A NEW CALCULATING METHOD OF THE EFFECT OF NATURAL VENTILATION CONTROL IN OFFICE BUILDINGS WITH BUOYANCY DRIVEN VENTILATION

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ABSTRACT

The main purpose of this study is to evaluate the performance of natural ventilation control in office buildings. A new airflow balance simulation tool that can be estimate the effect of natural ventilation control is proposed. This simulation tool can also be used to evaluate the effect of setting the lower limit control of the room temperature to prevent overcooling due to natural ventilation. This is achieved by adjusting the opening ratio (e.g. opening area, number of opening or opening duration) of the natural ventilation opening. The authors confirmed the fundamental effect of natural ventilation control using the proposed simulation tool.

INTRODUCTION

Of late, the use of natural ventilation in office buildings, schools, and public facilities has become popular. The purpose of natural ventilation is to not only to reduce air-conditioning usage and enhance comfort (ASHRAE. 2004) but also to facilitate the improvement in the intellectual productivity (REHVA. 2006). However, the natural ventilation rate must be appropriate in order to achieve such results. As this rate is affected by vatiarions in the outdoor conditions, it is necessary to adjust the opening ratio (e.g. opening area, number of opening or opening duration) of the natural ventilation opening. The main purpose of this study is to evaluate the performance of natural ventilation control in office buildings.

There are several studies on natural ventilation analysis. A representative example is *COMIS* (Haas et al. 2002) jointly developed by IEA and Lawrence Barkeley laboratories, which is a program that simulates ventilation in multiple rooms. Each room is regarded as a mass point, and the natural ventilation is calculated based on the difference between the room temperature and outdoor temperatures. These temperature values are provided in advance; hence, the room temperature calculation is not performed at the same time. As natural ventilation is affected by the difference between the room temperature and outdoor temperature, it is desirable to calculate the thermal and ventilation balance simultaneously during the analysis of the natural ventilation period. In January 2001, *COMISv3.1* was released and integrated with *TRNSYS* in addition, calculation methods such as the *Ping-Pong* and *ONION* (Hensen 1995) were proposed. *COMIS* was also used along with *EnergyPlus* (Huang et al. 1999).

VentSim (National Institute for Land and Infrastructure Management, Building Research Institute 2005) was jointly developed by the National Institute for Land and Infrastructure Management (Japan) and the Building Research Institute (Japan); however, it can be used only for ventilation calculation. Okuyama is developing *NETS* (Okuyama 1999), which is a method for thermal and ventilation network by mathematical modeling, rendering it possible to obtain the temperatures and pressures considering the effect of air-conditioning and ventilation equipment, as well as natural ventilation. Togari et al. proposed a *block model* (Togari et al. 1991) that divides a large space into blocks and solves the thermal and ventilation balance of this large space, considering the influence of wall flow and air-conditioning jets to obtain the vertical temperature distribution. Moreover, there is a numerical study that incorporates natural ventilation (Miura et al. 2011). As an example of the *New HASP / ACLD* application, the thermal and moisture response coefficient method was introduced (Yoshida et al. 2002). A method for solving the ventilation balance by providing the room temperature of the previous time-step is also available. *BEST* (Kohri et al. 2017) accords priority to practical input, does not solve the ventilation balance of the entire building, and provides the neutral pressure level, when there is no wind. Instead, various natural ventilation permission conditions can be set, and the thermal balance of multiple zones can be solved with the natural ventilation necessary for maintaining the room

