Successive Indoor Air Pressure Calculation Method for Natural Ventilation Rate Prediction

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ABSTRACT

Installing Natural Ventilation (NV) system in office buildings leads to the reduction of energy consumption of heating, ventilation and air conditioning (HVAC), which accounts for approximately 50% of total in an office building in Japan. However, it is difficult to estimate the NV performance before its completion, because the NV system is easily affected by the outdoor environment. Thus, its design method is not yet established. This study aims to easily estimate the NV performance by using transient airflow network calculation, and the wind pressure coefficient used in the method was obtained from Computational Fluid Dynamics (CFD). The theory of the model is described in detail by this study. Natural ventilation rate was calculated for two different models. Firstly, in order to learn about the availability of the calculation method, to know about available range of the time step and to calculate the transient conditions in a short period, a simple model, which consists of one node and two branches, was used. Secondly, in order to learn about the applicability of the method to actual buildings, an actual building was simulated as a complicated model, which consists of seven nodes and thirteen branches, and its natural ventilation rate was calculated by the method. As a result, at the simple model with the wind pressure coefficient that varies over time, the time-series change of the airflow rate was able to be obtained. In addition, at the actual building model, though its complexity, the time-series change of temperature and ventilation flow rate was obtained by the method. It was shown that the temperature changes are slower than that of pressure, because of the heat capacity of the air, which correspond the real phenomenon.

KEYWORDS

Natural ventilation, Network model, Transient calculation, Ventilation performance prediction

1 INTRODUCTION

Natural ventilation (NV) has long been used in Japanese buildings because of hot and humid climate in summertime [1]. It was mainly applied in residential buildings in the past years, and now it has been spread to non-residential buildings including office buildings. With the need of energy conservation and Business Continuity Planning (BCP) is on the rise, NV system, which basically does not use non-renewable energy, is attracting increasing attention. In Japanese commercial sector, energy consumption of Heating, Ventilation and Air-Conditioning (HVAC) accounts for approximately 30% of total energy consumption [2]. Subsector “Offices and buildings”, which is a subsector in commercial sector, accounts for more than 20% of energy consumption in the sector. In the subsector, HVAC equipment is the largest consumer of energy, which accounts for 50% of all [3]. Furthermore, in western countries, it was shown that HVAC is the main end use in office buildings, whose proportion was close to 50% of the total energy consumption for non-residential buildings [4]. Thus, reducing energy consumption in

HVAC system has a large impact on running cost of the building as well. NV system uses renewable energy for driving force of ventilation, i.e. the air temperature difference (difference of air density) and wind pressure [5-8]. Using renewable energy saves expenses for ventilation, compared to mechanical ventilation systems. Yamamoto et al. [9] conducted a survey of natural ventilation system in 72 naturally ventilated buildings. It was shown that the reasons for installing NV system was divided as; saving energy and ensuring comfort. Most of the reasons for designers to install NV system are reducing the operation hours of air conditioning system. Since the range of acceptable thermal conditions seems to be wider under naturally ventilated condition, compared to centralized HVAC system [10], NV system can be used to enhance the satisfaction of thermal condition of buildings. Hummelgaard et al. [11] operated simultaneous field measurement in five mechanically and four naturally ventilated open-plan office buildings. It was reported that compared to the mechanically ventilated buildings, even though the air temperature and CO_2 concentration varied more and in some cases higher values were recorded, higher degree of satisfaction with the indoor environment and lower prevalence/intensity of symptoms among the occupants were obtained in the naturally ventilated buildings.

Chen [12] summarized methodology for predicting the performance of ventilation. The methods were classified into seven models; analytical model, empirical model, small-scale experimental model, full-scale experimental model, multizone model, zonal model and CFD model. However, this system causes unstable flow patterns [13] and fluctuation of airflow rate through NV apparatus. Because it is difficult to evaluate the NV performance before its completion, the method for estimating and predicting the NV performance has not yet been established. The designers are generally referring to the past cases, and are still designing it by rule of their thumb to some extent [14].

The aim of this study is to establish and propose a simplified prediction and estimation method of the NV performance for non-residential buildings, using a transient network model method and the wind pressure coefficient obtained from CFD analysis.

