Dynamic Insulation System applied to Window Frames (Part 1)

Evaluation of the thermal insulation efficiency of the proposed window frames

Sihwan Lee[1], Miho Tanaka[1] and Shinsuke Kato[2]

[1] Graduate Student, The University of Tokyo, Dept. of Architecture, Tokyo, Japan 153-8505
[2] Professor, The University of Tokyo, Institute of Industrial Science, Tokyo, Japan 153-8505

Abstract
In order to insulate buildings more efficiently, many insulation methods have been proposed and successfully applied to the building envelope, including areas such as walls and windows. However, it is also important to insulate window frames efficiently because they usually contribute the greatest heat loss. The authors propose a new dynamic insulation system for window frames, with an active ventilation function and a heat pump for heat recovery. This system is composed of three parts: window frames that use a porous material for dynamic insulation, a mechanical ventilation system, and a heat-recovery heat pump system. This paper describes a computational simulation study of the technical feasibility and the thermal insulation efficiency of the porous material in the proposed system. First, a window frame was designed containing a porous material such as a packed bed of particles (i.e. glass wool, mineral wool, aluminum particles, etc.). Then, to verify its thermal insulation efficiency, the temperature contribution of the window frame was evaluated using computer fluid dynamics with different coupled conditions, such as the indoor/outdoor pressure difference. In addition, to verify the effect of moisture condensation, the relative humidity in the porous material was calculated based on conditions such as the outdoor air temperature, humidity ratio, indoor/outdoor pressure difference, and porosity of the insulation material. The calculated results show the thermal load was inversely proportional to the indoor/outdoor pressure difference. Moisture condensation in the insulation material depends on the outdoor temperature, humidity ratio, and porosity.

Keywords: Dynamic insulation, Thermal insulation efficiency, Computational fluid dynamics

Introduction

In recent years the world has been facing an escalating energy crisis, and reducing energy consumption is a serious concern [1], [2]. This being so, many different energy saving possibilities must be investigated, especially the use and loss of energy in buildings. Most heat loss in buildings occurs by heat conduction through the building envelope, including walls, windows, and window frames. However, heat loss also occurs by infiltration through cracks. Existing residential buildings often have very poor thermal performance, with a high U-value (more correctly called the overall heat transfer coefficient) and numerous cracks, resulting in high energy use for heating, cooling and ventilation. Therefore, buildings built recently are more airtight and use a great deal of insulation to minimize the loss of energy through the building envelope. However, a sole focus on air-tightness and insulation to reduce energy consumption in buildings will make it difficult to maintain indoor air quality (IAQ). Sick building syndrome (SBS) and building-related health concerns have become a driving force for improving IAQ via various technical and policy approaches [3]. One technical solution involves dynamic insulation that blocks heat transport by making the incoming airflow pass through a porous material. Because dynamic insulation reduces heat loss and also helps maintain indoor air quality, several different dynamic insulation systems have been proposed and successfully applied to the building envelope, including walls and windows [4], [5]. Furthermore, the Building Standard Law of Japan has been in force since

July 1st, 2003, requiring a minimum indoor ventilation rate of 0.5 replacements per hour for the entire 24 hours. Many studies have shown that it is possible to use dynamic insulation efficiently in residential buildings.

Objectives

In this paper, we propose a new insulation system to insulate window frames efficiently in existing residential buildings, because they usually exhibit the greatest heat loss. The aim of this paper is to evaluate the thermal insulation efficiency of the insulation material in the proposed insulation system in order to confirm its feasibility. Moreover, we evaluate whether it produces excessive moisture condensation, depending on the outdoor temperature, the indoor/outdoor pressure difference, or the porosity of insulation material.

Methods

1. The new system proposed to increase thermal insulation and air-tightness

Figure 1 shows the concept of the new system proposed to increase thermal insulation and air-tightness of window frames in residential buildings. This system is composed of three parts, including dynamic insulation incorporated in the window frames, a mechanical ventilation system, and a heat-recovery heat pump system.

1.1. Dynamic insulation incorporated in the window frames

In this paper, in order to apply dynamic insulation to window frames, porous insulation material such as a packed bed of particulate material (i.e. glass wool, mineral wool, aluminium particles, etc.) is installed around the window so that fresh air, water vapour and heat can pass through. Figure 2 shows the principle of dynamic insulation. Dynamic insulation refers to the use of porous insulation material through which ventilation air can enter a building, thereby reducing the conductive heat loss through the material to a very low level. Assuming uniform air flow, heat transfer in the dynamic insulation can be described using a 1-D steady-state model, as given by Equation 1 [6].

$$k\frac{d^2T(x)}{dx^2} - u\rho_a C_P \frac{dT(x)}{dx} = 0 \qquad \text{(Eq. 1)}$$

where k [W/m·K] is the thermal conductivity of the insulation material, T [K] is the temperature, ρ_a [kg/m^3] and C_P [J/kg·K] are the density and the heat capacity of air, and u [m/s] is the air velocity.

Assuming a constant temperature boundary condition for the indoor and outdoor environments, the following dynamic U-value can be derived to represent the overall heat loss, as given by Equation 2. The dynamic U-value, U_{dyn} is the U-value of the wall modified by the air velocity across it and the insulation thickness.

$$U_{dyn} = \frac{u\rho_a C_p}{e^{\frac{u\rho_a C_p L}{k}} - 1} \qquad \text{(Eq. 2)}$$

where L [m] is the insulation thickness. It is clear that the dynamic U-value is a function of the air velocity, or, more exactly, the Pe number, as given by Equation 3. This is defined to be the ratio of the rate of advection of a physical quantity by flow to the rate of diffusion of the same quantity driven by an appropriate gradient.

$$Pe = \frac{u\rho_a C_p L}{k} \qquad \text{(Eq. 3)}$$

1.2. Mechanical ventilation system

A mechanical ventilation system is used to maintain an adequate supply of fresh air and to maintain the thermal insulation efficiency of the dynamic insulation. This means that indoor air leaves the room through the ventilation system, while fresh air enters the room through the porous material in the window frames.

1.3. Heat-recovery heat pump system

The heat pump system recovers exhaust heat, enabling the creation of a zero-energy house. However, the heat recovery function of the heat pump system is used only in winter, because a positive pressure condition must be maintained indoors to prevent moisture condensation in summer.

2. Numerical evaluation of thermal insulation efficiency

Computer fluid dynamics (CFD) was used to model fluid, heat flow, and condensation in the insulation material of the proposed system. CFD has been widely used to simulate air movement, heat transfer, mass transfer, and the interaction between indoor and outdoor environments.

2.1. Calculation model

To determine the thermal insulation efficiency of the proposed system, the temperature contributions of the window frames were calculated using computer fluid dynamics under different coupled conditions, i.e. the indoor/outdoor pressure difference. The calculation model was applied to simulate the insulation material, as shown in Fig. 3(a). The model included an indoor zone, an outdoor zone, a window, and a window frame. Details of the window frame (1.10 m × 1.04 m × 1.04 m) used to for calculation are shown in Fig 3(b). The insulation material applied to the window frame acts as an air supply opening, allowing fresh air into the room. In this study, the effects of the heat pump system and the window are not considered, in order to keep the model simple.

