Numerical study on heat blocking efficiency of non-recirculating air curtain and its optimal discharge velocity

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Abstract. From the point of view to reduce energy consumption, door open while air conditioner running on buildings have a problem. To solve the problem, many facilities for entrance with vestibule, revolving door, and air curtain are utilized. Among the facilities, the air curtain cuts off the indoor and outdoor air by discharging the wide air surrounding the opening, thereby preventing the heat loss from the indoor. The purpose of this study is to evaluate the heat blocking efficiency of non-recirculating air curtain and to evaluate its optimal discharge velocity. To achieve this goal, the infiltration rate across the single-side opening were investigated with air temperature differences between areas by transient CFD simulation and the results were compared with the steady-state calculation method. In addition, to evaluate the heat blocking efficiency of non-recirculating air curtain, the calculation model was set up and several cases with discharge velocity were compared. The results show that the discharged air from the air curtain causes a deflection from the high temperature area to the low temperature area, and the deflection decreases with increasing the discharge air velocity. In this study, the safety factor for deflection modulus of the non-recirculating air curtain was calculated 2.75.

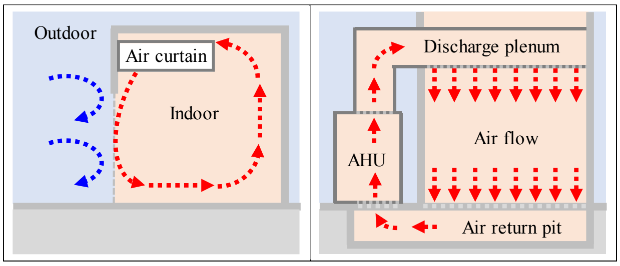
1 Introduction

While air conditioner is running, leaving doors and windows open is a great way to reduce operating efficiency and undermine the air conditioning system's ability to bring the indoor to a comfortable temperature. Thus, in commercial stores on the sidewalks, the door open while air conditioner running causes a problem against the global trend toward an energy-saving society. However, merchants want to business with open the door to attract more customers and to increase sales.

Several countries have established policies to impose fines on commercial store with the door open while air conditioner running. New York in the United States is a law [1] passed in 2015 to keep store and restaurant doors closed when their air conditioning is on. According to law, violators face fines of $250 for a first offense and up to $1,000 for an egregious violation. South Korea has also imposed penalties of up to $3,000 for violators on commercial store, shops, and shopping malls through a crackdown since 2012.

To solve the problem, many facilities for entrance with vestibule, revolving door, entry heater, door closer, and air curtain are utilized to reduce the energy loss. Among the facilities, the air curtain cuts off the indoor and outdoor air by discharging the wide air surrounding the front of the opening, thereby preventing the heat loss from the indoor. As a thermal barrier, the air curtain can reduce the energy consumption of HVAC systems when areas of different temperatures are separated. The air curtain is classified by two different types of construction [2]: non-recirculation and recirculating as shown in Fig. 1. A non-recirculating type draws air into the unit directly from the surrounding environment, while a recirculating system draws air from ductwork, which primarily collects and returns the discharge air back to the inlet. Although it is mainly used in shops, department stores, banks, hotels, history, factories, etc. where many persons and objects are in and out, there are few exact measured or calculated data.

The purpose of this study is to evaluate the heat blocking efficiency of non-recirculating air curtain for decreasing the infiltration rate across the door and to evaluate its optimal discharge velocity. To achieve this goal, the infiltration rate across the single-side opening were investigated quantitatively with air temperature differences between areas by transient CFD simulation and the results were compared with the steady-state calculation method. In addition, to evaluate the heat blocking efficiency of non-recirculating air curtain, the calculation model was set up and several cases with discharge velocity were compared.



(a) Non-recirculating type (b) Recirculating type

Fig. 1. Air curtain: non-recirculation and recirculating type.

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2 Methods

2.1 Infiltration rate across the single-side opening

The steady-state infiltration calculation method of single-side opening is proposed by various experimental and numerical studies and it is used to calculate the heat loss in the opening. Natural convection through an opening is caused by the temperature difference and thus the density difference between the air inside and outside the room. This effect is commonly known as the stack effect.