2 THE THEORY OF THE MODEL

In the airflow network model, each of the room is assumed to be a node of air pressure and temperature; each of the openings between rooms is assumed to be the branch connecting the rooms with the flow resistance. Air flow and heat transfer through the network are calculated by solving the balance equations. In the network model of NV, differential pressure Δp between ends of a branch was calculated considering the buoyancy and wind force. The airflow rate F through a branch is defined as:

$$F = sign(\Delta p) C_D A \sqrt{2/\rho \left| \Delta p \right|} \tag{1}$$

where C_D [-] is the discharge coefficient, A [m^2] is the area of the opening and ρ [kg m^{-3}] is the air density.

In many network model calculations, the air is commonly assumed to be incompressible fluid, so the density doesn't change by time. Thus, under the steady state, because of the law of mass conservation, the sum of mass flow rate and volumetric flow rate at a node is:

$$\sum \rho F = \Sigma F = 0 \tag{2}$$

However, the airflow rate was calculated over time and air is assumed to be compressible in the model in this paper. In other words, the model does not hold Eq. (2). The air flow rate, the air density, air temperature and the air pressure were calculated successively in the model.
Here, the density of the air in the room at $(k+1)\Delta t$ [s] is defined as:

$$\rho_i^{k+1} = \rho_i^k + \frac{\partial \rho}{\partial t}\Delta t = \rho_i^k + \frac{\partial M}{\partial t}\frac{\Delta t}{V_i} \approx \rho_i^k + \Sigma\left(\rho F_{i,j}^k \frac{\Delta t}{V_i}\right) \tag{3}$$

where, M_t [kg] is the mass of the air in a room and V [m^3] is the volume of the room. In this model, it is assumed that: the condition is kept isothermal during infinitesimal time interval Δt [s]; the temperature change occurs after the density change. The temperature of the air in a room at $(k+1)\Delta t$ [s] is defined as:

$$T_i^{k+1} = T_i^k + \Sigma\left\{\left(Q_{v\,i,j}^{\;k} + Q_{h_i}\right)\Delta t \,/\, \left(C_p \rho_i^{k+1} V_i\right)\right\} \tag{4}$$

where T [K] is the temperature of the air in a room, Q_v [W] is the heat gain at the room caused by ventilation, Q_h [W] is the heat generation load at the room, and C_p [J·kg^{-1}K^{-1})] is the specific heat capacity of the air.

Here, the ideal gas law and the deformed equations are shown below:

$$pV = nRT \tag{5}$$

$$pm = \rho RT \tag{6}$$

$$p_i^{k+1} = \rho_i^{k+1}\, T_i^{k+1}\, R/m \tag{7}$$

where p [Pa] is the air pressure in a node, n [mol] is the number of moles, R [J K^{-1}mol^{-1}] is the gas constant and m [g mol^{-1}] is the molar mass. The air pressure of each node at $(k+1)\Delta t$ [s] was calculated by Eq. (6)' with using the values of density and temperature obtained by Eq. (3) and Eq. (4), respectively.

The flow of the model is shown in Table 1. The merit of this model is that: (1) the time-series results are able to be obtained, and (2) the air is assumed to be compressible in this model, thus this model is expected to be correspond to the real phenomenon. Moreover, this method can calculate the airflow network without convergence calculation. Here, in this paper, this model shall be called as "Successive Indoor Air Pressure Calculation Method".

Table 1: Flow of the calculation program

	Incident	**Cause**	**Eq.**
Step 0	Set the initial and boundary conditions		
Step 1	Differential pressure occurs between each end of the branch	*Step 0 & 5*	-
Step 2	Air flows into the branch	*Step 1*	(1)
Step 3	Total mass and density of air at a node change	*Step 2*	(2) & (3)
Step 4	Temperature change occurs because of the ventilation and other heat fluxes	*Step 2*	
Step 5	Pressure change occurs	*Step 3 & 4*	

3 TRANSIENT CALCULATION WITH A SIMPLE MODEL

At first, a simple rectangular room model was chosen to verify if the proposed method works well for the transient calculation of the fluctuating airflow. The results from the conventional method are compared with the new calculation method.