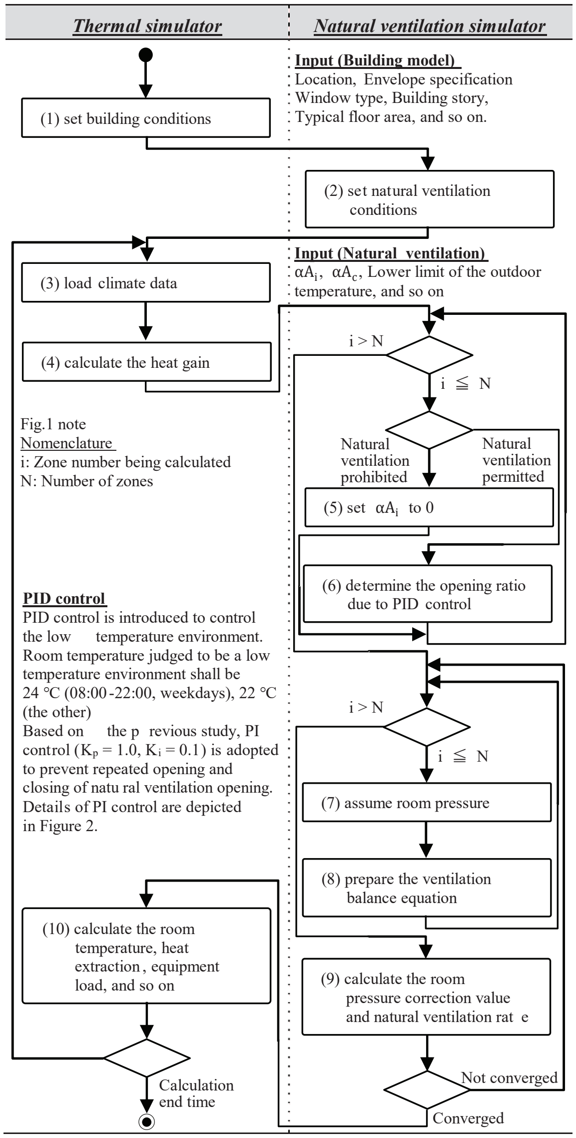


Figure 1 Activity diagram

temperature at the lower limit set value as an unknown. However, the thermal and ventilation balance of the entire building cannot be precisely solved, and the accurancy is limited.

Many natural ventilation calculator assumes that the natural ventilation opening is either fully open or fully close. By adjusting the opening ratio of the natural ventilation opening, it is possible to prevent overcooling by natural ventilation and differences in natural ventilation rate on each floor. Hence, in this paper, a new airflow balance simulation tool that can be estimate the effect of natural ventilation control is proposed. As a preliminary study, various properties are examined,

Table 1 Calculation conditions

【Calculation】

Weather: Expanded AMEDAS ver. 2010, typical year at Tokyo, Japan

Calculation time interval: 10 min.

【Natural ventilation】

The criteria of outdoor or room to introduce natural ventilation.

1. Lower limit of the outdoor temperature (08:00-22:00, weekdays): 18 °C (64 °F)
   Lower limit of the outdoor temperature (the other): 15 °C (59 °F)
2. Upper limit of the outdoor relative humidity: 90 %RH
3. Upper limit of the outdoor dew point: 19 °CDP (66 °FDP)
4. Upper limit of the wind velocity: 10 m/s (33 ft/s)
5. Lower limit of the room temperature (08:00-22:00, weekdays): 24 °C (75 °F)
   Lower limit of the room temperature (the other): 22 °C (72 °F)
   This control is by adjusting the opening ratio.
6. (Outdoor temperature) < (Room temperature)
7. (Outdoor enthalpy) < (Room enthalpy)
8. Not in warming

Natural ventilation schedule: April-Novenmber, 24h

Natural ventilation opening

αA_i: 1.0 m^2 (10.8 ft^2), αA_c: 10.0 m^2 (107.6 ft^2)

Effective opening area of between room and chimney: Twice as much as the floor αA_i

Effective opening area of entrance: 2.0 m^2 (21.5 ft^2)

Natural ventilation driven force: Only buoyancy driven ventilation

【Building】

Building story: 10 stories,

Floor height: 4 m (13 ft), Building height: 40 m (131 ft)

Typical floor area: 1,000 m^2 (10764 ft^2)

Envelope specification

Outdoor wall: PUF 20 mm (0.79 in) +Concrete 350 mm (13.78 in) + Cement 20 mm (0.79 in) + Tile 8 mm (0.31 in)

Window: Low-E pair glass

Internal heat generation

Equipment: 10.0 W/m^2 (3.2 Btu/h/ft^2),

Light: 9.5 W/m^2 (3.0 Btu/h/ft^2),

Human: 0.15 person/m^2 (0.014 person/ft^2)