Emswiler [3] expressed the basic theory for natural convection through openings in a partition separating fluids at different densities. His investigation concentrated on multiple openings and his theory was based on the Bernoulli equation for ideal flow and introduced the concept of the neutral level. This is the height at which the pressure is the same either side of the partition as shown in Fig. 2(a). Brown [4] developed a theory of natural convection through single vertical rectangular openings in partitions as shown in Eq. 1.

$$Q = \frac{C_d}{3} A \sqrt{\frac{gH\Delta T}{T}} \tag{1}$$

Here, Q [m^3/s] is the infiltration rate out of the indoor area, C_d [-] is the discharge coefficient, A [m^2] is the opening area, g [m/s^2] is the gravity acceleration, H [m] is the height of opening, ΔT [°C] is the temperature difference.

Brown and Solvason [5] developed a theory of natural convection through single vertical rectangular openings in partitions. They showed that a pressure profile is developed in the opening that is caused by the difference in density due to temperature difference between the environments on either side of the partition as shown in Eq. 2.

$$Q = 0.343A(gH)^{0.5}\left[\frac{\rho_i-\rho_o}{\rho_{avg}}\right]^{0.5}\left[1-0.498\left(\frac{W}{H}\right)\right] \tag{2}$$

Here, ρ [kg/m^3] is the air density, W [m] is the width of opening. The subscript '*i*' used in this equation means indoor, '*o*' means outdoor, and '*avg*' means average value.

Tamm [6] improved on this model, calculating the height of the neutral level and using inside and outside densities for inflow and outflow, respectively, where appropriate, instead of an average value as shown in Eq. 3.

$$Q = 0.333A(gH)^{0.5}\left[\frac{\rho_i-\rho_o}{\rho_i}\right]^{0.5}\left[\frac{2}{1+\left(\rho_o/\rho_i\right)^{0.333}}\right]^{1.5} \tag{3}$$

Fritzsche and Lilienblum [7], who conducted experiments using vane anemometers, added a correction factor to Tamm's equation as shown in Eq. 4. The correction factor takes into account the contraction of the flow, friction, and thermal effects as shown in Eq. 5.

$$Q = 0.333K_{f,L}A(gH)^{0.5}\left[\frac{\rho_i-\rho_o}{\rho_i}\right]^{0.5}\left[\frac{2}{1+\left(\rho_o/\rho_i\right)^{0.333}}\right]^{1.5} \tag{4}$$

$$K_{f,L}=0.48+0.004(T_o-T_i) \tag{5}$$

Here, $K_{f,L}$ [-] is the correction factor.

Gosney and Olama [8] provided an equation for constant mass flow rate and by fitting measurements with their model provided a different correction factor as shown in Eq. 6.

$$Q = 0.343A(gH)^{0.5}\left[\frac{\rho_i-\rho_o}{\rho_{avg}}\right]^{0.5}\left[1-0.498\left(\frac{b}{H}\right)\right] \tag{6}$$

Pham and Oliver [9] conducted experiments on airflow through refrigerated room doors and produced a factor of 0.68 that should be applied to Tamm's equation to fit their experimental data as shown in Eq. 7.

$$Q= 0.226A(gH)^{0.5}\left[\frac{\rho_i-\rho_o}{\rho_i}\right]^{0.5}\left[\frac{2}{1+\left(\rho_o/\rho_i\right)^{0.333}}\right]^{1.5} \tag{7}$$

Using Pham and Oliver's equation, the infiltration load is calculated approximately 10 kW when the temperature difference is 10 °C, the height of the opening is 3.0 m, and the width of the opening is 1.2 m as shown in Fig. 2(b).

