# THE APPLICABILITY OF GLAZING SYSTEM WITH DYNAMIC INSULATION FOR RESIDENTIAL BUILDINGS

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## ABSTRACT

It is essential to reduce the inordinate amount of energy used for climate control in buildings. To reduce heat loss in residential buildings, it is necessary to insulate building envelopes more airtight. Many air tightness and insulation methods have been proposed and successfully applied to the building envelope, including areas such as walls, windows and the others. However, if it concentrates only air tightness and insulation to save energy consumption in the buildings, that'll make a problem to maintain indoor air quality within acceptable levels, such as sick building syndrome.

To solve this problem, this paper proposed a new dynamic insulation system applied to the glazing and frame of the windows. Dynamic insulation refers to the use of porous insulation material through which ventilation air enters a building, thereby reducing the conductive heat loss through the material to very low level. Moreover, the proposed system is composed of three parts by installing two additional parts to control indoor/outdoor pressure difference and to reduce ventilation loads: a double pane airflow window system with window frame made of a porous material, a mechanical ventilation system, and a heat-recovery heat pump system.

The aim of this paper is to evaluate the thermal insulation efficiency and probability of moisture condensation in the proposed glazing system in order to confirm its feasibility and applicability. First, a double pane airflow window system was designed to ventilate through the window frame and the air space of a double pane window. Then, to verify its thermal insulation efficiency, the temperature distribution of the window system was evaluated using computer fluid dynamics with different coupled conditions, such as the indoor/outdoor pressure difference and outdoor temperature, after confirming calculation accuracy using glazing model. In addition, to verify the probability of moisture condensation, the relative humidity in the window system was calculated based on the various conditions.

The calculated results show the thermal load was proportional to the outdoor temperature and inversely proportional to the indoor/outdoor pressure difference. Moisture condensation depends on the outdoor temperature and humidity ratio and it does not occurred when outdoor temperature is more than 6.0 ºC in the proposed system. Therefore, the proposed system is technically feasible to reduce the home energy consumption by installed residential buildings.

## KEYWORDS

dynamic insulation, airflow window, thermal insulation efficiency, moisture condensation

## INTRODUCTION

Solution offerings to the inordinate amount of energy used for climate control in buildings are of paramount importance. To insulate buildings more efficiently, many insulation methods have been proposed and successfully applied to the building envelope. One technical solution involves dynamic insulation that blocks heat transport by making the incoming airflow pass through a porous material, same principle as airflow window system. Because dynamic insulation not only reduces heat loss but also helps maintain indoor air quality, several different dynamic insulation systems have been proposed to improve in the performance of specific building elements and successfully applied to the building envelope. Furthermore, because the Building Standard Law of Japan has been in force since July 1st, 2003 in Japan requiring minimum indoor ventilation rates of 0.5 air changes per hour for the entire 24 hours, many studies have shown that it is possible to use dynamic insulation efficiently in residential buildings. In spite of their efforts, it still remains a heat loss at glass and frame of window because they have relatively poor insulating qualities and usually contribute the greatest heat loss by heat conduction. Moreover, they have also a high risk of moisture condensation occurs because they have low surface temperature than the other building envelope. Although many studies have shown that it is possible to use low-emissivity glazing, gas-filled glazing, or vacuum glazing to solve this problem, it has also a demerit such as high cost [1], [2], [3], [4], [5], [6]. This paper deals with a new insulation system to insulate glass and frame of the window efficiently by using dynamic insulation and airflow window system.

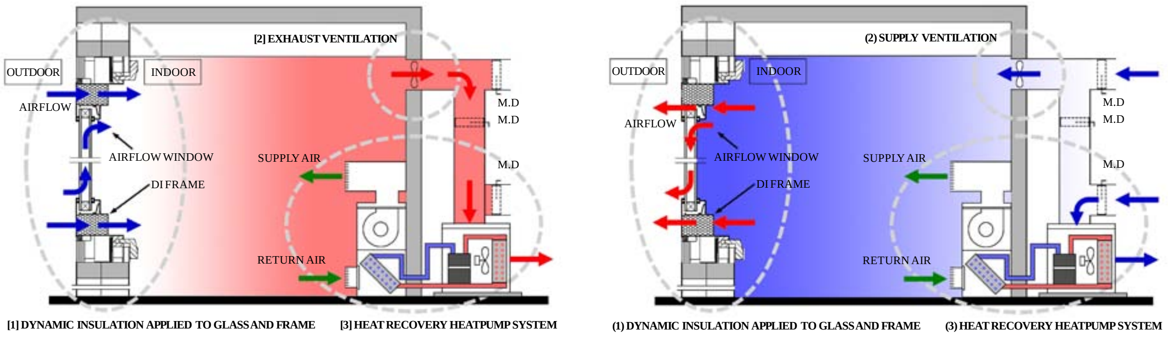
## OBJECTIVE

In this paper, a new insulation system is proposed to insulate glass and frame of the window efficiently in 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 applicability. We also evaluate whether it produces excessive moisture condensation, depending on the outdoor temperature, the indoor/outdoor pressure difference.