2.2. Flow model and boundary conditions

A high-Reynolds number k-epsilon turbulence model was used for computing the turbulent viscosity and diffusivity. For modeling of fluid, heat flow, and condensation, the boundary conditions required for the simulation were those associated with heat transfer through air and insulation material, and properties such as porosity and diameter. The boundary conditions and material properties for the simulation are summarized in Tables 1, 2, and 3.

2.2.1. Flow model for the porous media

The steady state flow model for simulation of the porous media is represented by a mass conservation equation as follows.

$$\frac{\partial(\rho U_i)}{\partial x_i} = 0 \qquad \text{(Eq. 4)}$$

where U_i is the mean superficial air velocity in the x_i direction. The superficial air velocity (velocity based on volumetric flow rate) is related to the physical velocity V_i (true velocity through pores of the medium for instance) by the porosity, $U_i = \varepsilon V_i$.

The permeability and inertial resistance factor of the porous media were derived from the Ergun equation, as given by Equation [7]. The Ergun equation is applied here for the pressure drop, *dp*, over the length, *dL*, determined by the diameter of the porous material, assuming that the U-value is 0 W/m^2 when the pressure difference is 10 Pa.

$$\frac{dp}{dL}=\frac{150\mu(1-\varepsilon)^2}{\varepsilon^3{\phi_C}^2D_P^2}U+\frac{1.75\rho(1-\varepsilon)}{\varepsilon^3\phi_C D_P}U^2 \qquad \text{(Eq. 5)}$$

where φ_C [-] is the shape factor, U [m/s] is the superficial velocity through the medium, ρ [kg/m^3] is the fluid density, D_P [m] is the diameter of the porous material, μ [kg/m·s] is the molecular viscosity, and ε [-] is the porosity or void fraction of the porous medium.

2.2.2. Air density

The density ρ of a mixture of dry air molecules and water vapour molecules can be expressed by Equation 6. To determine the density of the air, it is necessary to know the actual air pressure, the water vapour pressure, and the air temperature.

$$\rho=\frac{P_{dry}}{R_{dry}\times T}+\frac{P_{vapor}}{R_{vapor}\times T} \qquad \text{(Eq. 6)}$$

where P_{dry} [Pa] is the pressure of dry air in pascals, P_{vapour} [Pa] is the pressure of water vapour in pascals, R_{dry} [287.05 J/kg·K] is the gas constant for dry air, and R_{vapour} [461.49 J/kg·K] is the gas constant for water vapour.

2.2.3. Thermal conductivity

The effective thermal conductivity of the porous material, k_{eff}, can be expressed as the volume average of the fluid conductivity and the solid conductivity, as shown in Equation 7.

Figure 5 shows the applied thermal conductivity in porous media in terms of porosity.

$$k_{eff} = \varepsilon \times k_{fluid} + (1-\varepsilon) \times k_{solid} \qquad \text{(Eq. 7)}$$

where k_{solid} [W/m·K] is the solid medium thermal conductivity, and k_{fluid} [W/m·K] is the fluid phase thermal conductivity.

2.2.4. Mass diffusivity

The diffusion of moisture through building materials is a natural phenomenon, and it has significant effects on the comfort of the indoor environment. The effective diffusion coefficient in porous media, D_e, describes diffusion through the pore space of porous media, as shown in Equation 8 [8]. Figure 6 shows the applied effective diffusion coefficient in porous media in terms of porosity.

$$D_e = \frac{D \varepsilon_t \delta}{\tau} \qquad \text{(Eq. 8)}$$

where D [m^2/s] is the diffusion coefficient of the gas or liquid filling the pores, ε_t [-] is the porosity available for transport, δ [-] is constrictivity, and τ [-] is tortuosity. In this study, we calculate the diffusion coefficient D using the following formula [9], [10].

$$D = 2.31 \times 10^{-5} \left(\frac{T}{273.16} \right)^{1.81} \left(\frac{P_a}{P_a + P_v} \right) \qquad \text{(Eq. 9)}$$

where P_a [Pa] is the air pressure, in this case the atmospheric pressure, and P_v [Pa] is the vapour pressure.

2.3. Simulated cases

Figure 4 shows the calculated cases for the CFD simulation. These cases were based on the indoor/outdoor pressure difference, the outdoor temperature and the porosity of the insulation material in summer and winter. Table 2 shows the calculated cases in summer operating mode and Table 3 shows the calculated cases in winter operating mode.

Results and Discussion

1. Effect of indoor/outdoor pressure difference

Figures 7(a) and 10(a) show the calculated result of the temperature distribution across the insulation material versus the indoor/outdoor pressure difference in summer and winter. In winter, the air temperature rises slowly as the outdoor air passes through the insulation materials, and it is cooled slowly in summer. The heat loss/gain in the room was reduced with increases in the indoor/outdoor pressure difference, depending upon the estimated pressure drop across the porous material, as shown figure 13(a). However, it is necessary to calculate suitable ventilation rates because it is possible to increase ventilation loads by increasing the indoor/outdoor pressure difference. Therefore, this is the best way to use the heat pump system to recover heat from the exhaust air to realize zero-energy residential buildings.

Figures 7(b), 7(c), 10(b), and 10(c) show the calculated relative humidity and absolute humidity distribution versus the indoor/outdoor pressure difference in summer and winter. The results show that no moisture condensation occurred in any calculated case. Condensation did not occur in summer because no vapour barrier was used in the insulation material. It did not occur in winter either, because lower humidity of the outdoor air entered the indoor environment directly.

2. Effect of outdoor temperature

Figures 8(a) and 11(a) show the temperature distribution across the insulation material versus the outdoor temperature at an indoor/outdoor pressure difference of 10 Pa. The heat loss/gain in the room was smaller with a smaller indoor/outdoor temperature difference, as shown figure 13(b). Furthermore, the variation of the indoor wall surface temperature increased with a decrease in the indoor/outdoor temperature difference at a fixed pressure difference.

Figure 8(b), 8(c), 11(b), 11(c) show the calculated results for the relative humidity and absolute humidity distribution versus the outdoor temperature, showing that no moisture condensation occurred in the porous material in any calculated cases.

3. Effect of porosity

Figures 9 and 12 show the calculated heat loss/gain versus the porosity of insulation material. The heat loss/gain is approximately 0 W/m^2 with a porosity of greater than 50% when the indoor/outdoor pressure difference is 10 Pa, as shown in Figure 13(c). Therefore, we know that thermal insulation efficiency increases with increasing porosity of the insulation material.

Conclusions

This paper proposed a new system of dynamic insulation for window frames to reduce energy consumption, and conducted a feasibility study on its effectiveness using CFD simulation. In this paper, we found that the thermal insulation efficiency of the proposed system increased with increasing indoor/outdoor pressure difference, with decreasing indoor/outdoor temperature difference, and with increasing porosity of the insulation material. A summary of the general findings of this study is as follows.

