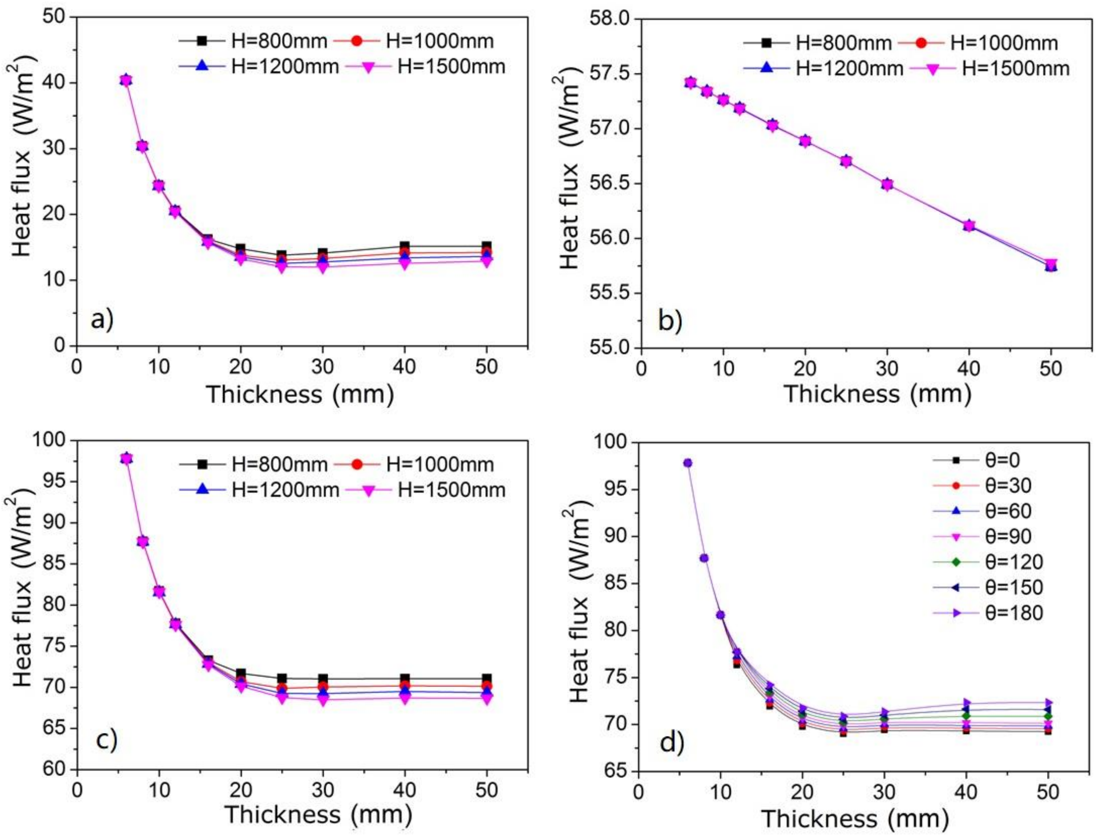


Fig.6 Effect of layer height and thickness on a) convective heat flux, b) radiative heat flux, c) total heat flux, and d) effect of inclination angle on total heat flux

Seen from Fig.6a and 6c, the changing tendencies of the convective heat flux and total heat flux are similar. These two heat fluxes decline with the increase of the layer height, thus, increasing the layer height has an inhibiting effect on the convective and total heat transfers. In Fig. 6b, the radiative heat flux curves under different layer heights are almost coincident with each other, thus, the layer height has little effect on the radiation. Increasing the layer height would be helpful to weaken the convective and total heat transfer.

In the thickness range of 6-25mm, increasing the air layer thickness can effectively reduce both the convective and the total fluxes. For the thickness bigger than 25mm, the effect of the thickness becomes very limited. The radiative heat flux slightly declines when the thickness increases. When ΔT=10K, every 1mm increase in the layer thickness results in a radiative heat flux reduction of 0.008W/m^2.

Seen from the heat flux curves under different inclination angles in Fig.6d, for the thickness lower than 12mm, the curves are almost coincident, for the reason that the heat transfer is pure conduction and unaffected by the inclination in this region. For the thickness bigger than 12mm, a lager inclination angle results in a higher total heat flux, but the increment is very small. Generally, the effect of the inclination angle on the thermal performance of the air layer is very weak.