【Air-conditioning】

Air-conditioning schedule: 08:00-22:00, weekdays

Set point

Midterm (April-May, October-November): 26 °C (79 °F), 50%RH

Summer (June-September): 28 °C (82 °F), 60%RH

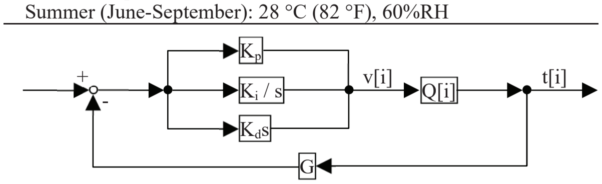


Figure 2 Block diagram

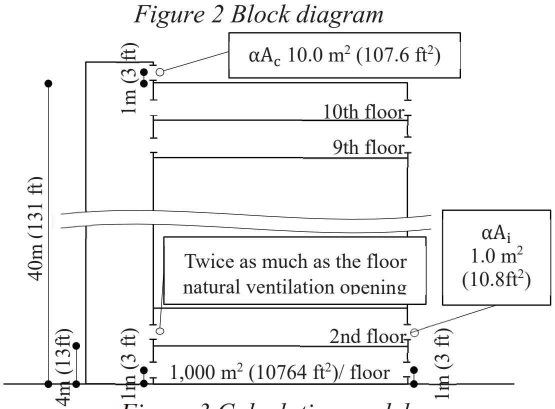


Figure 3 Calculation model

Table 2 Calculation parameters

	Lower limit of the outdoor temperature	αA_i on the lower half floor (1F-5F)	αA_i on the upper half floor (6F-10F)	αA_c	Lower chimney up to the floor
(1)Representative week	18 °C (64 °F)	1.0 m^2 (10.8 ft^2)	1.0 m^2 (10.8 ft^2)	10.0 m^2 (107.6 ft^2)	–
(2)Lower limit of the outdoor temperature	15 + X °C (X = 0, 1, 2, 3, 4, 5)	1.0 m^2 (10.8 ft^2)	1.0 m^2 (10.8 ft^2)	10.0 m^2 (107.6 ft^2)	–
(3)αA_i on the lower half floor	15 °C (59 °F)	0.1∗X (X = 0, 1, 2, ⋯, 10)	1.0 m^2 (10.8 ft^2)	10.0 m^2 (107.6 ft^2)	–
(4)Separate the chimney into two	15 °C (59 °F)	1.0 m^2 (10.8 ft^2)	1.0 m^2 (10.8 ft^2)	5.0 m^2 (53.8 ft^2)×2	X (X = 0, 1, 2, ⋯, 10)

when adjusting the opening ratio for buoyancy driven ventilation alone.

SIMULATION MODEL

The activity diagram of the proposed simulation tool is depicted in Figure 1. This tool inputs information such as the effective opening area of natural ventilation opening of "i-th floor" (αA_i) and the effective opening area of chimney-top opening (αA_c) for natural ventilation calculation, in addition to the thermal loads calculation conditions. According to these input values, the thermal simulator loads the weather data and calculates the various thermal balances, excluding the natural ventilation. Based on the outdoor conditions at the current time-step and the room conditions at the previous time-step, natural ventilation calculation is performed by natural ventilation simulator. αA_i is set to 0, if the natural ventilation permission conditions is *not* satisfied; when these conditons are satisfied, the opening ratio is determined using the PID control theory (Figure 2). PI control ($K_p = 1.0$, $K_i = 0.1$) was adopted to prevent repeated opening and closing of natural ventilation opening. Based on the obtained opening ratio, the pressure of the floor surface is assumed, and a ventilation balance equation is generated. Convergence calculation of the ventilation balance equation for all the zones is performed, and the obtained natural ventilation rate is returned to the thermal simulator; the room temperature and equipment load at the current time-step is calculated. The existing heat load calculation method (Ishino et al. 2017) was used for the equipment load calculation.

As the natural ventilation permission conditions, the lower limit of the outdoor temperature, upper limit of the outdoor relative humidity, upper limit of the outdoor dew point, and upper limit of the wind velocity, when there is natural ventilation in the room, can be set. These conditions determine the opening and closing of the natural ventilation opening based on the current time-step weather data. In addition, natural ventilation permission conditions such as "*lower limit of the room temperature* (refers to the adjustment of the opening ratio, preventing the room temperature during natural ventilation falls below the lower limit), (outdoor temperature) < (room temperature), and (outdoor enthalpy) < (room enthalpy) can be set. These conditions determine the opening and closing of the natural ventilation opening based on the current time-step and the room conditions at the previous time-step.

In the following section, the various properties when the opening ratio is adjusted are confirmed using the proposed simulation tool. The calculation conditions are listed in Table 1, and the calculated building-model is shown in Figure 3. It is assumed that the calculated building-model has a chimney dedicated to natural ventilation, based on the previous survey (Shimonosono et al 2019). The building has 10 floors (the building height is 40 m [131 ft]) and the typical floor area is 1,000 m^2 (10764 ft^2). αA_i is 1.0 m^2 (10.8ft^2) on each floor, and αA_c is 10.0 m^2 (107.6 ft^2). In these conditions, the neutral pressure level is 32.1 m (105.0 ft). The natural ventilation period for a room is from April-November. Air-conditioning was operated from 08:00 to 22:00 on weekdays, and set to 26 °C (79 °F), 50%RH during midterm and 28 °C (82 °F), 60%RH during summer. Hereinafter, the model shown in Figure 3 is reffered to as a reference conditon.