1. The heat loss/gain in the room was reduced with increasing indoor/outdoor pressure difference, depending upon the estimated pressure drop across the porous material. Furthermore, it was also reduced with decreasing indoor/outdoor temperature difference.

2. According to the calculations on porosity, the heat loss/gain is approximately 0 W/m^2 for porosities greater than 50% when the indoor/outdoor pressure difference is 10 Pa.

3. No moisture condensation occurred in the porous material in any calculated case in summer and winter.

4. The properties of other porous materials should be measured and a new material developed with improved characteristics. Moreover, thermal comfort should be calculated for a realizable room model by examining the effects of any cold drafts and the energy-saving effects of the heat pumps included in the proposed system, and this will be evaluated in future investigations.

Acknowledgments

This study was made possible by the financial support received from the Ministry of the Environment, Japan. Moreover, we would like to thank the staff at Sankyo Tateyama Aluminium Inc., J Architecture System Inc., and Tsuchiya Hometopia Inc. for their generous cooperation.

References

1. IPCC Fourth Assessment Report (AR4), “Climate Change 2007: Synthesis Report”, November, 2008, (http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm).

2. Materials of the International Energy Agency (IEA), “Energy Policies of IEA Countries – Japan 2008 Review”, June, 2008, (http://www.oecd.org/LongAbstract/0,3425,en_33873108_33873539_40804559_1_1_1_1,00.html).

3. Spengler J., Samet J., McCarthy J., Indoor Air Quality Handbook, Vol. 1.1–1.1 9, McGraw-Hill Professional Publishing, USA, 2001, pp. 22.1–22.11.

4. A. Dimoudi et al. “Experimental work on a linked, dynamic and ventilated, wall component,” Energy and Buildings 36, 2004, pp. 443-453.

5. Arvid Dalehaug et al. “Dynamic Insulation in a wall,” Report Collection of Architectural Institute of Japan, No. 66, 1993.

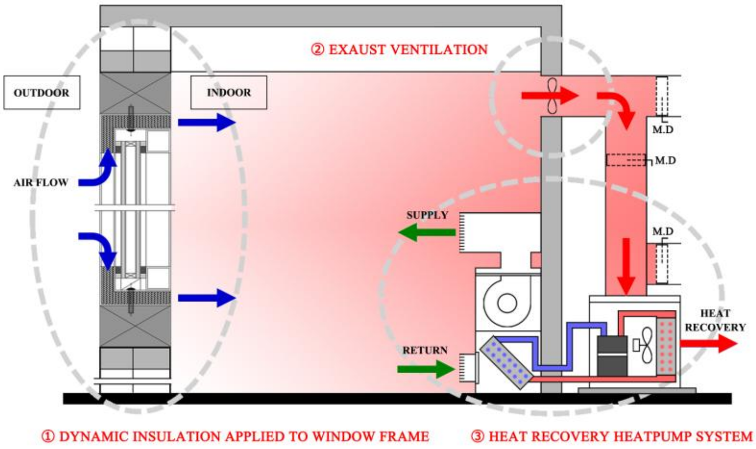
6. Annex 44 A3, “Dynamic Insulation Systems,” Annex 44 State-of-the-Art Working Report Part A3, (www.civil.aau.dk/Annex44).

7. Sabri Ergun, “Fluid Flow Through Packed Columns,” Vol. 48, No. 2, Chemical Engineering Progress, 1952, pp.89~94.

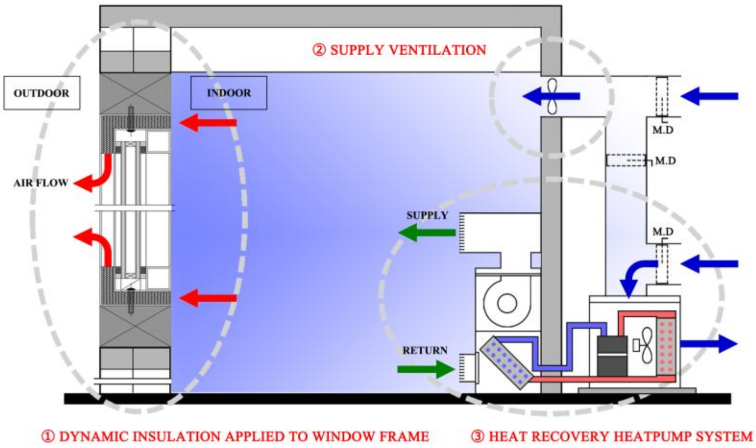
8. P. Grathwohl, “Diffusion in natural porous media: Contaminant transport, sorption / desorption and dissolution kinetics,” Kluwer Academic Publishers, 1998.

9. Boynton, W.P., Brattain, W.H., 1929. Interdiffusion of gases and vapors. International Critical Tables 5.

10. Schirmer, R., “The diffusion coefficient water vapour-air mixtures and the rate of evaporation,” VDI Beihaft Verfahrestechnik 6, 1938.

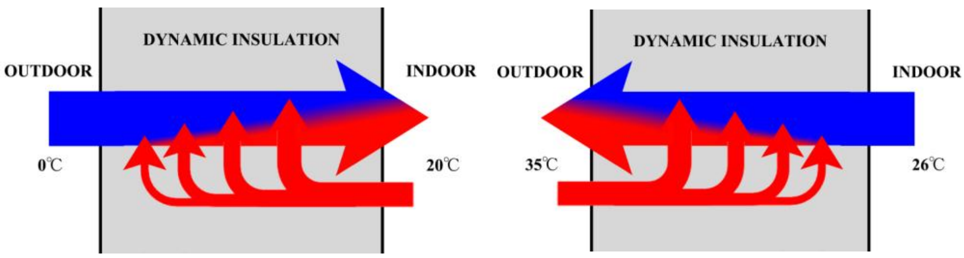


(a) Winter mode [negative indoor pressure]



(b) Summer mode [positive indoor pressure]

Fig. 1 Mechanisms of the proposed system



(a) Winter mode [negative indoor pressure]   (b) Summer mode [positive indoor pressure]