3.4.2 Temperature difference

The temperature difference is the driving force of air movement in the air layer and the heat transfer through the air layer. Fig.7 illustrates the influence of the temperature difference on the heat transfer intensity.

Seen from Fig. 7a, for the thickness lower than 12mm, the curves agree perfectly with each other, since the convection is very weak and the heat transfer is almost pure heat conduction. When the thickness lies between 12mm and 50mm, the bigger the temperature difference, the larger the convective heat flux can be produced by unit temperature difference. The reason is that the temperature difference determines the intensity of the natural convection in the air layer. A larger temperature difference results in a stronger airflow and heat transfer. Fig. 7b shows the influence of the temperature difference on the radiative heat flux. The bigger the temperature difference, the larger the radiative heat flux will be produced, since the radiative heat flux is a fourth-order function of the temperature. For the total heat flux caused by unit temperature difference, a larger temperature difference results in a stronger total heat transfer, since both the convective and the radiative heat transfer are strengthened.

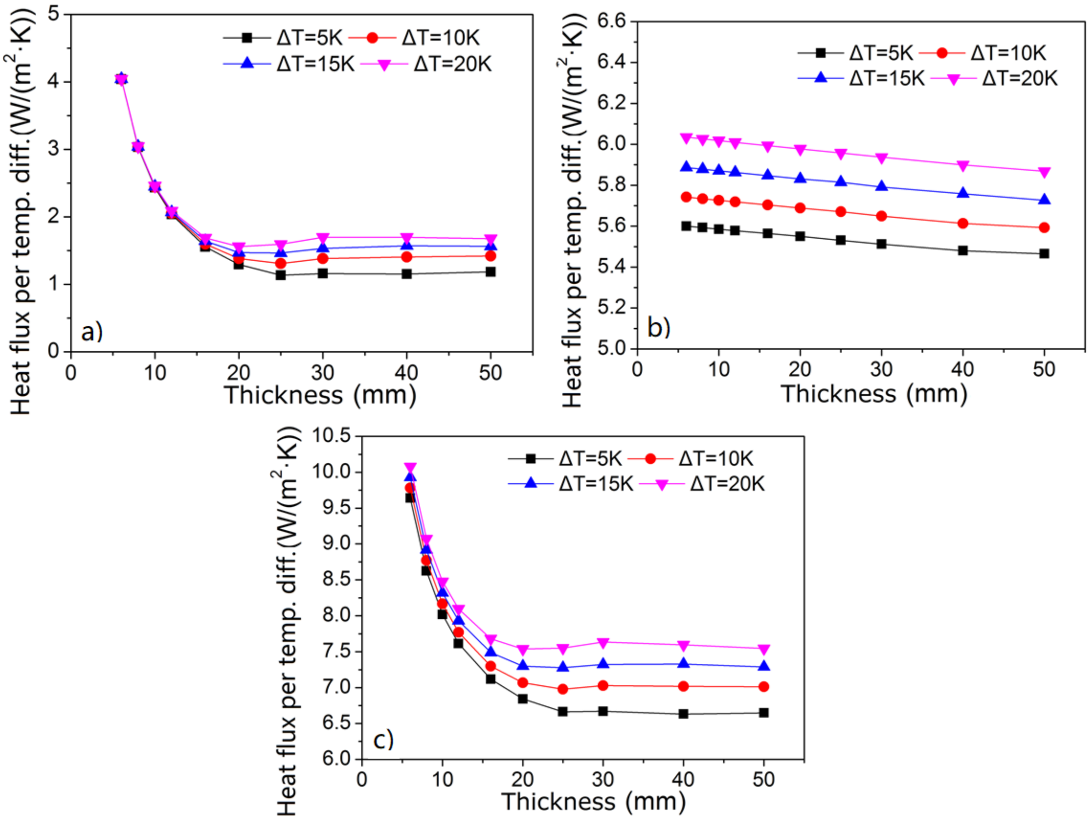


Fig.7 Changes of a) convective, b) radiative and c) total heat fluxes caused by unit temperature difference under air layer height of 1.0m