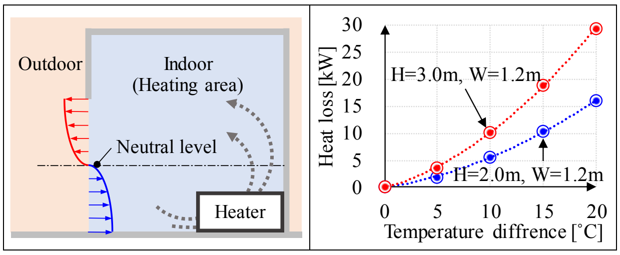
However, the calculation error should be considered because the air flow behavior varies from time to time. Thus, the purpose of this section is to investigate the infiltration rate across the single-side opening by using transient CFD simulation quantitatively and to compare with the steady-state calculation method.

Figure 3(a) shows the numerical calculation model in this investigation. The calculation model consists of the indoor space of 2.5(x) × 2.5(y) × 2.5(z) m and the outdoor space of 10.0(x) × 10.0(y) × 10.0(z) m with the door of 2.1(y) × 0.8(z) m. Table 1 shows the boundary conditions and calculation cases. The calculation cases are examined in four cases of indoor and outdoor temperature differences of 5, 10, 15 and 20 °C with the indoor temperature fixed at 20 °C. The infiltration rate through the doorway was calculated based on the concentration decay as shown in Fig. 3(b) and Eq. 8. Equation 8 is generally used to solve for the infiltration rate by measuring the tracer gas concentration periodically during the decay and fitting the data to the logarithmic form.

$$C(t)=C_0\cdot e^{-\frac{Q}{V}t} \tag{8}$$

Here, t [s] is the time, C_0 [ppm] is the concentration in the indoor area at t=0, $C(t)$ [ppm] is the tracer gas concentration at time t, V [m^3] is the volume of the indoor area.

The calculation results are also compared with the steady-state infiltration calculation method of single-side opening as shown in Eq. 7 proposed by Pham and Oliver.



(a) Infiltration characteristic (b) Heat loss due to infiltration

Fig. 2. Infiltration characteristic and heat loss due to infiltration.

2.2. Heat blocking efficiency by non-recirculating air curtain and its optimal discharge velocity

Air curtains reduce infiltration without taking up as much space as vestibules and without impeding traffic. Their origin dates back to a patent applied for by Van Kennel in 1904 [10]. The air curtain cuts off the indoor and outdoor air by discharging the wide air surrounding the front of the opening, thereby preventing the heat loss from the indoor or preventing dust, noxious gas and insect from the outdoor. Thus, it is mainly used in shops, department stores, banks, hotels, history, factories, etc. where many persons and objects are in and out. This section is to investigate the heat blocking efficiency by non-recirculating air curtain and to find its optimal discharge velocity.

The factors determining the heat blocking efficiency of the air curtain are the height and width of the opening, the discharge velocity, the discharge flow rate, the indoor and outdoor temperature differences, and the pressure differences. By these factors, the heat blocking efficiency of the air curtain is expressed as shown in Eq. 9.

$$\eta = 1 - q/q_0 \tag{9}$$

Here, q [W] is the infiltration load when air curtain is not used, and q_0 [W] is the infiltration load when the air curtain is used.

To increase this value, the discharge air flow momentum of the air curtain should be made larger than the pressure difference due to the temperature difference between indoor and outdoor. As the discharge velocity is increased, the heat loss due to natural convection is reduced as shown in Fig. 4(a). However, if the discharge velocity increases above an optimal value, the heat loss is increased rapidly.

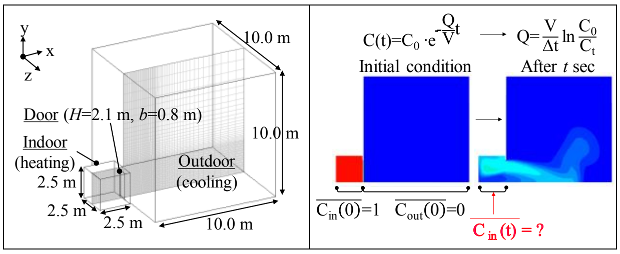
Hayes and Stoecker [11] were proposed mathematical model to assist in the design of air curtains as shown in Eq. 10. This model expresses the momentum of the discharged air from the air curtain against the pressure difference caused by the temperature difference, and this value is called deflection modulus.

$$D_m = \frac{bu^2}{gH^2\left(\frac{T_o}{T_c}-\frac{T_o}{T_w}\right)} = \frac{\rho_o b u^2}{gH^2(\rho_c-\rho_w)} \tag{10}$$

Here, D_m [-] is the deflection modulus, b [m] is the inlet width of the air curtain, u [m/s] is the discharge air velocity, T [°C] is the air temperature. The subscript 'o' used in this equation means air curtain, 'c' means low temperature area, and 'w' means high temperature area.