Fig. 2 Principle of dynamic insulation

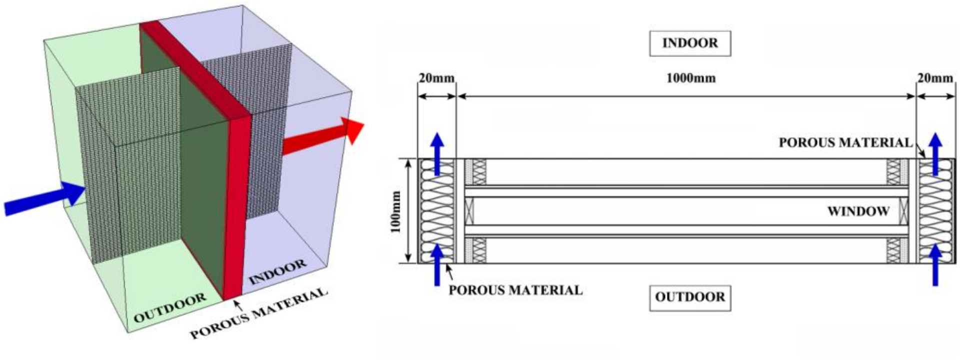
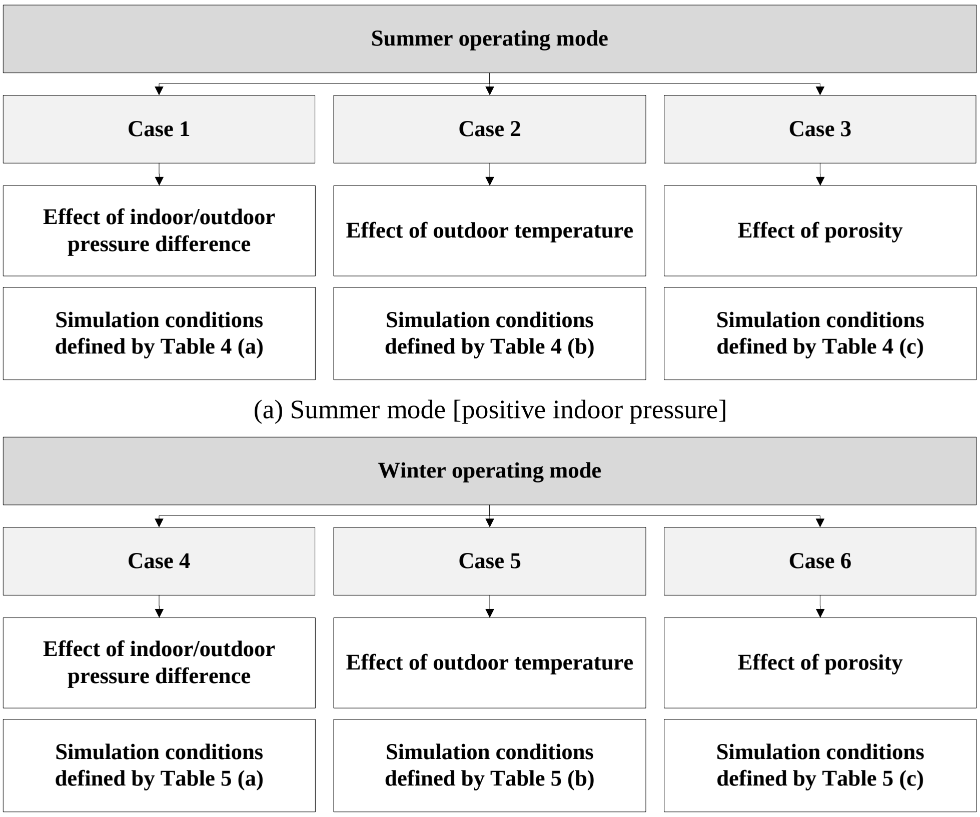


Fig. 3 Calculation model



(a) Summer mode [positive indoor pressure]

(b) Winter mode [positive indoor pressure]

Fig. 4 Simulated Cases

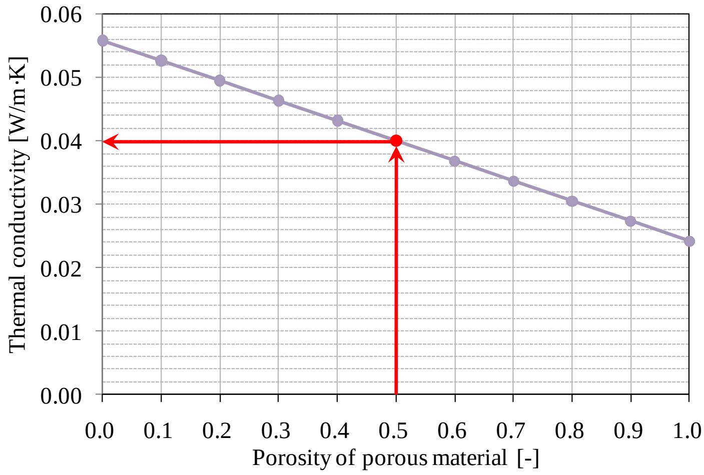
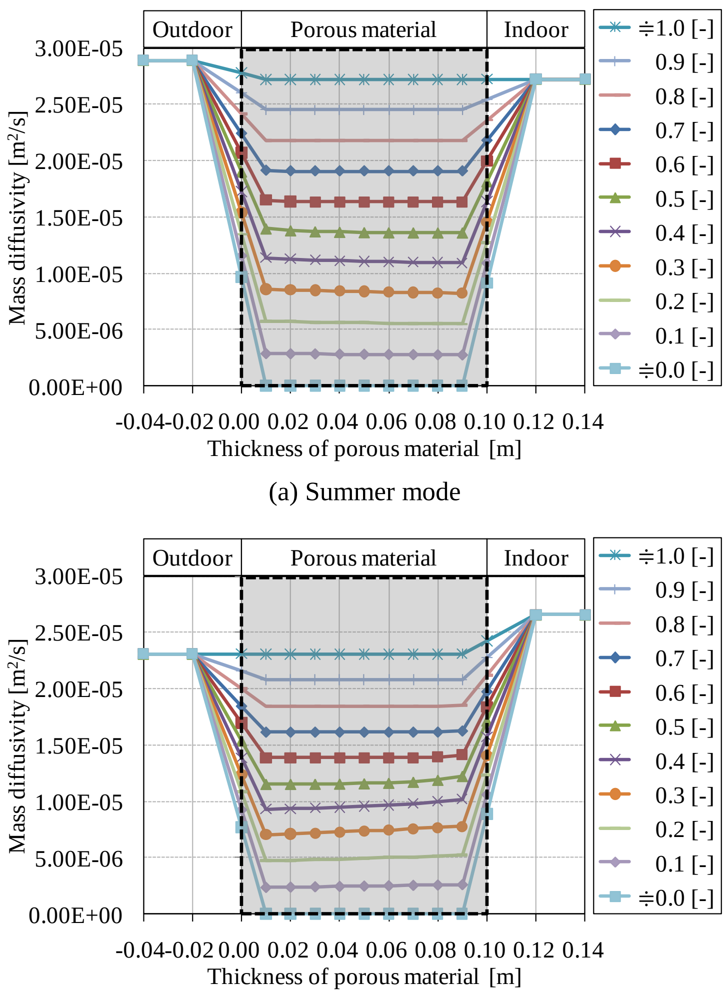


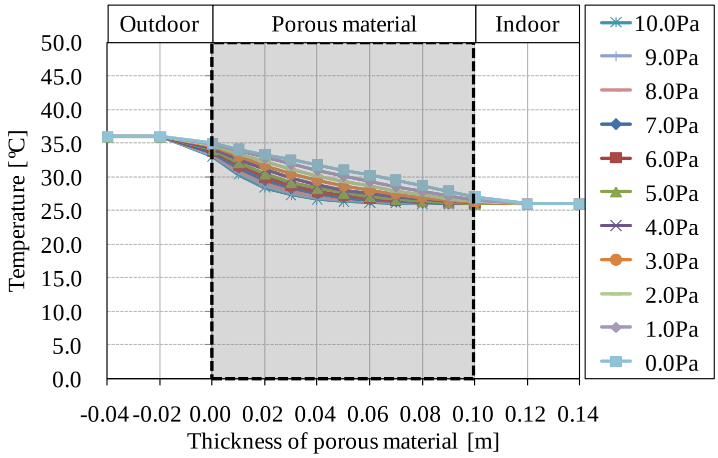
Fig. 5 Thermal conductivity of porous media versus porosity [W/m·K]