The calculation parameters are shown in Table 2. The characteristics of the proposed simulation tool are depicted during the transition of a representative week. Further, the room temperature and equipment load when the lower limit of the outdoor temperature during natural ventilation (reffered as to the *lower limit of the outdoor temperature*) was varied are shown. Finally, sensitivity analysis of a technique for reducing the difference in the natural ventilation rate between each floor is performed.

In this paper, opening area was adjusted by PID control; however, in the real building, the simulation result can be applied by adjusting the number of opening and the opening duration and so on.

RESULT AND DISCUSSION

The weekly characteristic value are shown in Figure 4. As a representative week, 10/22 (Sun) ‑10/28 (Sat) was adopted, during which there was natural ventilation in the room, and the opening ratio was adjusted. In order to

Figure 4 notes:
State 1: Natural ventilation, -1: Low outdoor temperature, -2: High outdoor relative humidity,
-3: High outdoor dew point, -4: High outdoor wind velocity, -5: Missing number,
-6: (Outdoor temperature) > (Room temperature),
-7: (Outdoor enthalpy) > (Room enthalpy), -8: Missing number, -9: Warming (State < 0: No natural ventilation)
Heat extraction Heat rate to cool the room by natural ventilation.
Equipment load covers cooling and dehumidification.

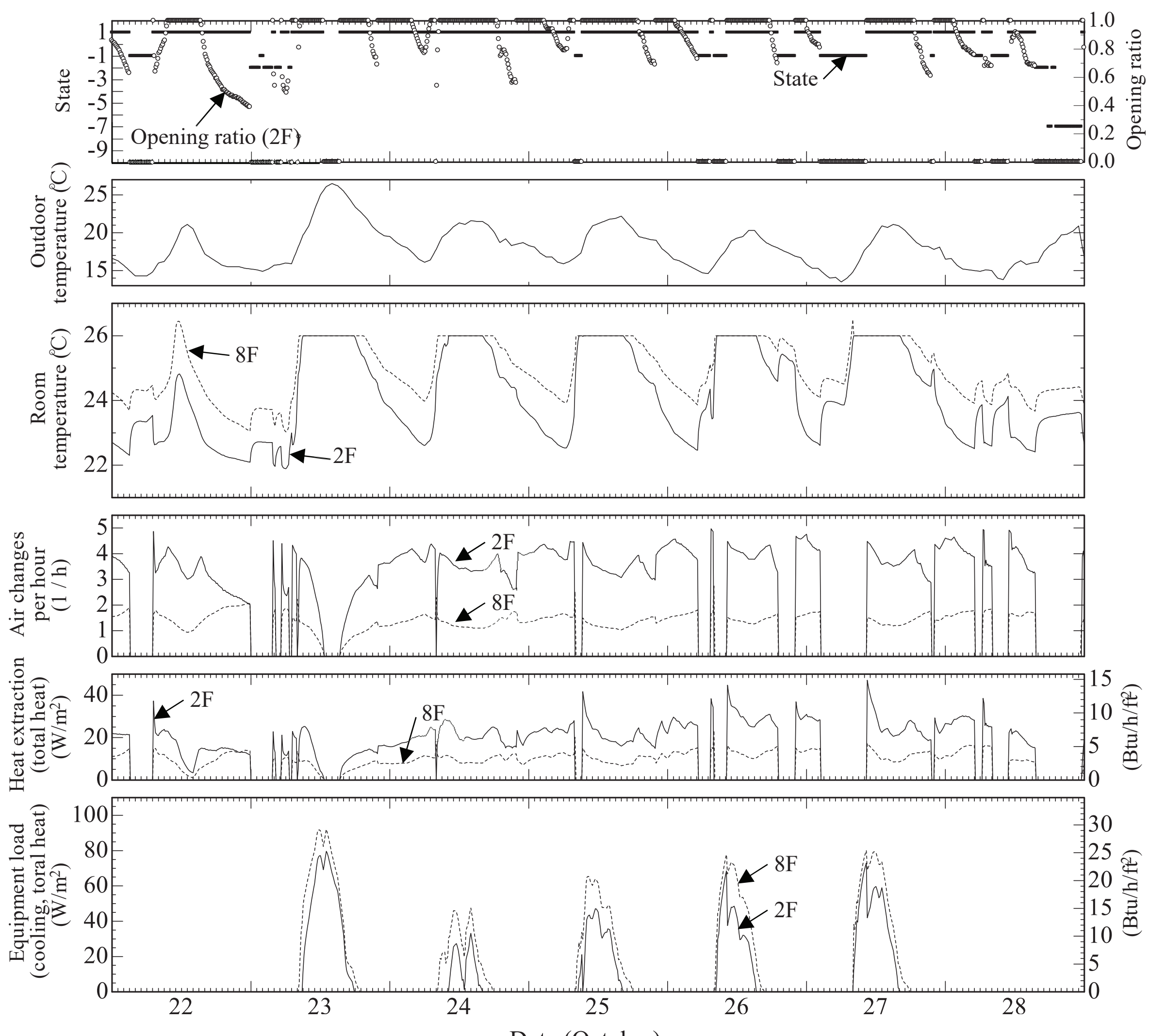


Figure 4 Weekly characteristic value (2F and 8F)