Hayes and Stoecker were also proposed a chart showing the minimum outlet momentum required to maintain an unbroken air curtain as shown in Fig. 4(b). This minimum deflection modulus should be considered a safety factor from the viewpoint of heat transfer, because it is to calculate the minimum discharge air velocity to maintain the air flow stably. They also suggested that it is generally useful to consider the safety factor of 1.3 to 2.0 to use in this model.

In this section, the safety factor for the deflection modulus is evaluated to determine the optimal discharge air velocity. The calculation model is the same as shown in Fig. 3(a) in chapter 2.1. The three-dimensional transient

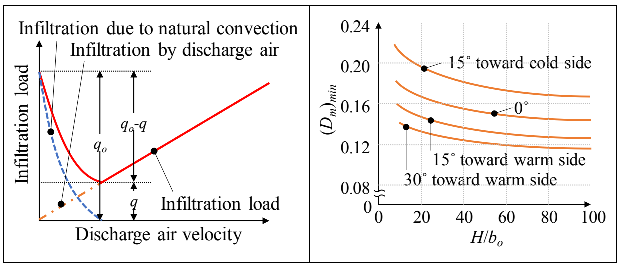


(a) Calculation model (b) Concentration decay method

Fig. 3. Calculation model and method.

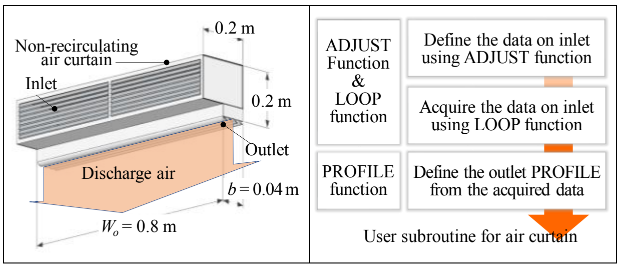
Table 1. Solver settings for the single-side opening.

Item	Contents
Meshes	Approximately 600,000
Turbulence model	High-Reynolds number k-epsilon model
Time dependence	Transient (Courant number < 1)
Buoyancy	Boussinesq approximation
Mass diffusivity	1.6×10^{-5} m²/s
Initial condition	k = 0.0 m²/s², ε = 0.0 m²/s³ C_0 (indoor) = 1.0, C_0 (outdoor) = 0.0
Calculation cases	T_i = 20 °C, T_o = 15, 10, 5, 0 °C



(a) Characteristic of heat loss (b) Minimum deflection modulus

Fig. 4. Characteristic of heat loss and minimum deflection modulus.



(a) Detail of air curtain (b) User subroutine for air curtain

Fig. 5. Detail of air curtain and user subroutine

Table 2. Calculation cases for the heat blocking efficiency.

Item	Contents
Calculation model	Same model as shown in Fig. 3(a)
Turbulence model	High-Reynolds number k-epsilon model
Time dependence	Transient (Courant number < 1)
Air curtain	0.2(x) × 0.2(y) × 0.8(z) m
Initial concentration	C_0 (indoor) = 1.0, C_0 (outdoor) = 0.0
Temperature	T_i = 20 °C (fixed), T_i = 0 °C (fixed)
Discharge velocity	1, 2, …, 20 m/s (20 cases)
Turbulence variables	I = 2%, $l = 0.07 \cdot b$ m Here, I [%] is the turbulence intensity, l [m] is the length scale, b [m] is the outlet width of the air curtain.