## METHODS

### 1. The new system proposed to increase thermal insulation of window

Figure 1 shows the concept of the proposed system to increase thermal insulation and air-tightness of glass and frame of the window in residential buildings. This system is composed of three parts: a double pane airflow window system with window frames made of a porous material, a mechanical ventilation system, and a heat-recovery heat pump system.



(a) Winter mode [negative indoor pressure]

(b) Summer mode [positive indoor pressure]

Figure 1. Mechanisms of the proposed system.

## 1.1 Dynamic insulation incorporated in glass and frame of the window

### 1.1.1 Dynamic insulation applied to frame of the window

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. 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 [7], [8], [9], [10], [11], [12], [13], [14], [15].

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

where $k$ [W/(m·K)] is the thermal conductivity of the insulation material, $T$ [K] is the temperature, $\rho_a$ [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.

$$U_{dyn} = \frac{u\rho_a C_p}{e^{\frac{u\rho_a C_p L}{k}} - 1} \tag{2}$$

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.

$$Pe = \frac{u\rho_a C_p L}{k} \tag{3}$$

### 1.1.2 Airflow window system applied to glass of the window

An airflow window system is used to reduce thermal loss from glass of the window in dwelling houses. Outdoor air can be directed through the window from either bottom to top. It has useful function to reduce the energy transfer of indoor/outdoor because it has minimal temperature difference of outdoor and air space between glass panels of the window.

## 1.2 Mechanical ventilation system (exhaust / supply ventilation)

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. A mechanical ventilation system works as exhaust ventilation functionally in winter to prevent moisture condensation by entering low humidity air from outdoor at building envelops as shown in Fig. 1(a). On the contrary, it works as supply ventilation functionally in summer to prevent high humidity air entered at building envelops as shown in Fig. 1(b).

### 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

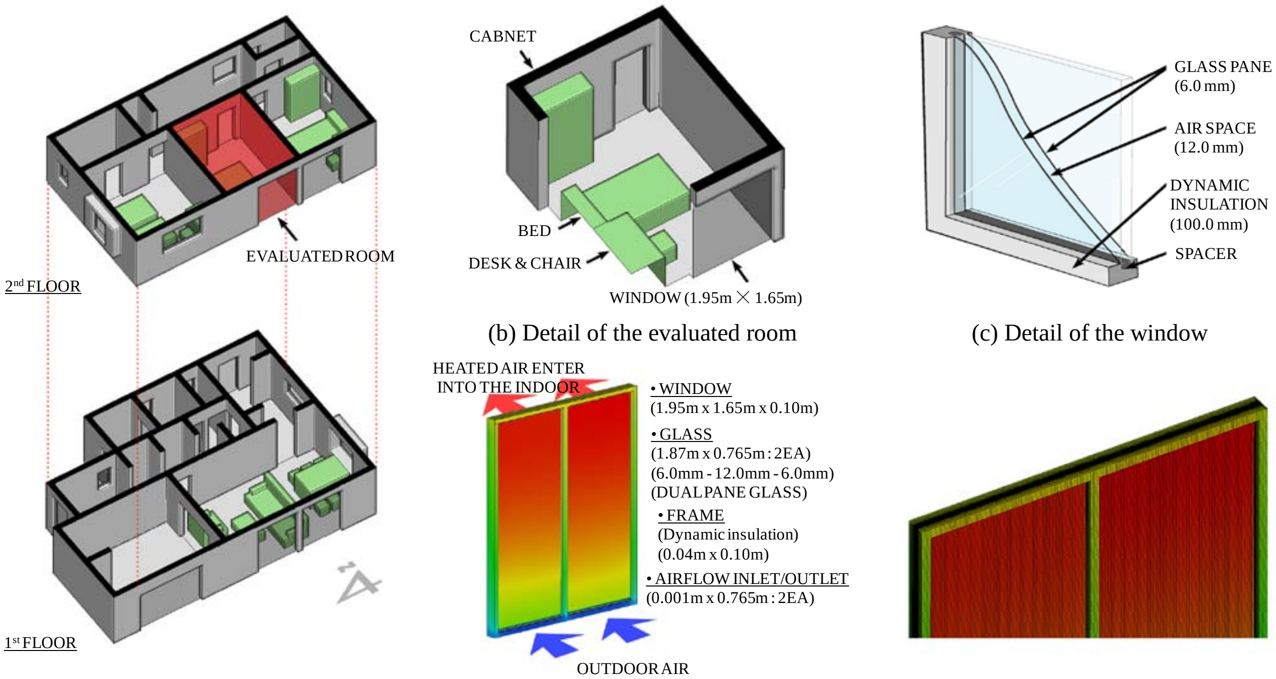
Computer fluid dynamics (CFD) was used to model fluid, heat flow, and moisture condensation in the porous material of the proposed system. CFD has been widely used to simulate air movement, heat transfer, mass transfer, and the interaction between indoor and outdoor environments.