3.1 Calculation method and conditions

A simple single room model is shown in Figure 1. The model is a 3,000×3,000×3,000 cube with two openings at each side of the wall parallel to the approaching flow of 5 m s^{-1} at upper air. The wind pressure coefficient at each opening is required for the calculation as the boundary condition, thus the results of large eddy simulation (LES) by Kobayashi et al [15] were applied as input data. The CFD model analysed to obtain wind pressure coefficient by Kobayashi et al was a 200×200×200 sealed cube without any openings, which is 15 times smaller than the model used in this paper, with the approach flow of 10 m s^{-1} at upper air, which is 2 times larger than the calculation condition in this paper. The time-series result of wind pressure coefficient for two openings (Op-R and Op-L) is shown in Figure 2. Due to the scale difference and wind velocity difference, the data had to be modified. To make the time scale equal, the time was multiplied by 30 before the calculation, thus the data in Figure 2 was assumed to be the time-series result for 150 [s] (= 5 [s] × 15 × 2) in the calculation.

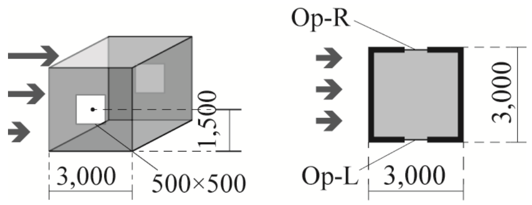


Figure 1: Single room Model

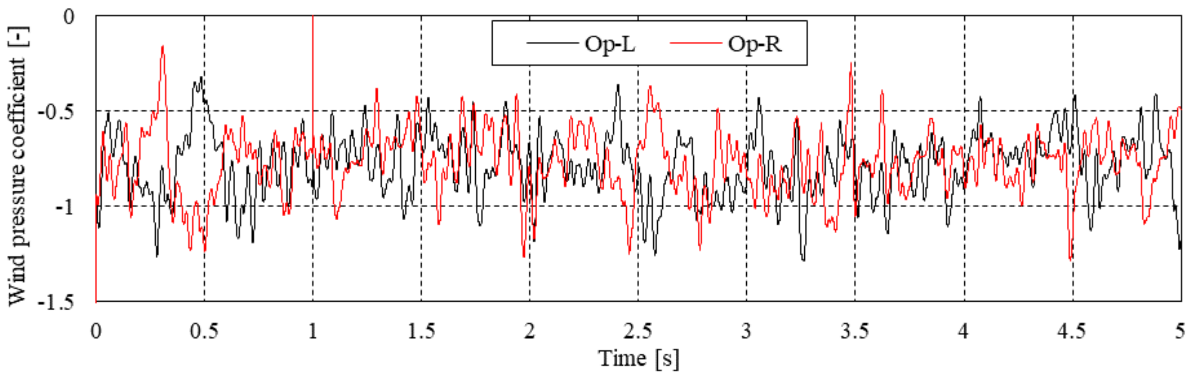


Figure 2: Time-series change of wind pressure coefficient

(Note: The figure shows the CFD result with measurement scale.)

With using the data of wind pressure coefficient, the following two transient calculations were conducted:

1) Successive Indoor Air Pressure Calculation Method

The model that has been explained in Chapter 2.

2) Instantaneous steady-state calculation assuming incompressible fluid
   Resistance coefficients of two openings were summed up to evaluate “overall effective opening area” through flow path as follows:

$$\overline{(\mathrm{C_D A})} = \{(C_D A)_1^{-2} + (C_D A)_2^{-2}\}^{-0.5} \tag{8}$$

   where $C_D A$ is the effective opening area for each opening (branch) [m^2]. Airflow rate through the room was also calculated by Eq. (1), and differential pressure in the equation is equal to the difference of static pressure across the openings in this method.

Air temperature and pressure were set as initial condition, and air density was calculated with the equation deformed from Eq. (6):

$$\rho = Pm/RT \tag{9}$$

where ρ [kg m^{-3}] is the air density, p [Pa] is the air pressure in a node, m [g mol^{-1}] is the molar mass, R [J K^{-1}mol^{-1}] is the gas constant and T [K] is the air temperature. The calculation condition is shown in Table 2.