Reynolds-averaged Navier-Stokes equations were solved in combination with the high-Re number k-ε turbulence model. In dealing with the buoyancy forces in the momentum equations, the Boussinesq approach was adopted, i.e., I assumed that the fluid properties are constant except for the density change with temperature, which gives rise to the buoyancy forces - this process is achieved using the linear relationship between the density and temperature changes. The boundary condition and calculation case are shown in Table 2. As shown in Fig. 5(a), the air curtain is a model of 0.2(x) × 0.2(y) × 0.8(z) m, where the width of the outlet is 0.04 m. The user subroutine [12] using C code is adopted to apply the concentration and the temperature inhaled from an inlet to an outlet as shown in Fig. 5(b). As the calculation case, the discharge velocity of the air curtain is changed from 1 m/s to 20 m/s while the temperature difference between the areas is fixed at 20 °C (T_i=20 °C, T_o=0 °C).

3 Results

3.1 Results of Infiltration rate across the single-side opening

Figure 6 shows the velocity profile at the vertical centerline of opening and concentration distribution with temperature difference at 20 seconds. As the results, inflow and outflow are separated at the neutral level, and its height is calculated approximately 0.9 to 1.1 m. Increasing the indoor and outdoor temperature difference, the indoor concentration is leaked out to outdoor rapidly. The maximum velocity at the vertical centerline of opening is also increased, thus the infiltration rate across the single-side opening is increased with temperature difference.

Figure 7 shows the infiltration rate by comparing the transient CFD simulation result and the theoretical value of the steady-state method, when the temperature difference between indoor and outdoor is 20, 15, 10, 5 °C. The calculated infiltration rate increases rapidly in the initial state for about 2 to 3 seconds, and then increases to 16 to 17 seconds. After 20 seconds, it is maintained at almost the same value as the steady state infiltration rate. This means that the air flow from the outside causes a sudden heat loss until the indoor flow becomes steady state. The average value of the infiltration rate is calculated 0.4439 m^3/s, 0.3741 m^3/s, 0.3108 m^3/s, and 0.2251 m^3/s respectively, when the temperature difference between indoor and outdoor is 20, 15, 10, 5 °C. The numerical error of the infiltration rate was consistent within 10% at 100 seconds by comparing with the theoretical value of the steady-state method and the transient CFD simulation result.

3.2 Results of heat blocking efficiency by the air curtain and its optimal discharge velocity

Figure 8 shows the calculation results of the pathline with the discharge air velocity of the air curtain, when the temperature difference between indoor and outdoor is 20 °C. The results show that the discharged air from the air curtain causes a deflection from the high temperature area