maintain the room temperature above the lower limit, the opening ratio of the 2nd floor was adjusted from evening to midnight; therefore, the natural ventilation rate on the 2nd floor decreased. However, the neutral pressure level increased, increasing the natural ventilation rate on the 8th floor. Such characterisitics can be demonstrated by proposed simulation tool.

When the opening ratio is adjusted, there is a possibility that the value of lower limit of the outdoor temperature can be set low; thereby, the natural ventilation time can be increased, and the equipment load reduced. Therefore, sensitivity analysis was performed on the room temperature and the equipment load by varying the value of lower limit of the outdoor temperature in the 08:00-22:00, weekdays. Here, the lower limit of the outdoor temperature was varied in the 15-20 °C (59-68 °F) range. The room temperature and the equipment load, with the variation in the lower limit of the outdoor temperature, are shown in Figure 5 and Figure 6, respectively. And Figure 7 and Figure 8 depicted the data of the outdoor temperature and humidity ratio of Tokyo. When the opening ratio was *not* adjusted, the time ratio at 24 °C (75 °F) or less was 19.9%, when the lower limit of the outdoor temperature was 15 °C (59 °F). In particular, there was a time zone during which the room temperature dropped to 22.3 °C (72.1 °F). On the other hand, when the opening ratio was adjusted, the time ratio at 24 °C (75 °F) or less was 2.7% at the lower limit of the outdoor temperature of 15 °C (59 °F), which can considerably suppress the occurrence of a low temperature environment. It can be observed that by lower limit of the outdoor temperature was 15 °C (59 °F), the equipment load can be reduced by 2.8% compare to the reference condition, while suppressing a low temperature environment.

Generally, buoyancy driven ventilation involves higher natural ventilation rate in the lower floors, and lower rates in the upper ones. The proposed simulation tool can adjust the opening ratio in the lower floors, reducing the difference in the natural ventilation rate on each floor. Here, the lower limit of the outdoor temperature was set to 15 °C (59 °F); the following two methods were undertaken to reduce the difference in the natural ventilation rate between the floors: (1) A smaller αA_i on

Figure 6 note: Equipment load covers cooling and dehumidification in all seasons.

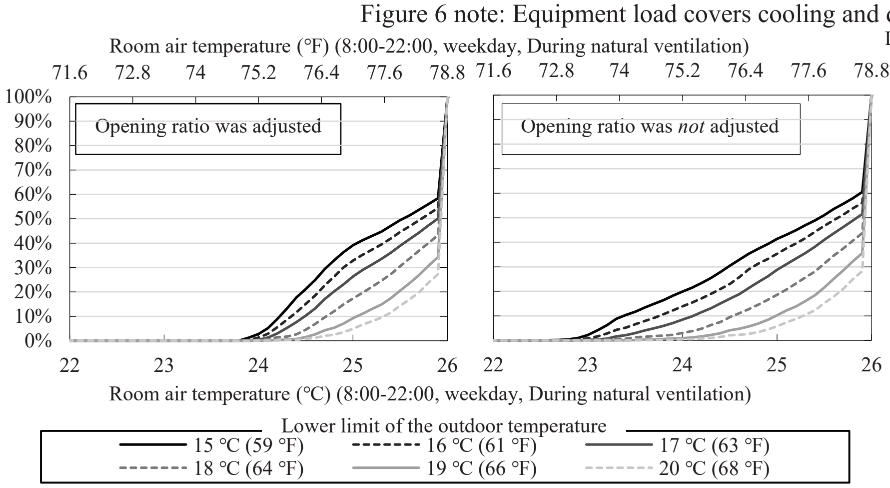


Figure 5 Cumulative frequency of the room temperature (2F)