3.4.3 Surface emissivity

Besides the above factors, the surface emissivity of the sidewalls can also influence the heat transfer, since it has a considerable effect on the radiation between the surfaces. Fig.8 shows the effect of the surface emissivity on the radiative and total heat flux. For the radiative heat flux, the variation curves under different thicknesses are almost coincident. The heat flux increases with the increase of emissivity. The bigger the emissivity, the larger the flux will be produced. An increase of 0.1 in the emissivity results in a 6.02W/m^2 improvement in the radiative heat flux. For the total heat flux, the heat flux also increases with the increasing emissivity. The rate of the increase is also 6.02W/m^2. The differences between the curves are totally caused by the variations in convective heat transfer.

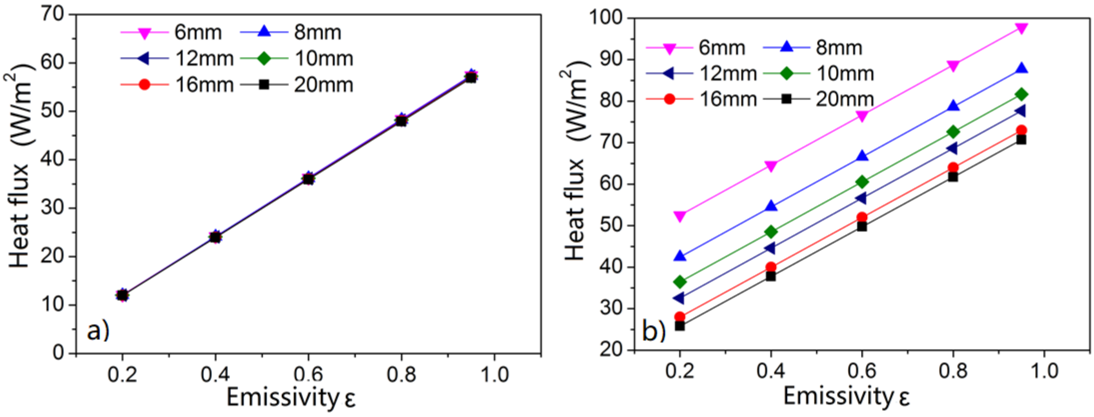


Fig.8 Influence of surface emissivity on a) radiative heat flux and b) overall heat flux under temperature difference of 10K and air layer height of 1.0m

3.5 Two ways to enhance the thermal resistance of the air layer

In insulation air layers of building envelopes, the height, thickness, inclination angle, surface emissivity and the temperature boundary can effectively influence the heat transfer intensity. Actually, in a real building, there are many restrictions when the air layer is employed to be the insulation. The inclination angle the air layer is directly determined by the type of the building envelope. When employed in walls, windows or façades, the air layer can only be vertical, while when used in flat roof or sloped roof, the air layer can be horizontal or inclined. Similarly, the layer height is strictly limited by the size of the occupant envelope. The performance of a single air layer with larger height would be better than that of multiple air layers with lower height, since it is beneficial for weakening the convective heat transfer. The temperature boundary of the air layer usually receives restriction of the climate condition. Therefore, for these three factors, there is little optimization potential to improve the thermal resistance of the air layer. Fortunately, there are still two measures to optimize the thermal performance of an insulation air layer: to optimize the thickness and to reduce the surface emissivity.