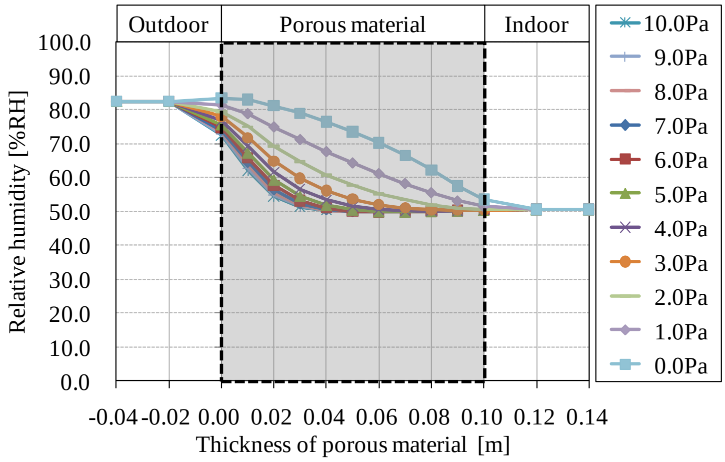
(a) Summer mode

(b) Winter mode

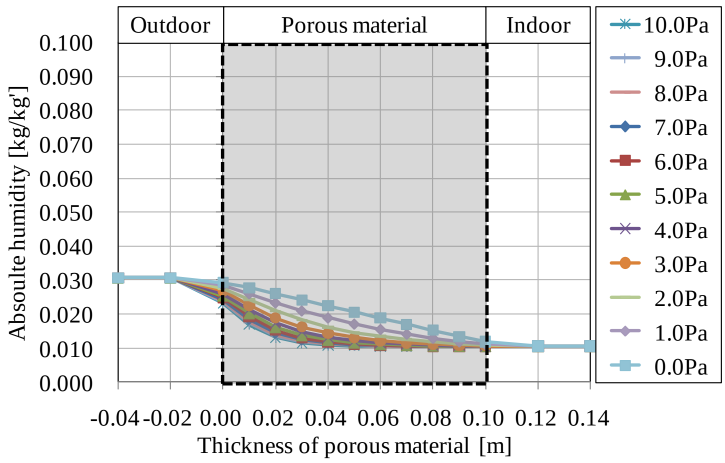
Fig. 6 Mass diffusivity versus porosity [m^2/s]