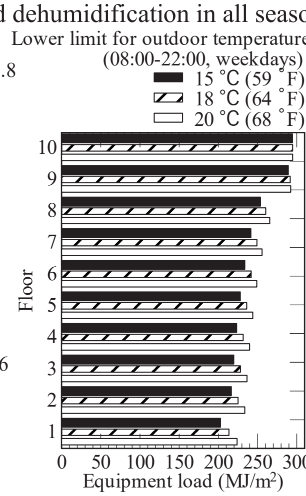


Figure 6 Equipment load

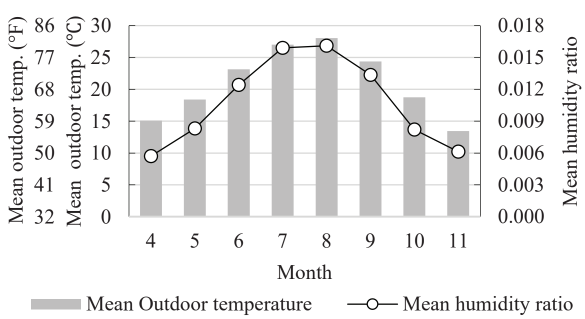


Figure 7 Monthly weather data in Tokyo

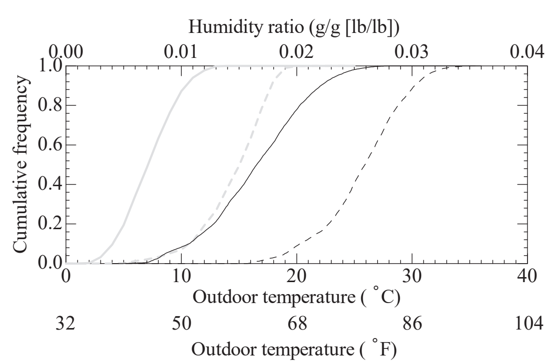


Figure 8 Cumulative frequency of weather data in Tokyo

the lower half of the floor and (2) separation of the chimney into two, upper and lower of the floor. D_{Ave} which is used to evaluate the difference in the natural ventilation rate on each floor can be expressed as follows:

$$D_{Ave} = \frac{\sum_i |N_{Ave} - N_i|}{f}$$

Nomenclature N_{Ave}: mean air changes per hour

N_i: air changes per hour (i-th floor, i>2)

f: ([building stories] -1)

Figures 9 to 12 depict D_{Ave} and the air changes per hour in each floor, when the above two methods are used; D_{Ave} and air changes per hour for each floor during *midterm* are demonstrated. The minimum and maximum values, and the quartile and median when the opening ratio is adjusted, as well as the median, when the opening ratio is *not* adjusted are depicted in Figure 13. As there is a entrance opening, the air changes per hour on the 1st