3.5.1 The optimal thickness of insulation air layers

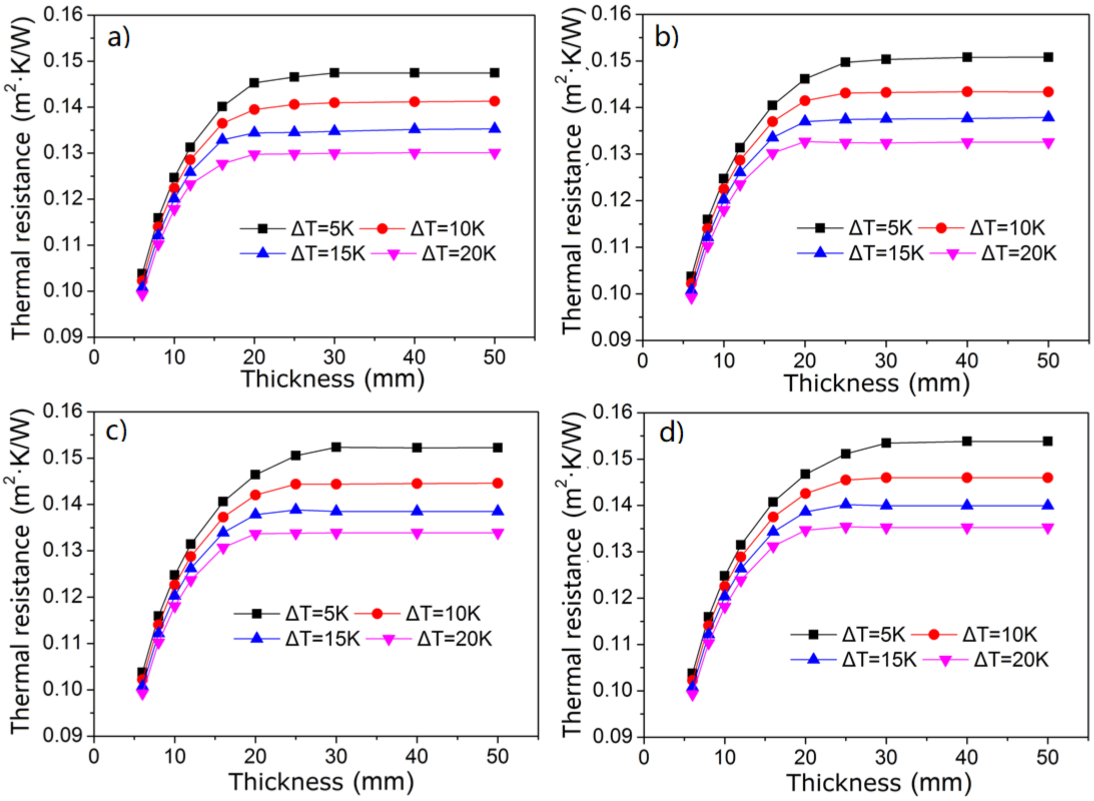


Fig.9 Thermal resistance variations with the air layer thickness when the layer height is a) 0.8m, b) 1.0m, c) 1.2m, and d) 1.5m

Fig.9 presents the changing tendencies of the air layer thermal resistance with the thickness under different layer heights. For air layers with the height of 0.8m-1.5m and the thickness below 20mm, an increment in the thickness results in significant improvement in the thermal resistance of the air layer, but the growth rate gradually reduces. With the thickness of 20-30mm, the thermal resistance receives very weak impact from the thickness, and the changing tendencies show diversities according to the temperature difference. When the thickness grows bigger than 30mm, the influence of the thickness on the thermal resistance vanishes. Increasing the thickness from 10mm to 20mm, 14.77% improvement could be achieved in the thermal resistance. However, a further increase from 20mm to 30mm only produces 1.42%. Therefore, to get a better thermal property of the insulation air layer, increasing the thickness would just be effective when the thickness is blow 20mm. Otherwise, the effectiveness would be very limited. For insulation air layer of building envelopes, the thickness of 20-30mm is recommended. If the air layer generally operates under big temperature difference condition, the optimal thickness should just be 20mm, while if it works under small temperature difference condition, the optimal thickness should be 30mm.

3.5.2 Reducing the surface emissivity

The radiative heat transfer contributes for more than 60% of the total heat transfer through an insulation air layer. Weakening the surface radiation would be an effective way to reduce the total heat transfer. Therefore, reducing the surface emissivity of the sidewalls of the air layer is a promising measure.