(a) Temperature distribution

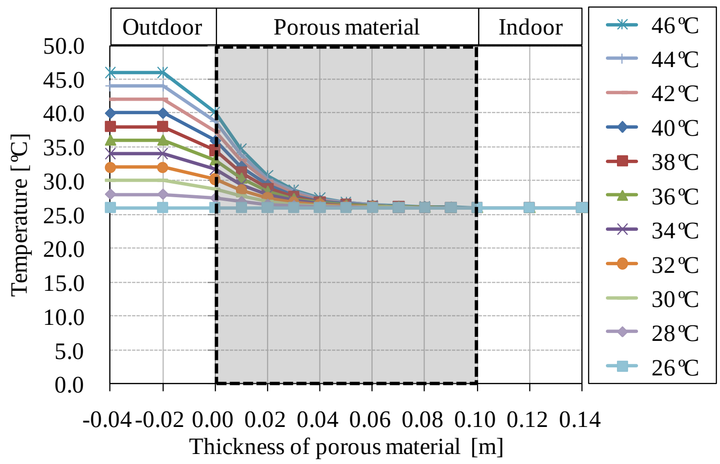


(b) Relative humidity distribution

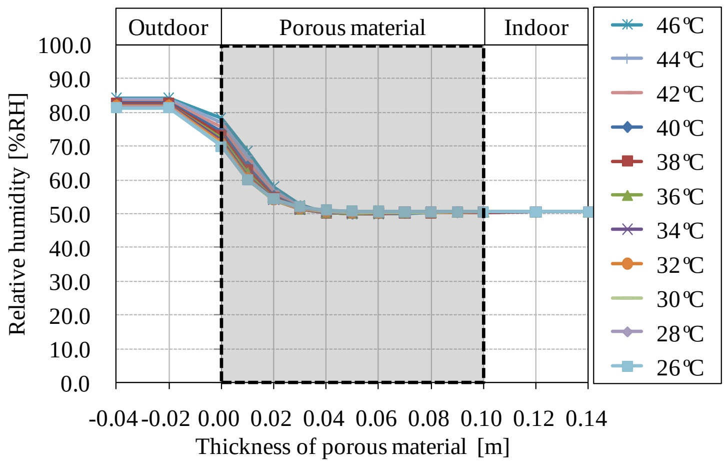


(c) Absolute humidity distribution

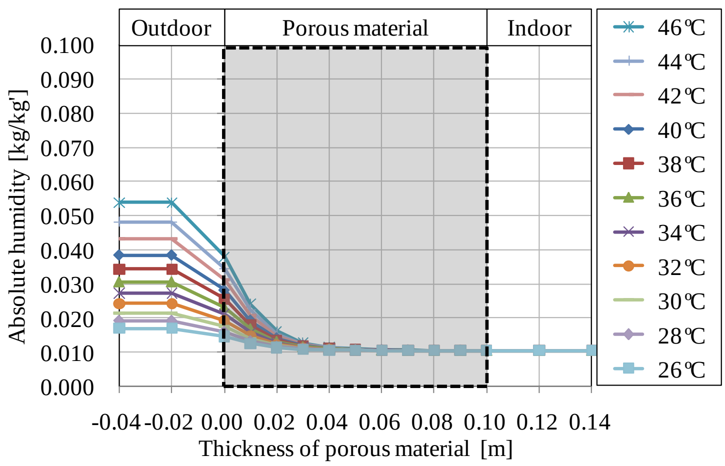
Fig. 7 Simulation results for Case 1



(a) Temperature distribution

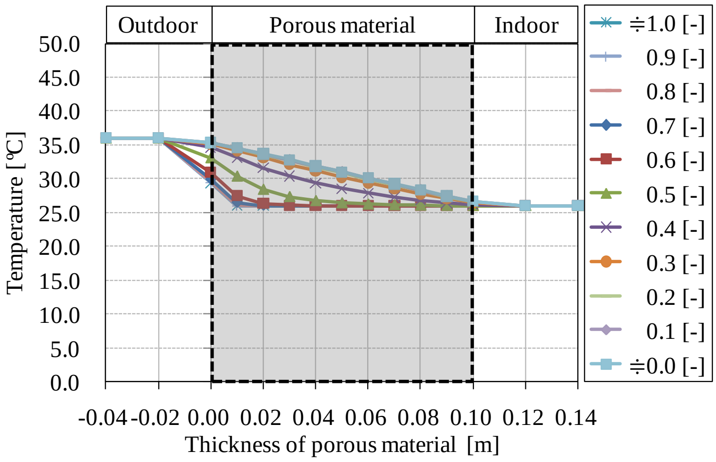


(b) Relative humidity distribution

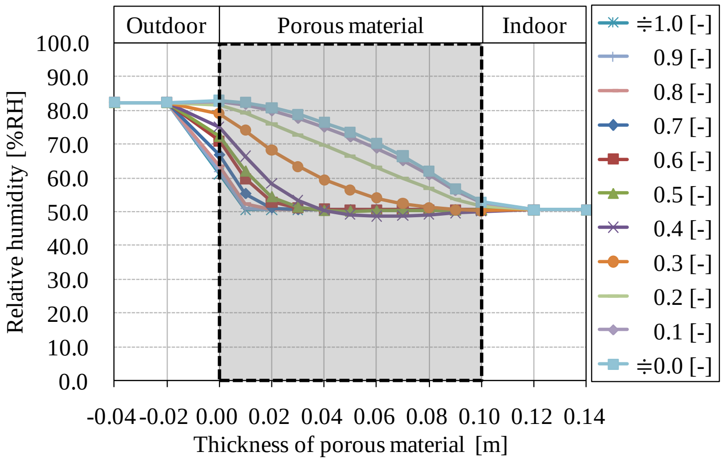


(c) Absolute humidity distribution

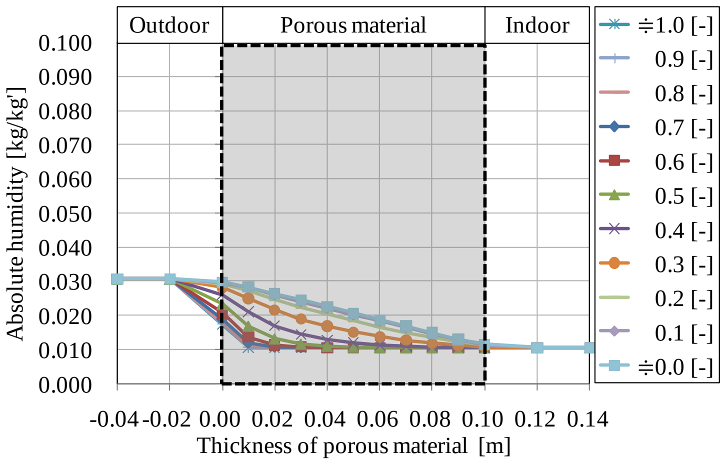
Fig. 8 Simulation results for Case 2



(a) Temperature distribution

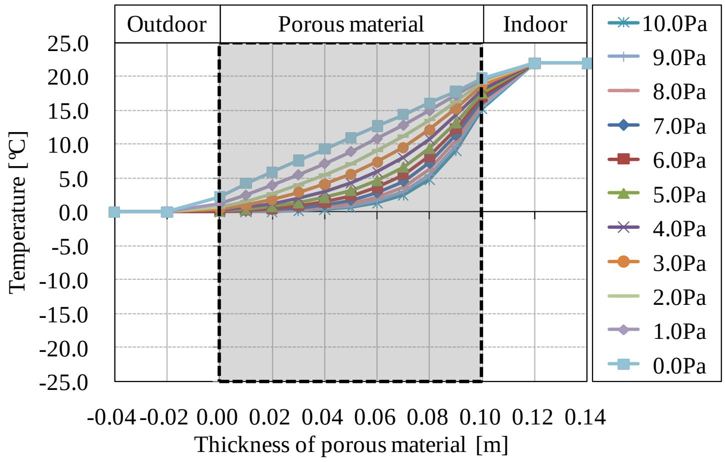


(b) Relative humidity distribution

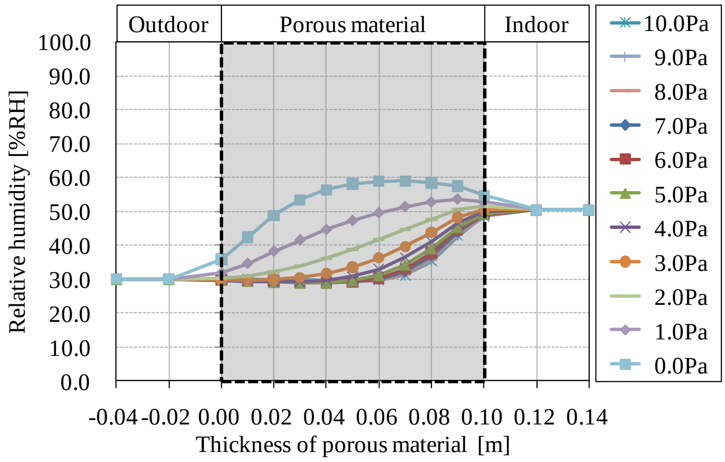