### 2.1 Calculation model

To evaluate the thermal insulation efficiency of the proposed system, the temperature contributions of frame and glass of the window were calculated using 3-D steady-state CFD simulation includes detailed ray-tracing-based radiation modelling as well as direct modelling of convective heat transfer under different coupled conditions, i.e. the indoor/outdoor pressure difference or outdoor temperature etc. Figure 2(a) shows the plan of the building model used for the calculation, which is proposed as a standard dwelling house model in Japan by the Institute for Building Environment and Energy Conservation. In this study, a children’s room of 2nd floor (2.40 m (H) × 2.90 m (W) × 3.50 m (D) = 24.36 $m^3$) is only used for calculations as shown in Fig. 2(b). Figure 2(c) shows the detail of window (1.95 m (H) × 1.65 m (W) × 0.10 m (D)) installed the calculation model with Fig. 2(d) and Fig. 2(e). The model included an indoor zone, an outdoor zone, a window, and a window frame. The insulation material applied to the window frame acts as an air supply opening and an airflow window system applied to the window glass allowing fresh air into the room. The porosity of the porous material at window frame is 0.5 [-] and the frame area is about 10% of the whole window area. Opening size (0.001 m (H) × 0.0765 m (W) : 2EA) of airflow window system was determined to satisfy about 90% of a room required ventilation rates at the indoor/outdoor pressure difference of 10 Pa. In Japan, indoor ventilation rates need to provide at least one half air changes per hour (0.5 ACH) for the entire 24 hours. Unfortunately, the effect of the heat-recovery heat pump system is not considered, in order to keep the calculation model simple in this study.

### 2.2 Flow model and boundary conditions

A Abe-Kondoh-Nagano low-Reynolds number k-epsilon turbulence model [16], [17] was used for computing the turbulent viscosity and diffusivity. For modelling of fluid, heat flow (detailed ray-tracing-based radiation model, direct model of convective heat transfer), and moisture condensation (species transfer model), the boundary conditions required for the simulation were those associated with heat transfer through air and porous material, and properties such as porosity and diameter. The material properties for the simulation are summarized in Table 1. This calculation used 4 materials, such as air, water vapour, porous material and glass pane.



(b) Detail of the evaluated room (c) Detail of the window

(a) Applied dwelling house (d) Detail of the calculation model (e) Calculation mesh

Figure 2. Principle of dynamic insulation and calculation model

| Item | Air | Water vapour | Porous material | Glass pane |
|---|---|---|---|---|
| Specific heat ($C_P$) | 1006.43 [J/(kg·K)] | 2014 [J/(kg·K)] | 2100 [J/(kg·K)] | 753 [J/(kg·K)] |
| Conductivity ($\lambda$) | 0.0242 [W/(m·K)] | 0.0261 [W/(m·K)] | 0.0558 [W/(m·K)] | 0.65 [W/(m·K)] |
| Viscosity ($\mu$) | $1.79\times10^{-5}$ [kg/(m·s)] | $1.34\times10^{-5}$ [kg/(m·s)] | - | - |
| Moler weight ($M$) | 28.97 [kg/kgmol] | 18.02 [kg/kgmol] | - | - |
| Thickness ($l$) | - | - | - | 6.0-12.0-6.0 [mm] |
| Emissivity ($\varepsilon$) | - | - | - | 0.90 [-] |

Table 1. Material properties.