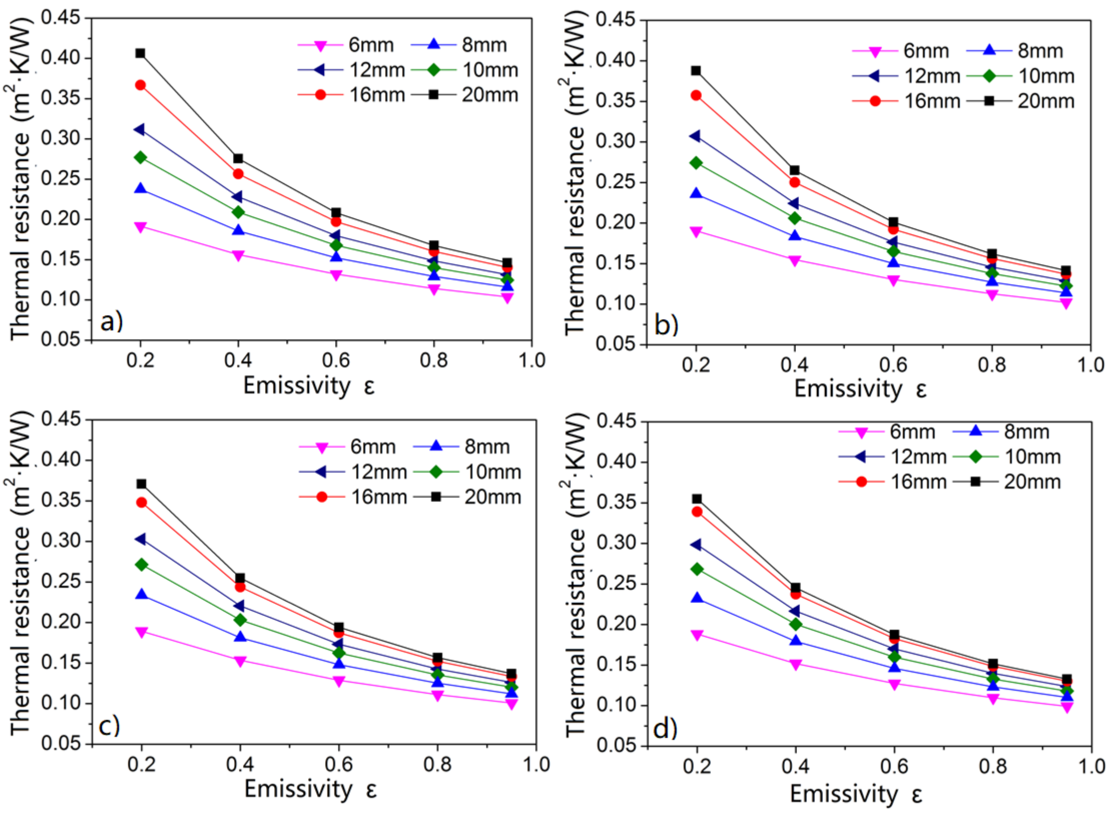


Fig.10 Thermal resistance variations with the surface emissivity when the temperature difference is a) 5K, b) 10K, c) 15K, and d) 20K

Fig.10 presents the changing tendencies of the thermal resistance with the surface emissivity, under different temperature differences. Seen from these figures, a lower surface emissivity is beneficial for the thermal resistance enchantment. The lower the emissivity, the larger the thermal resistance will be achieved. If the emissivity reduces from 0.95 to 0.8, the thermal resistance of the air layer is improved by 10.27%-14.50%. When the emissivity decreases from 0.95 to 0.6, the thermal resistance improvement is 27.76%-41.95%; when the emissivity decreases from 0.95 to 0.2, the thermal resistance improvement is 87.15%-172.73%. Therefore, reducing the surface emissivity enjoys a great potential for the thermal performance improvement of insulation air layers.

3.6 Case study

To investigate the performance of using insulation air layers in real buildings, a simplified case study was performed, and the heat loss/gain reduction effectiveness of the air layer was discussed. Fig.11 illustrates the established room model in the EnergyPlus software. It was an air-conditioned room with two windows mounted on the south and north walls. The size of room is 5.0m × 4.0m × 3.5m (length × depth × height), and the window size is 1.0m ×1.5m (width × height). All surfaces of the room are exposed to outdoor environment. Two types of building envelope systems were employed in the simulation. One is a conventional envelope system, including single layer walls, single roof and single-glazing window. The other is an air layer involved envelope system, in which insulation air layers are employed in the wall, roof, and the window. Compared with the conventional envelopes, in the air layer wall, air layer with the thermal resistance of $0.15m^2 \cdot K/W$ is added in-between the wall structural layers; in the air layer roof, air layer with the thermal resistance of $0.18m^2 \cdot K/W$ is added in-between the roof structural layers; and for the windows, a 12.7mm air layer and a glazing layer are added to form a double-glazing window. The U-values of the conventional envelopes and the air layer envelopes are illustrated in Table 3.