(c) Absolute humidity distribution

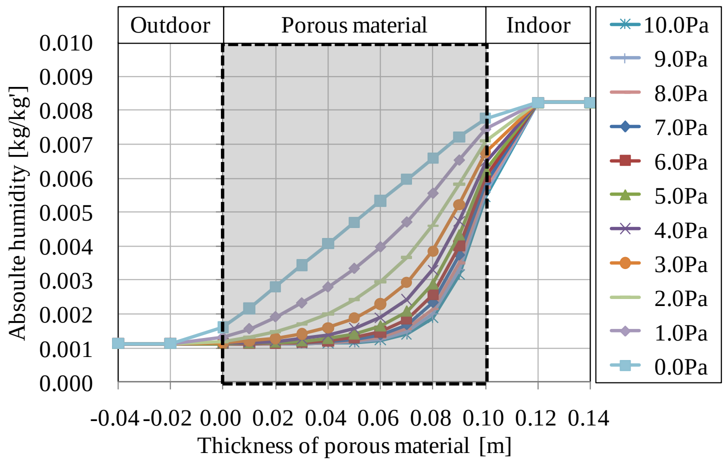
Fig. 9 Simulation results for Case 3



(a) Temperature distribution

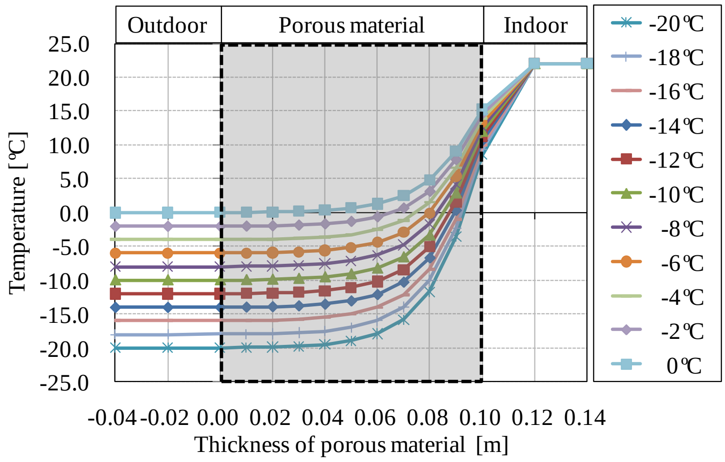


(b) Relative humidity distribution

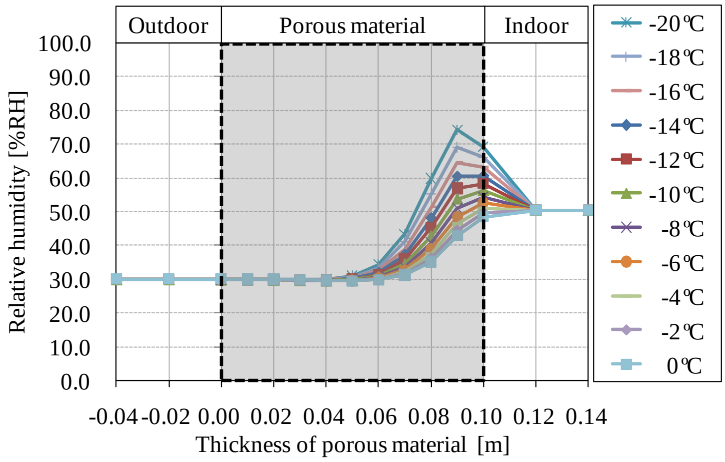


(c) Absolute humidity distribution

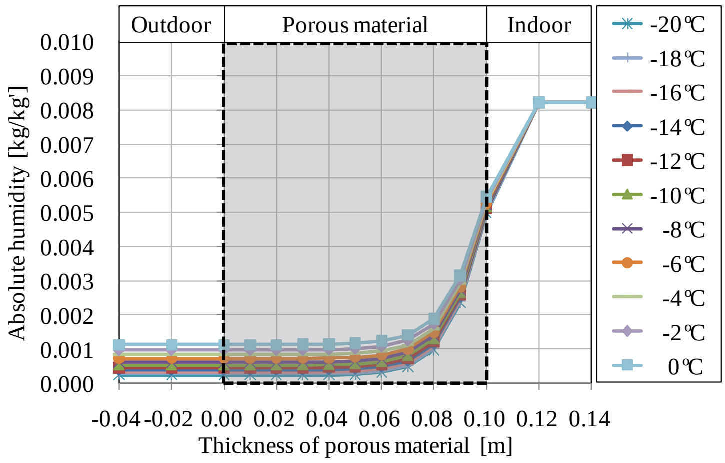
Fig. 10 Simulation results for Case 4



(a) Temperature distribution



(b) Relative humidity distribution



(c) Absolute humidity distribution

Fig. 11 Simulation results for Case 5

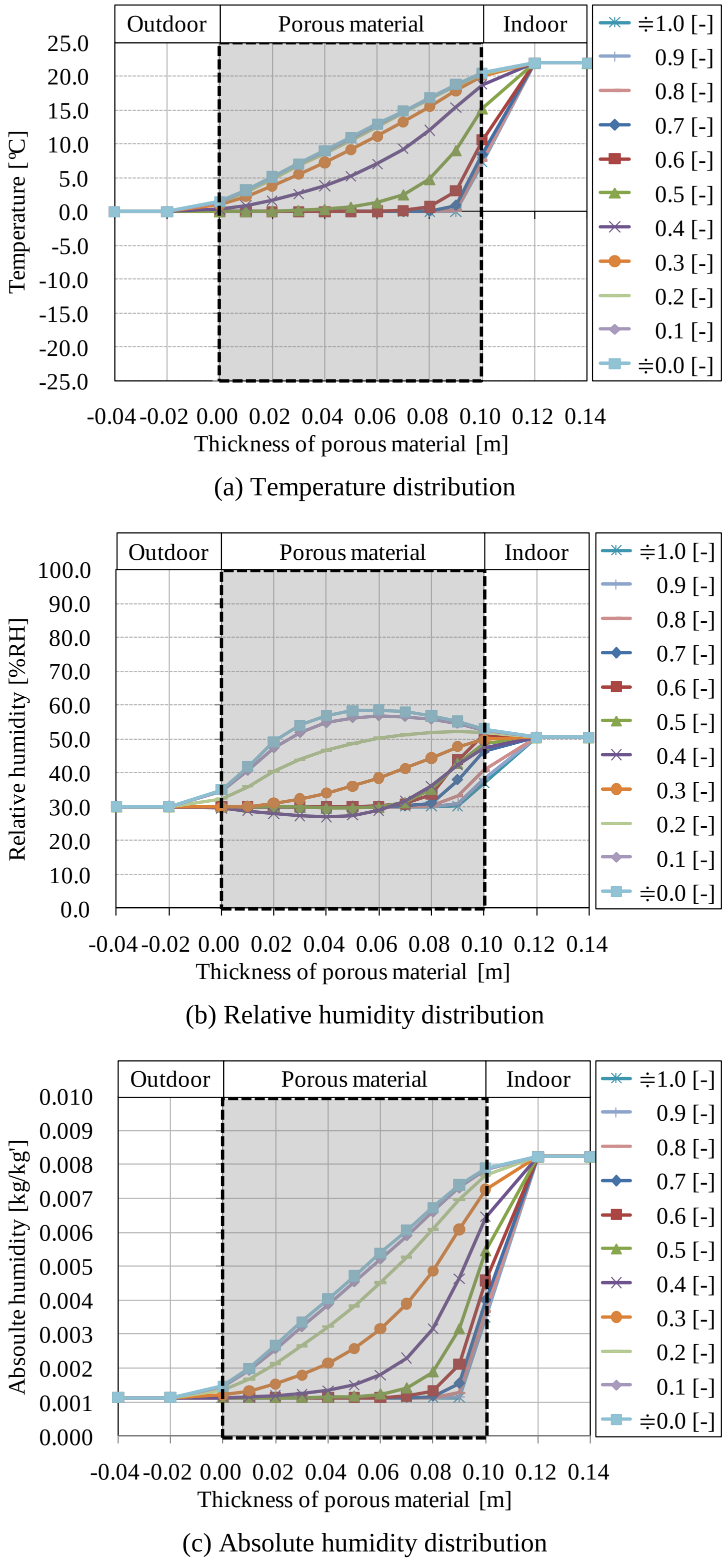
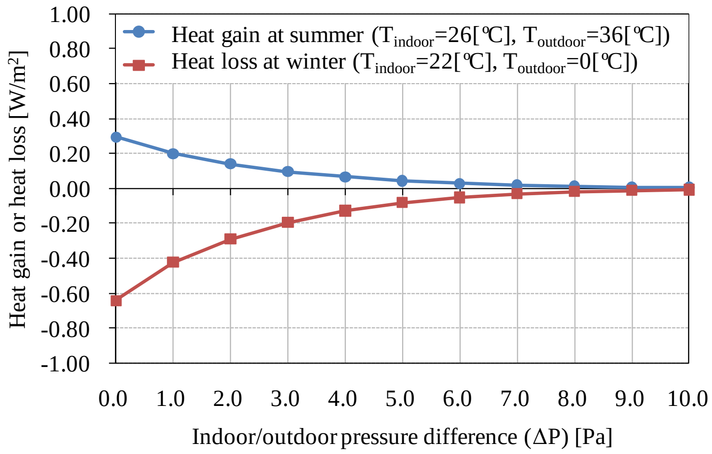
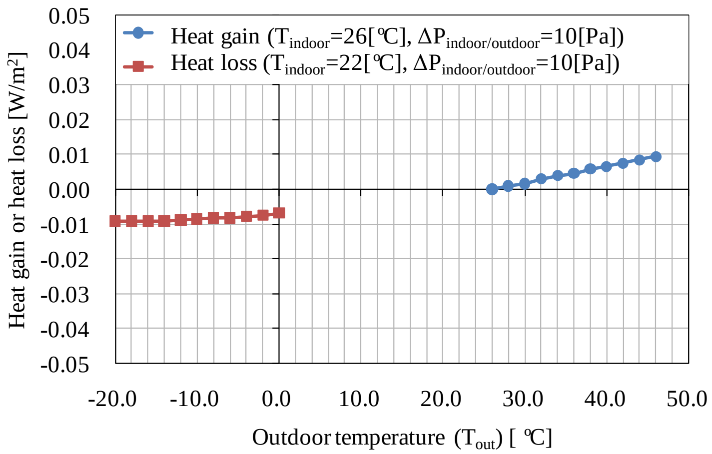