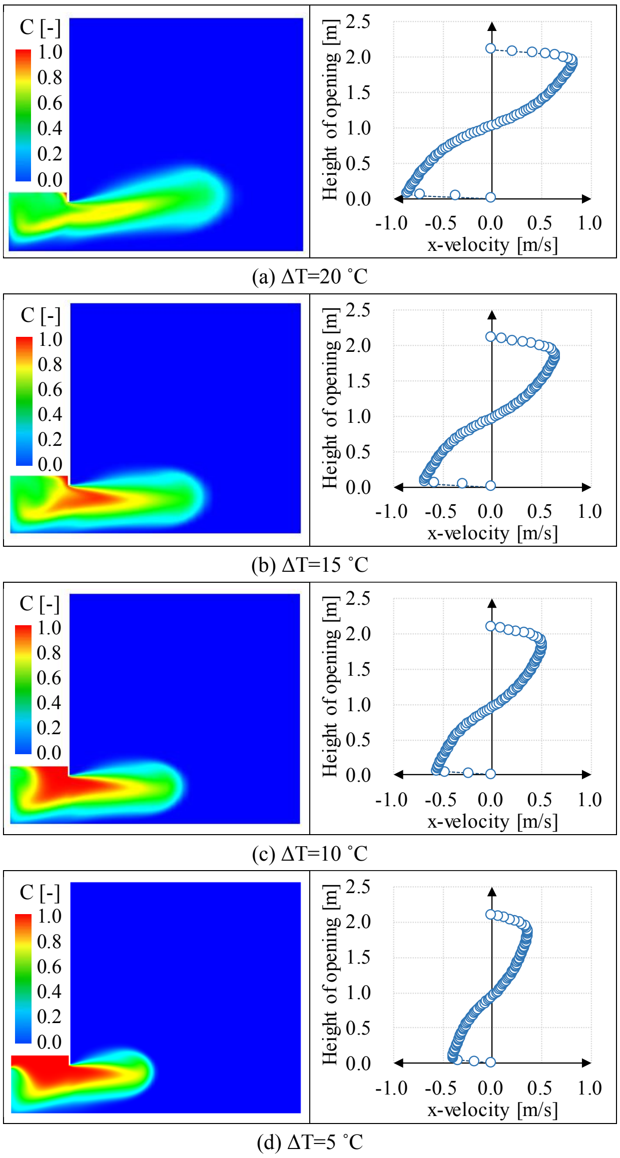


Fig. 6. Concentration distribution and velocity profile at 20 seconds.

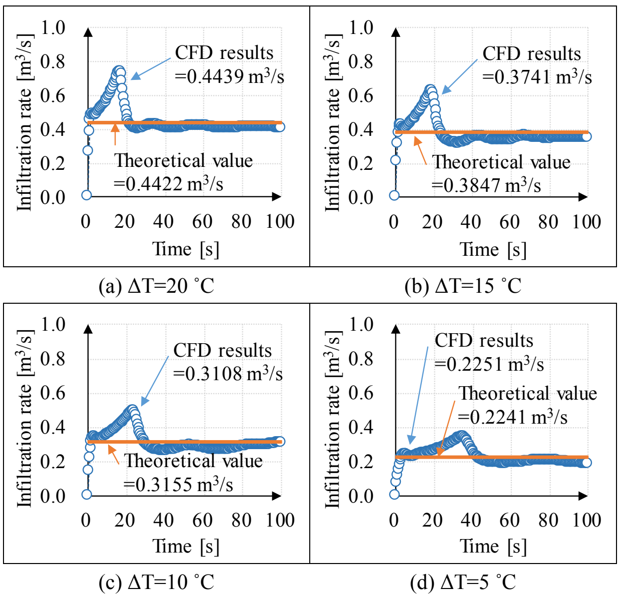


Fig. 7. Infiltration rate with temperature difference at the single-side opening.

to the low temperature area, and the deflection decreases with increasing the discharge air velocity. It means that the heat blocking efficiency of the air curtain is more stable, if the airflow is discharged toward the high temperature area.

Figure 9 shows the calculation result of the infiltration rate. As the results, an optimal discharge air velocity of the air curtain is the point at which the outflow to the outdoor is minimized by natural convection. This point was 5.7 m/s that the air barrier is formed without any deflection as shown in Fig. 8. The infiltration rate was 0.1048 m^3/s at this point. It means that the infiltration rate of 0.4422 m^3/s when the single-side opening is opened, can be decreased to 0.1048 m^3/s using the non-recirculating air curtain. Figures 10(a) and 10(b) show the calculation results of the heat loss, and the heat blocking efficiency with the discharge air velocity of the air curtain, respectively. The maximum heat blocking efficiency of non-recirculating air curtain having a value of H/b=52.50 (H=2.1 m, b=0.04 m) is calculated approximately 76.3%.

Figure 11 shows the velocity profile at the vertical centerline of opening and concentration distribution with temperature difference at 20 seconds when the discharge air velocity is the optimal value as 5.7 m/s. As the results, the indoor concentration is decreased less than non-air curtain case as shown in Fig. 6(a). Moreover, the maximum velocity at the vertical centerline of opening is also decreased less than non-air curtain case.