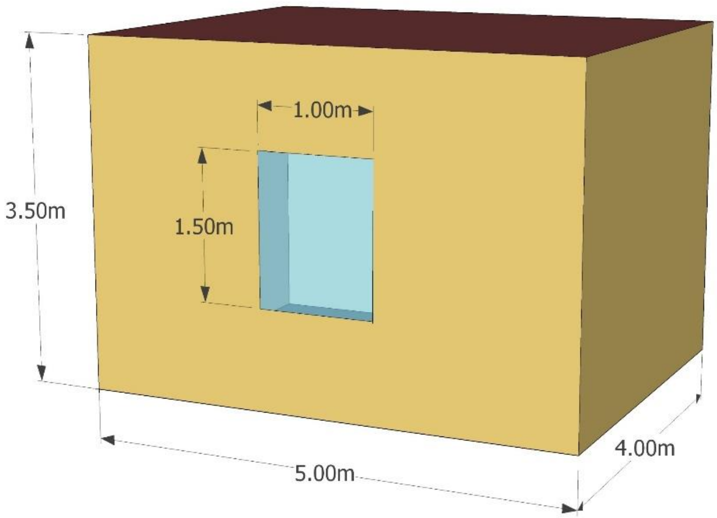


Fig.11 Simulation model of the room in EnergyPlus

Table 3 U-values of the room enclosures (W/m^{2}K)

Type	Roof	Wall	Window	Ground
Without air layer	0.274	0.860	6.424	2.945
With air layer insulation	0.261	0.761	3.149	2.945

Four cities, viz. Harbin, Beijing, Wuhan and Hong Kong, were selected to represent the different climatic zones of China. In the simulation, except the heat loss/gain through the building envelopes, all the other thermal load contributing factors are ignored, since the main purpose of this case study is to investigate the effect of using air layer insulations on the heat loss/gain of building envelopes. Consequently, the power rates of the lighting system, the indoor equipment and indoor human activities were set to be zero, and the COPs of the heating and cooling system were set as one. As a result, the heating energy consumption and cooling energy consumption obtained from the simulation can be treated as the amounts of the heat loss and heat gain through the building envelopes. The heating and cooling thermostat set points were 18 and 26°C, respectively. The air-conditioning system was assumed to operate during a whole year. The simulation results are presented in Fig.12.