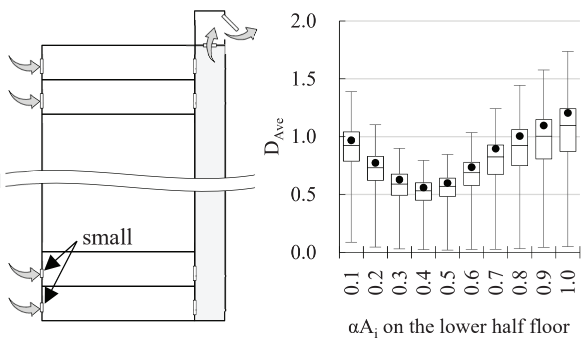


Figure 9 D_{Ave} due to change αA_i on the lower half floor

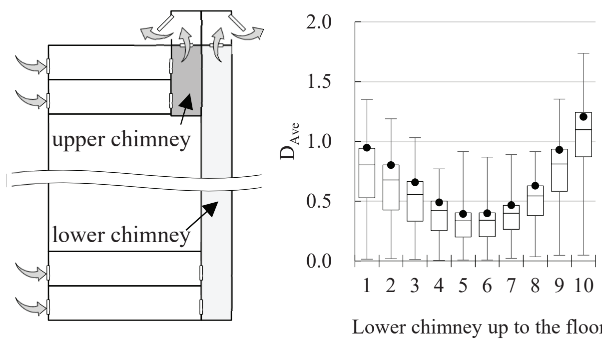


Figure 10 D_{Ave} due to separate chimney into two

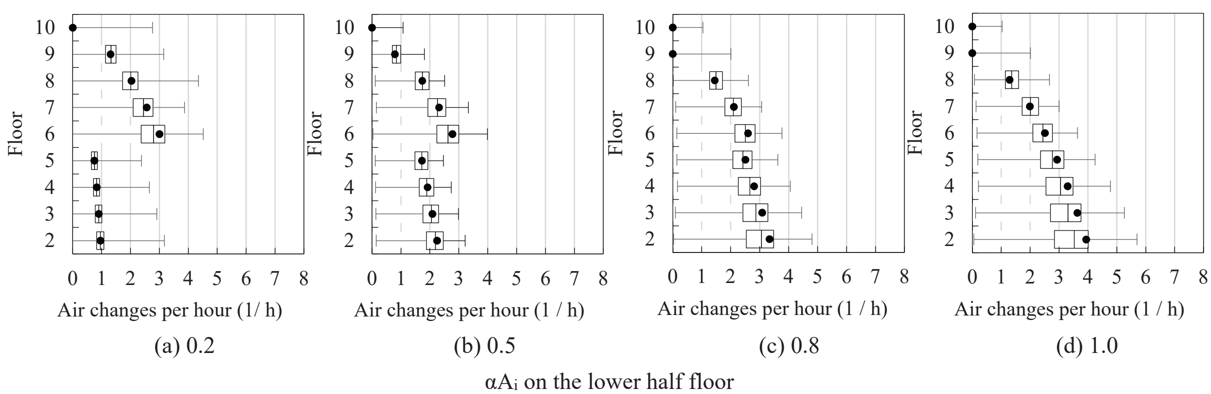


Figure 11 Air changes per hour due to change αA_i on the lower half floor

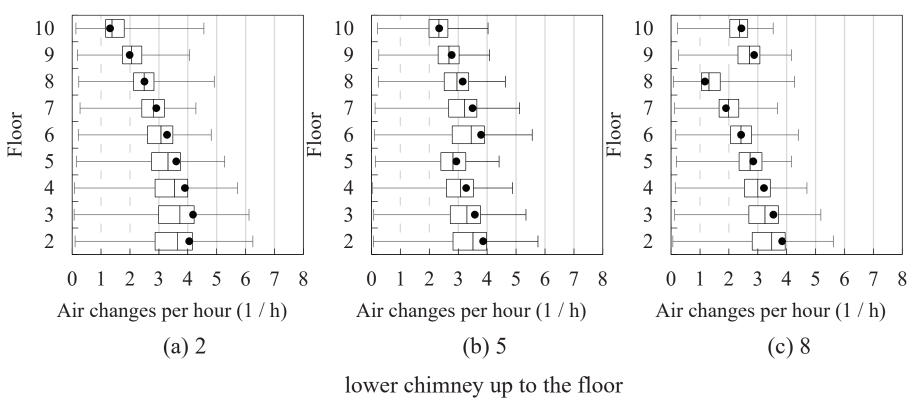


Figure 12 Air changes per hour due to separate chimney into two

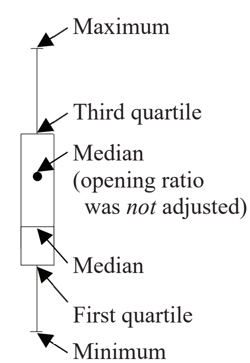
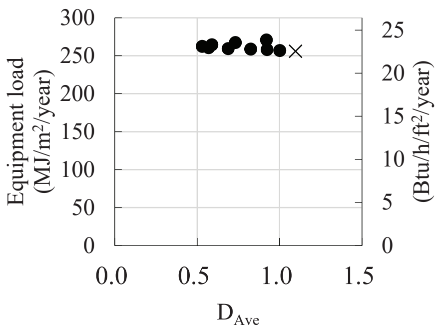
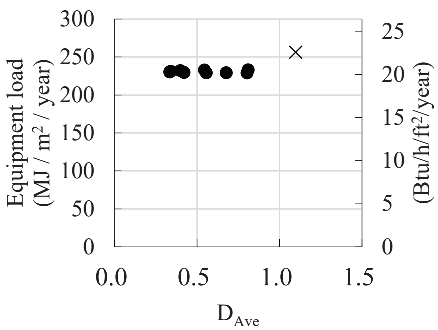


Figure 13 How to read the graph (Figure 9 to 12)



(a) A smaller αA_i on the lower half of the floor



(b) separation of the chimney into two, upper and lower, of the floor

Figure 14 Correlation between D_{Ave} and Equipment load

Figure 14 notes: (1) Equipment load covers cooling and dehumidification in all seasons, and mean of all floors.
(2) The plot "×" indicates reference condition

Figure 15 notes: (1) The "reference" is the building model shown in Figure 3.
(2) Equipment load covers cooling and dehumidification in all seasons, and mean of all floors.
(3) The "change ratio" indicates the equipment load compare to the reference condition.