4 Discussion

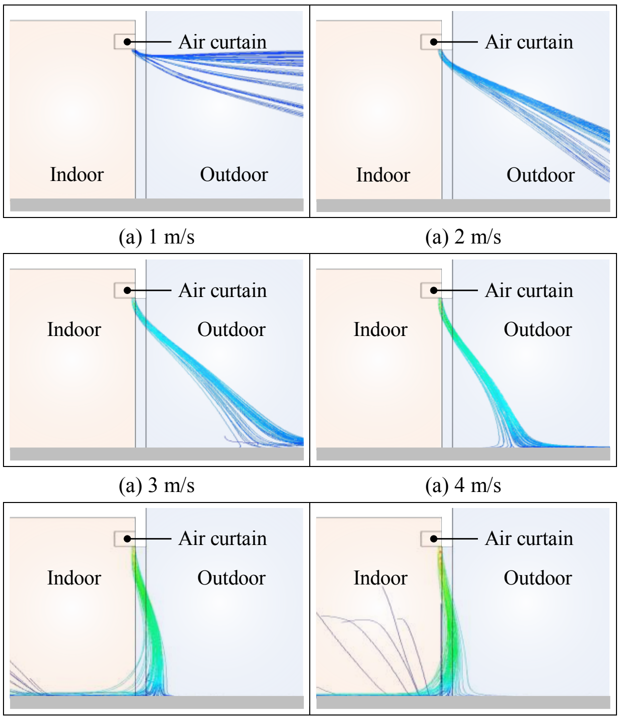
In this study, the infiltration rate across the single-side opening with air temperature differences between areas was evaluated by numerical simulation. Although the infiltration rate has a high value before reaching the steady state of indoor air distribution, it was kept a value similar when the air distribution reaches the steady state with the theoretical value by Pham and Oliver [9].

In this study, the heat blocking effectiveness of non-recirculating air curtain was also evaluated. When the outlet angle of the air curtain is 0°, the minimum deflection modulus shown in Fig. 4(b) can be expressed by a regression equation as shown in Eq. 11.

$$(D_m)_{min} = \frac{\left(\rho_o b u^2\right)_{min}}{gH^2(\rho_c-\rho_w)} \approx -0.016\ln\left(\frac{H}{b}\right)+0.2162 \qquad (11)$$

$(R^2=0.9882)$

To evaluate the safety factor for deflection modulus of the non-recirculating air curtain, this study is also calculated with inlet width of the air curtain, such as H/b=13.13, 26.25, 52.50, 105.00. Figure 12 shows the calculation results with H/b of air curtain. As the results, the optimal discharge air velocity was calculated 3.1 m/s, 4.2 m/s, 5.7 m/s, 8.0 m/s (H/b=13.13, 26.25, 52.50, 105.00), respectively. It means that the discharge air velocity should be increased as the inlet width of the air curtain gets narrower. A maximum heat blocking efficiency was also calculated approximately 80.9%, 78.6%, 76.3%, 74.4% (H/b=13.13, 26.25, 52.50, 105.00), respectively. As increasing the value of H/b, the heat blocking efficiency was increased.

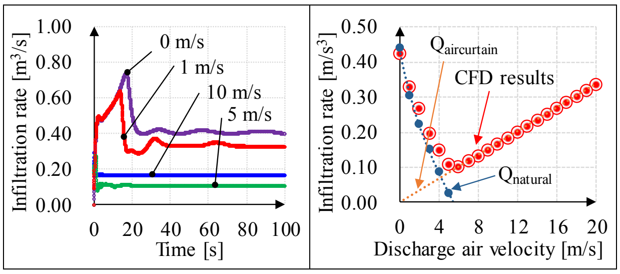


(a) 1 m/s (a) 2 m/s

(a) 3 m/s (a) 4 m/s

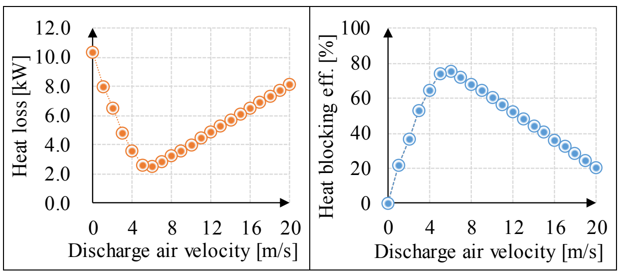
(a) 5 m/s (a) 6 m/s

Fig. 8. Pathline with the discharge air velocity of the air curtain.