### 2.2.1 Flow model for the porous media at window frame

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

$$\frac{\partial(\rho U_i)}{\partial x_i} = 0 \tag{4}$$

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 medium were derived from the Ergun equation defined by the Turkish chemical engineer Sabri Ergun in 1952, as given by Equation 5 [18]. The Ergun equation is applied here for the pressure drop, *dp*, over the length, *dL*, determined by the diameter of the porous material [19], [20], assuming that the U-value is 0 W/m$^2$ when the pressure difference is 10 Pa.

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

where $\varphi_C$ [-] is the shape factor, $U$ [m/s] is the superficial fluid velocity through the porous medium, $\rho$ [kg/m$^3$] is the fluid density, $D_P$ [m] is the diameter of the solid part on porous medium, $\mu$ [kg/(m·s)] is the molecular viscosity, and $\varepsilon$ [-] is the porosity of the porous medium.

### 2.2.2 Air density

The density $\rho$ 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.

$$\rho = \frac{P_{dry}}{R_{dry} \times T} + \frac{P_{vapour}}{R_{vapour} \times T} \tag{6}$$

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.

$$k_{eff} = \varepsilon \times k_{fluid} + (1-\varepsilon) \times k_{solid} \tag{7}$$

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 [21], [22].

$$D_e = \frac{D\varepsilon_t \delta}{\tau} \tag{8}$$

where $D$ [m$^2$/s] is the diffusion coefficient of the gas or liquid filling the pores, $\varepsilon_t$ [-] is the porosity available for transport, $\delta$ [-] is constrictivity, and $\tau$ [-] is tortuosity. In this study, we calculate the diffusion coefficient, $D$, using the following formula.

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

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

## 2.3 Calculation cases

Table 2 shows the calculated cases by indoor/outdoor pressure difference (case 1, 2) and Table 3 shows the calculated cases by outdoor temperature (case 3, 4) in winter/summer operating mode for the CFD simulation. These cases were used temperature and relative humidity of indoor based on design basis conditions to build dwelling houses generally in Japan. A total heat transfer coefficient of window surface is assumed 23.25 $\mathrm{W/(m^2 \cdot K)}$ at outdoor surface and 9.09 $\mathrm{W/(m^2 \cdot K)}$ at indoor surface for calculation.

| **Case 1 (Winter operating mode)** | | | **Case 2 (Summer operating mode)** | | |
|---|---|---|---|---|---|
| Indoor | Temperature | 22 [ºC] | Indoor | Temperature | 26 [ºC] |
| | Relative humidity | 50 [%RH] | | Relative humidity | 50 [%RH] |
| Outdoor | Temperature | 0 [ºC] | Outdoor | Temperature | 36 [ºC] |
| | Relative humidity | 30 [%RH] | | Relative humidity | 80 [%RH] |
| Indoor/outdoor $\Delta P$ | | 0, -1, ... , -9, -10 [Pa] | Indoor/outdoor $\Delta P$ | | 0, 1, ... , 9, 10 [Pa] |

Table 2. Calculation cases by indoor/outdoor pressure difference.

| **Case 3 (Winter operating mode)** | | | **Case 4 (Summer operating mode)** | | |
|---|---|---|---|---|---|
| Indoor | Temperature | 22 [ºC] | Indoor | Temperature | 26 [ºC] |
| | Relative humidity | 50 [%RH] | | Relative humidity | 50 [%RH] |
| Outdoor | Temperature | -20, -18, ... , -2, 0 [ºC] | Outdoor | Temperature | 28, 30, ... , 34, 36 [ºC] |
| | Relative humidity | 30 [%RH] | | Relative humidity | 80 [%RH] |
| Indoor/outdoor $\Delta P$ | | -10 [Pa] | Indoor/outdoor $\Delta P$ | | 10 [Pa] |

Table 3. Calculation cases by outdoor temperature.