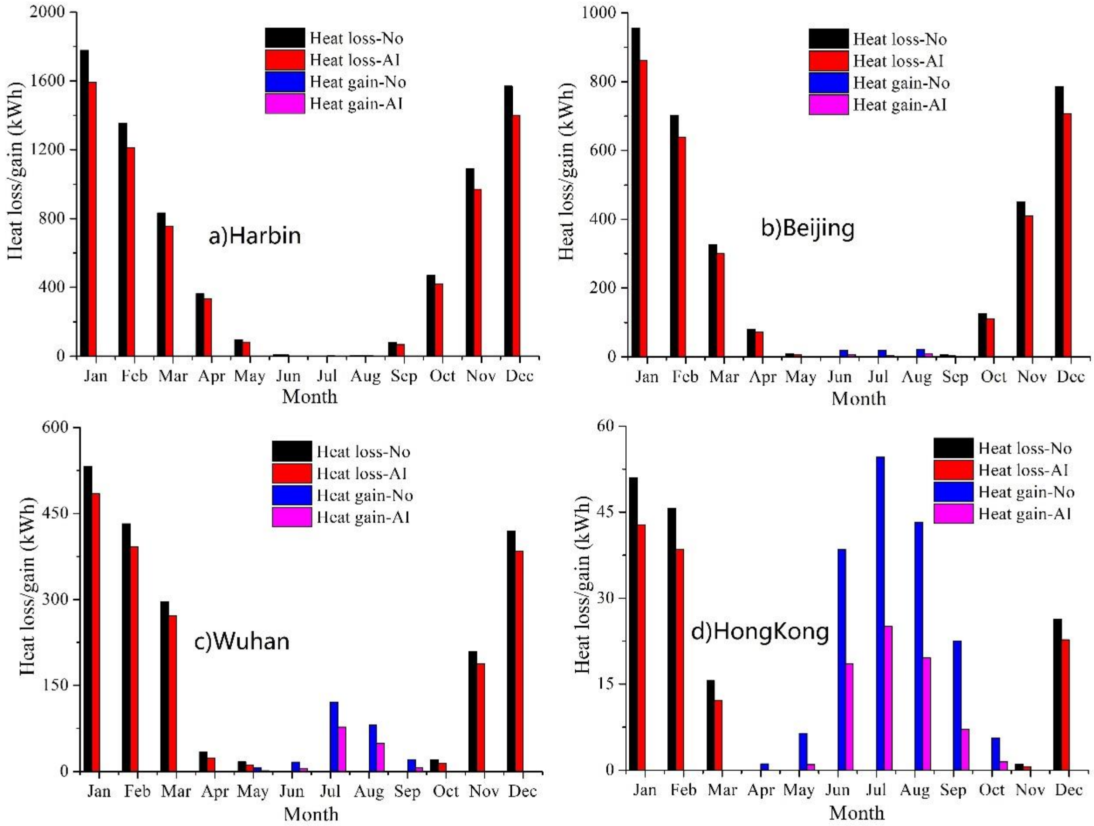


Fig.12 Effect of using insulation air layers on heat loss/gain of a typical room in different cities of China

Seen from the figure, the using of insulation air layers in the building envelopes can effectively reduce the monthly heat gain and heat loss from the building envelopes. For the room with conventional envelopes, the annual heat losses are 7642.37kWh, 3445.24kWh, 1961.18kWh and 139.65kWh, the annual heat gains are 4.65kWh, 59.56kWh, 244.93kWh and 172.00kWh, respectively for Harbin, Beijing, Wuhan, and Hong Kong. When air insulation is employed in the envelopes, the heat losses become 6840.67kWh, 3110.95kWh, 1768.14kWh and 116.80kWh, and the heat gains become 0.37kWh, 20.07kWh, 239.3kWh and 72.60kWh, respectively. The reduction rates of the heat loss are 10.49%, 9.70%, 9.84% and 16.37%, for Harbin, Beijing, Wuhan, and Hong Kong, respectively. For the heat gain, the ratios are 92.14%, 66.31%, 43.13% and 57.79% respectively. From the overall point of view, using the air layer as insulation in walls, roof and windows, the total annual heat transfer through the building envelopes can be reduced by 10.54%-39.23%, depending on the climate condition.

4. Conclusions

Designing and structuring intermediate enclosed air layers have become a popular way to improve the thermal insulation property of building envelopes. This study numerically investigates the heat transfer through the air layers with different temperature boundary conditions and geometrical sizes. The main findings of this study can be summarized as follows:

- According to the variation tendencies of the streamlines, isotherms and temperature profiles with the Ra and the aspect ratio, a simplified Ra judgment basis is established to identify the heat transfer pattern through the air layers of building envelopes. Accordingly, the critical thicknesses of these air layers are determined under different temperature boundary conditions.
- The coupled heat transfer characteristics and the influencing factors are examined. The radiation occupies more than 60% of the total heat transfer rate, thus playing the dominate role in the heat transfer though insulation air layers.
- The air layer height is inversely proportional to the natural convection intensity. When the thickness of the air layer is lower than 20mm, increasing the thickness could effectively weaken the heat transfer rate. However, if the thickness exceeds 20mm, further increment on the thickness would not be helpful for the performance improvement.
- For air layer applied in exterior building envelopes, the thickness of 20-30mm is recommended. If the air layer generally operates under big temperature difference condition, the optima thickness should just be 20mm, while if it works under small temperature difference condition, the optimal thickness should be 30mm.
- Reducing the surface emissivity enjoys a great potential for the thermal performance improvement of insulation air layers. When the emissivity decreases from 0.95 to 0.2, the thermal resistance of the air layer can be improved by 87.15%-172.73%.

- A case study indicates that using the air layer as insulation in walls, roof and windows, the total annual heat transfer through the building envelopes can be reduced by 10.54%-39.23%, depending on the climate condition.

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