(a) Infiltration rate with time (b) Infiltration rate with air velocity

Fig. 9. Calculation results of the infiltration rate.



(a) Heat loss (b) Heat blocking efficiency

Fig. 10. Calculation results of the heat blocking efficiency.

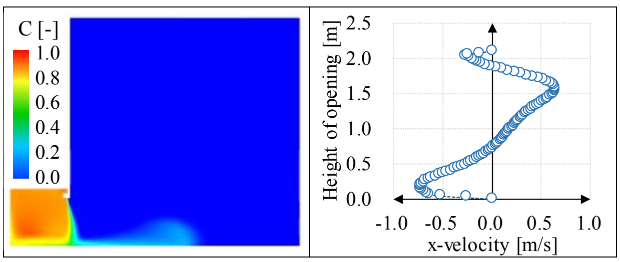


Fig. 11. Concentration distribution and velocity profile at 20 seconds when the discharge air velocity is 5.7 m/s.

From the results, the safety factor for deflection modulus of the non-recirculating air curtain was calculated approximately 2.75 as shown in Fig. 13. This value was higher than the proposed value as 1.3~2.0 by Hayes and Stoecker [11], and value as 2.2 by Foster et al. [13]. Using this value and the estimated regression equation from Eq. 11, the optimal discharge air velocity could be expressed as Eq. 12.

$$u^* = \sqrt{\frac{gH^2(\rho_c-\rho_w)\cdot\left[-0.016\ln\left(\frac{H}{b}\right)+0.2162\right]\cdot 2.75}{\rho_o b}} \tag{12}$$

Here, u^* [m/s] is the optimal discharge air velocity for non-recirculating air curtain to maximize the heat blocking efficiency.

5. Conclusions

From the point of view to reduce energy consumption, door open while air conditioner running on buildings have a problem. This paper had investigated the infiltration rate across the single-side opening by using transient CFD simulation. Moreover, this paper has also evaluated the heat blocking efficiency of non-recirculating air curtain. The following conclusions can be drawn from the results of the study:

(1) The infiltration rate across the single-side opening has a high value before reaching the steady state of indoor air distribution, and it was kept a value similar to the theoretical value of the steady-state method when the air distribution reaches the steady state.

(2) The numerical error of the infiltration rate was consistent within 10% by comparing with the theoretical value of the steady-state method and the transient CFD simulation result.

(3) Heat loss due to infiltration across the single-side opening can be reduced about 80% by using a non-recirculating air curtain.

(4) The safety factor for deflection modulus of the non-recirculating air curtain was calculated 2.75. Using this value and the deflection modulus equation, the optimal discharge air velocity for non-recirculating air curtain can be calculated simply.

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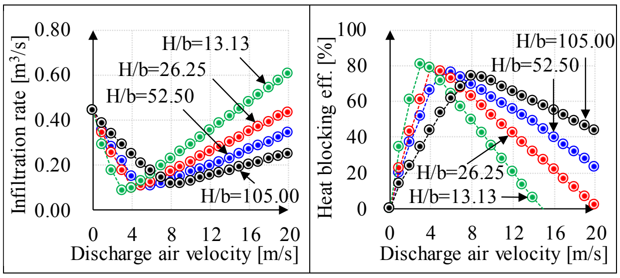

(a) Infiltration rate with air velocity (b) Heat blocking efficiency

Fig. 12. Calculation results with H/b of air curtain.

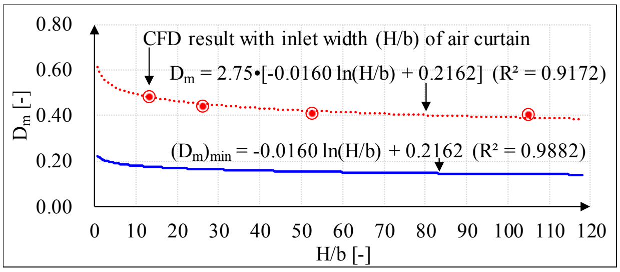

Fig. 13. Calculation results of the safety factor for D_m.

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