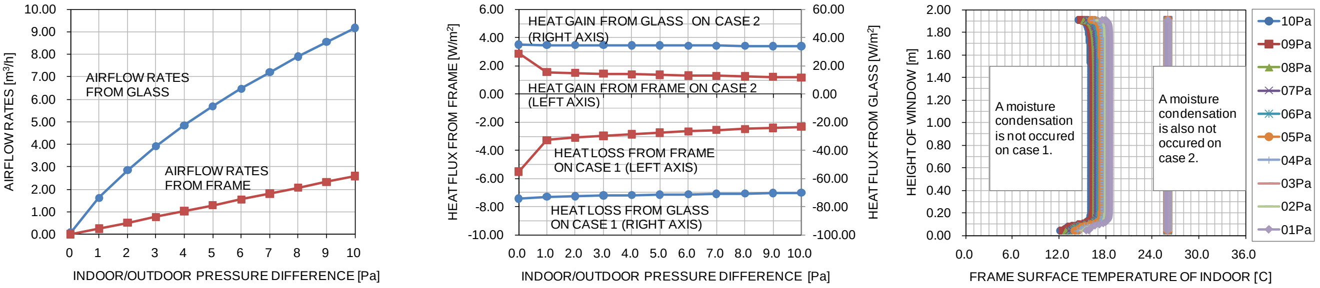
## RESULTS AND DISCUSSIONS

## 1 Effect of indoor/outdoor pressure difference

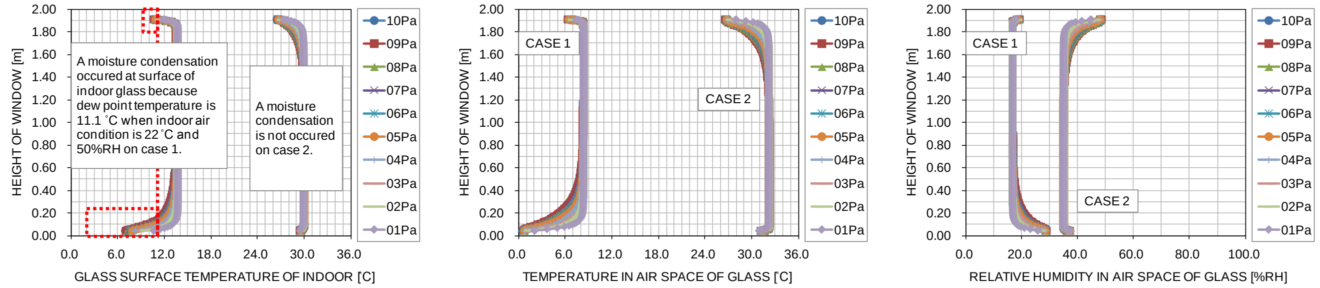
Figure 3 is showed the calculated results by indoor/outdoor pressure difference from 1 Pa to 10 Pa in summer and winter. Figure 3(a) is airflow rates for indoor ventilation from glass opening and frame made by porous material. It is decrease by indoor/outdoor pressure difference. The heat loss/gain in the room was reduced with increases in the indoor/outdoor pressure difference, as shown Fig. 3(b). Figure 3(c) and 3(d) show the surface temperature of frame and glass at indoor. Moisture condensation is not occurred in surface of indoor frame but it is occurred in surface of indoor glass because dew point temperature is 11.1 ºC when indoor air condition is 22.0 ºC and 50 %RH.

Figure 3(e) shows the temperature distribution versus the indoor/outdoor pressure difference in air space of glass. In winter, the air temperature rises slowly as the outdoor air passes through the insulation materials and air space of glass. On the contrary, it is cooled slowly in summer. However, 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.

Figure 3(f) shows relative humidity distribution versus the indoor/outdoor pressure difference in air space of glass. It is not occurred in porous material and air space of glass in any calculated case because supply/exhaust air flow make reduce the moisture condensation probability.

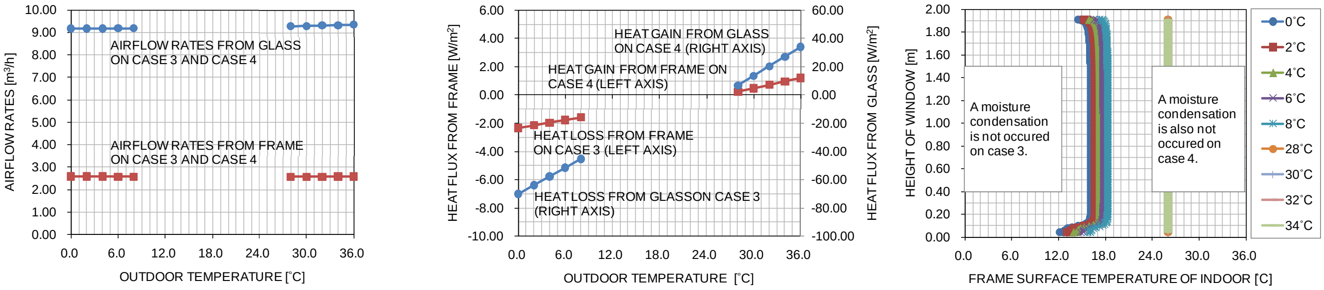


(a) Airflow rates for indoor ventilation (b) Heat flux from glass and frame (c) Frame surface temperature of indoor