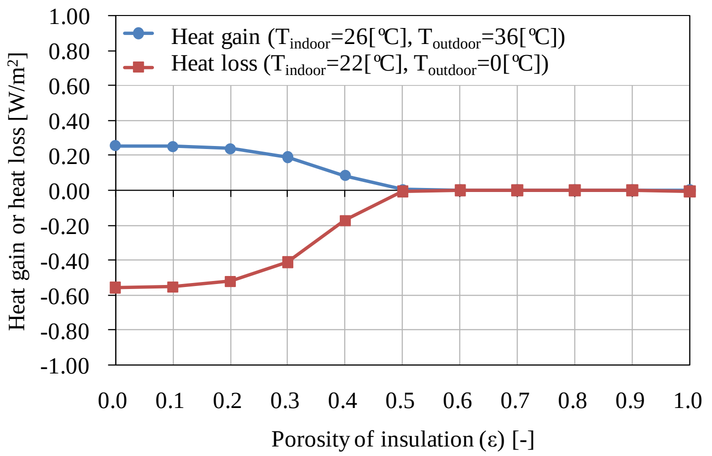
Fig. 12 Simulation results for Case 6



(a) Heat loss versus the indoor/outdoor pressure difference



(b) Heat loss versus the outdoor temperature



(c) Heat loss by the porosity

Fig. 13 Heat loss through the insulation material

Table 1 Boundary conditions

Items	Boundary conditions
Calculation domain	1.10 m(x) × 1.04 m(y) × 1.04 m(z)
Mesh	550,000 nodes with structured mesh
Turbulence model	High-Reynolds number k-epsilon turbulence model
Inlet boundary	0.0816 m^2, 0.002 m/s
Window	1.00 m(y) × 1.00 m(z), Adiabatic
Wall boundary	Defined in the calculated cases

Table 2 Material properties

Items	Air	Water vapour	Insulation material
Specific heat (C_P)	1006.43 [J/kg·K]	2014 [J/kg·K]	2100 [J/kg·K]
Thermal conductivity (λ)	0.0242 [W/m·K]	0.0261 [W/m·K]	0.0558 [W/m·K]
Viscosity (μ)	1.79×10^{-5} [kg/m·s]	1.34×10^{-5} [kg/m·s]	-
Molecular weight (M)	28.97 [kg/kgmol]	18.02 [kg/kgmol]	-

Table 3 Porous media properties

Items	Porous media
Viscous resistance (1/m^2)	Defined by Eq. 5
Inertial resistance (1/m)	Defined by Eq. 5
Fluid density (ρ)	Defined by Eq. 6
Thermal conductivity (λ)	Defined by Eq. 7
Porosity (ε)	0.5 [-] (Cases 1, 2, 4, 5) 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1 [-] (Cases 3, 6)
Diameter (D_p)	0.0003278 [m]
Shape factor (φ_C)	1 [-]
Mass diffusivity (D_e)	Defined by Eq. 8

Table 4 Calculated cases in summer operating mode

(a) Calculated case using the indoor/outdoor pressure difference (Case 1)

Case 1		Summer operating mode
Indoor	Temperature	26 [℃]
	Relative humidity	50 [%RH]
Outdoor	Temperature	36 [℃]
	Relative humidity	80 [%RH]
Indoor/outdoor pressure difference		0, -1, -2, -3, -4, -5, -6, -7, -8, -9, -10 [Pa]
Porosity of insulation material		0.5 [-]

(b) Calculated case using the outdoor temperature (Case 2)

Case 2		Summer operating mode
Indoor	Temperature	26 [℃]
	Relative humidity	50 [%RH]
Outdoor	Temperature	26, 28, 32, 34, 36, 38, 40, 42, 44, 46 [℃]
	Relative humidity	80 [%RH]
Indoor/outdoor pressure difference		-10 [Pa]
Porosity of insulation material		0.5 [-]

(c) Calculated case using the porosity (Case 3)

Case 3		Summer operating mode
Indoor	Temperature	26 [℃]
	Relative humidity	50 [%RH]
Outdoor	Temperature	36 [℃]
	Relative humidity	80 [%RH]
Indoor/outdoor pressure difference		-10 [Pa]
Porosity of insulation material		0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 [-]

Table 5 Calculated cases in winter operating mode

(a) Calculated case using the indoor/outdoor pressure difference (Case 4)

Case 4		Winter operating mode
Indoor	Temperature	22 [℃]
	Relative humidity	50 [%RH]
Outdoor	Temperature	0 [℃]
	Relative humidity	30 [%RH]
Indoor/outdoor pressure difference		0, -1, -2, -3, -4, -5, -6, -7, -8, -9, -10 [Pa]
Porosity of insulation material		0.5 [-]

(b) Calculated case using the outdoor temperature (Case 5)

Case 5		Winter operating mode
Indoor	Temperature	22 [℃]
	Relative humidity	50 [%RH]
Outdoor	Temperature	-20, -18, -16, -14, -12, -10, -8, -6, -4, -2, 0 [℃]
	Relative humidity	30 [%RH]
Indoor/outdoor pressure difference		-10 [Pa]
Porosity of insulation material		0.5 [-]

(c) Calculated case using the porosity (Case 6)

Case 6		Winter operating mode
Indoor	Temperature	22 [°C]
	Relative humidity	50 [%RH]
Outdoor	Temperature	0 [℃]
	Relative humidity	30 [%RH]
Indoor/outdoor pressure difference		-10 [Pa]
Porosity of insulation material		0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 [-]