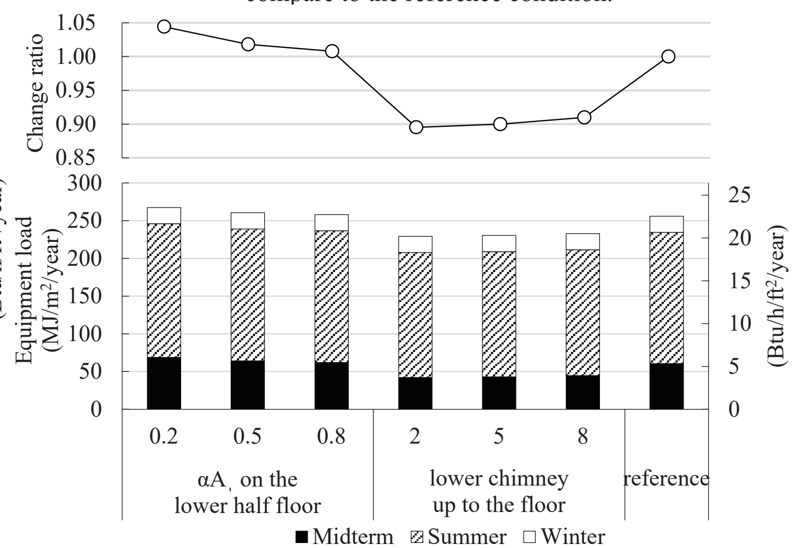


Figure 15 Equipment load and change ratio

floor is more than the other floors; thus, D_{Ave} covers the 2nd and higher floors, and Figures 11 and 12 depicted only the 2nd and higher floors for convenience. D_{Ave} decreases when the opening ratio is adjusted, compared to that when it is not; i.e., the difference in the natural ventilation rate of each floor is reduced. This is because the lower floor opening ratio was reduced. In addition, on varying αA_i from 0.1-1.0, when designing the 1st-5th floors, it was found that D_{Ave} was decreased, if αA_i was set to 0.4 or 0.5. On the other hand, in the method involving the separation of the chimney into two in the upper and lower floors, it was found that the D_{Ave} decreased by making the lower chimney up to the 5th or 6th floor. By setting αA_i from the 1st-5th floor to 0.5 during design, the neutral pressure level was increased, and the natural ventilation rate was also increased on the 9th floor. In addition, by making the lower chimney up to the 5th floor, natural ventilation rate of the 10th floor was apploximatly 2 / h. The equipment load when the above method were adopted is shown in Figure 14 and 15. When mehod (1) was applied, the equipment load increased by a maximum of 4.4%, compared to the reference condition. When mehod (2) was applied, the equipment load decreased by a maximum of 10.5%, compared to reference condition.

CONCLUSION

In this study, a new simulation tool that can be estimate the effect of natural ventilation control was proposed. Numerical analysis was performed focusing on the opening ratio.

In Summary,

1) A new simulation tool that can evaluate the opening ratio based on the PID control theory was proposed. PI control (K_p = 1.0, K_i = 0.1) was adopted to prevent repeated opening and closing of natural ventilation opening.
2) The characteristics of the proposed simulation tool were demonstrated base on the transition of a representative week. By adjusting the opening ratio of the lower floor, the neutral pressure level increased, and the natural ventilation rate of the upper floor increased.
3) The room temperature and the equipment load on each floor when the lower limit of the outdoor temperature, in the presence of natural ventilation in the room,

were demonstrted. By lower limit of the outdoor temperature was 15 °C (59 °F), the equipment load can be reduced by 2.8% compare to the reference condition.

4) Focusing on the possibility that the difference in the natural ventilation rate on each floor can be reduced by adjusting the opening ratio, this difference was evaluated using D_{Ave}. D_{Ave} was reduced by adjusting the opening ratio. Moreover, it decreased when the following two methods were adopted.

  (1) αA_i on the lower half of the floor was set to 50% of the αA_i of the upper half of the floor.

  (2) The chimney was separated into two in the upper and lower floors, which by making chimney up to the 5th floor.

  When mehod (1) was applied, the equipment load increased by a maximum of 4.4%; however when method (2) was applied, it decreased by a maximum of 10.5%.

ACKNOWLEGMENT

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NOMENCLATURE

D_{Ave}: mean absolute deviation
f: ([building stories]-1)
i: floor number (i > 2)
K_p, K_i, K_d: Proportional gain, Integral gain, Derivative gain
N: number of zones
N_{Ave}: mean air changes per hour
N_i: air changes per hour (i-th floor)
Q[i]: natural ventilation rate (i-th floor)
t[i]: room air temperature (i-th floor)
v[i]: opening raio (i-th floor)
z: zone number being calculation
αA_c: effective opening of chimney-top opening
αA_i: effective opening of natural ventilation opening of i-th floor

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