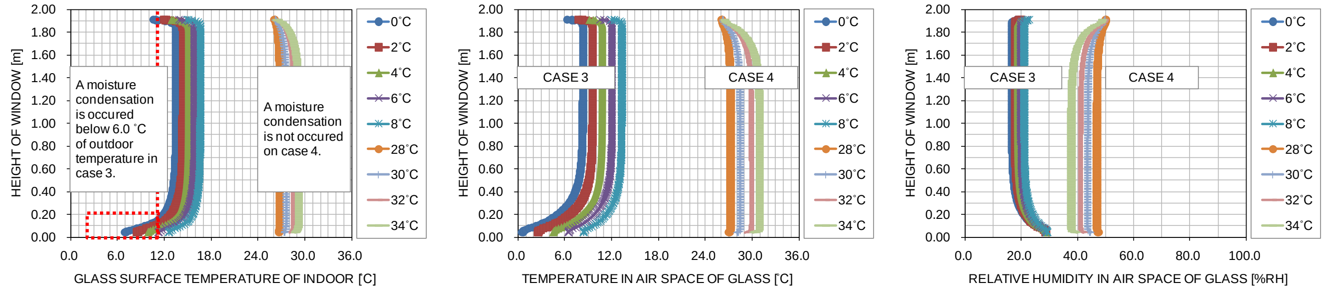


(d) Glass surface temperature of indoor (e) Temperature in air space of glass (f) Relative humidity in air space of glass

Figure 3. Simulation results by indoor/outdoor pressure difference (case 1, case 2)



(a) Airflow rates for ventilation (b) Heat flux from glass and frame (c) Frame surface temperature of indoor



(d) Glass surface temperature of indoor (e) Temperature in air space of glass (f) Relative humidity in air space of glass

Figure 4. Simulation results by outdoor temperature (case 3, case 4)

## Effect of outdoor temperature

Figure 4 shows the calculated results by the outdoor temperature at the fixed indoor/outdoor pressure difference of 10 Pa. Figure 4(a) shows constant airflow rates for indoor ventilation from glass opening and frame made by porous material. The heat loss/gain in the room was smaller with a smaller indoor/outdoor temperature difference, as shown Fig. 4(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 4(c) and 4(d) show the surface temperature of frame and glass at indoor. Moisture condensation is occurred when outdoor temperature is below than 6.0 ºC.

Figure 4(e) and 4(f) show the temperature and relative humidity distribution versus the indoor/outdoor pressure difference in air space of glass. It is not occurred in porous material and air space of glass in any calculated case. In winter, low-temperature outdoor air comes into the indoor through the porous material and the dual glass pane. The relationship of the temperature difference between indoor air/outdoor air and supply air/outdoor air is calculated and leads to Equation 10 and 11 as a linear approximation:

$$T_{s\_DIframe} = -0.3989 \times \left(T_{indoor} - T_{outdoor}\right) + T_{outdoor} \tag{10}$$

$$T_{s\_DIframe} = -0.3989 \times \left(T_{indoor} - T_{outdoor}\right) + T_{outdoor} \tag{11}$$

where $T_{s\_airflowwindow}$ [˚C] is the supply air temperature at opening boundary of window glass, $T_{s\_DIframe}$ [˚C] is the supply air temperature at opening boundary of window frame made by dynamic insulation material, $T_{outdoor}$ [˚C] is outdoor air temperature, $T_{indoor}$ [˚C] is the indoor air temperature.

## CONCLUSION

This paper proposed a new double pane airflow window system with window frames made of a porous material applied dynamic insulation technology to reduce energy consumption in residential buildings, and conducted an applicability 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. A summary of the general findings of this study is as follows.

- 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.

- Moisture condensation occurred in the surface of indoor glass because dew point temperature is 11.1 ºC when indoor condition is 22.0 ºC and 55.0 %RH. However, it is not occurred when outdoor temperature is more than 6.0 ºC. It is also not occurred in porous material and air space of glass in any calculated case because supply/exhaust air flow make reduce the moisture condensation probability.

- Next study, it need to evaluate various design model such as double dual pane, triple glass, low-e glass, drain materials etc., because it is important to prevent moisture condensation probability in indoor glass surface. 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.

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