Table 2: Calculation method and condition

Solution	Time step [s]	Boundary condition	Initial condition		
		Wind velocity of approach flow [m s^{-1}]	**Temperature [°C]**	**Pressure [Pa]**	**Density [kg m^{-3}]**
Explicit	5.0×10^{-6} (1×10^6 cycles)	5.0 (constant)	24 (constant)	0 (Gauge pressure)	Calculated by **Eq. (9)**

3.2 Result and discussion

Figure 3 shows the calculation result of the airflow rate through each opening by method 1 (Successive Indoor Air Pressure Calculation Method). Outflow was defined to be positive at each opening. The calculation result of the airflow rate through the room by method 1 and method 2 (instantaneous steady-state calculation) are compared in Figure 4. The airflow from Op-L to Op-R was defined to be positive in method 2. The calculation results of airflow rate by method 1 was approximately the same with the results obtained by method 2. Thus, the calculation result of airflow rate by method 1 assumed to be reasonable. As shown in Figure 5, the difference between inflow/outflow rate was approximately 1.0% of the airflow rate, however it was expected that the compressibility may not be able to be avoided in larger room.

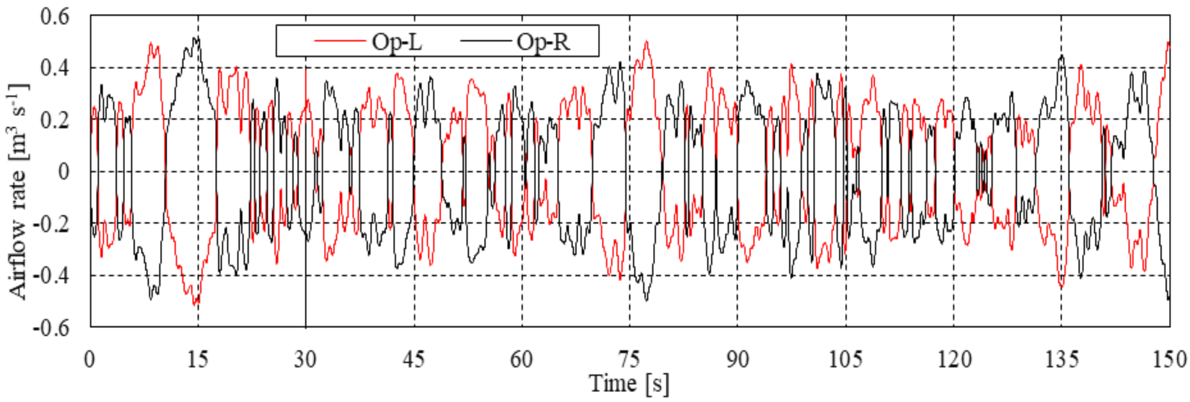


Figure 3: Airflow rate through openings by method 1 (Outflow was defined to be positive)

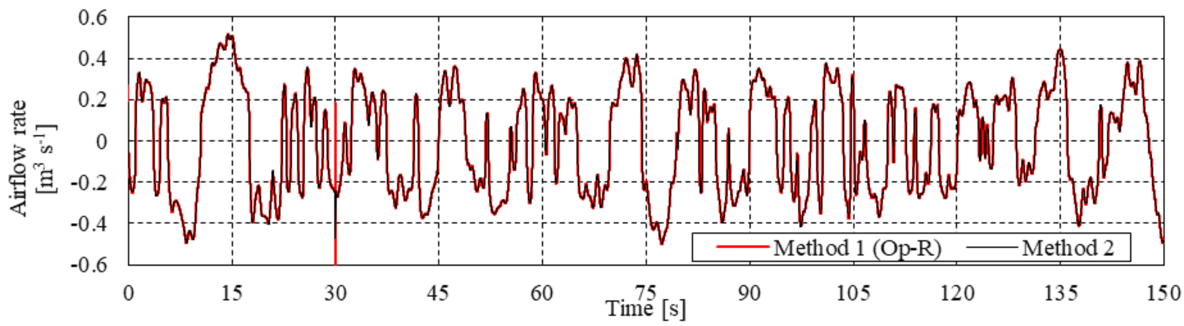


Figure 4: Airflow rate through the room by method 2 (Op-L → Op-R defined to be positive)

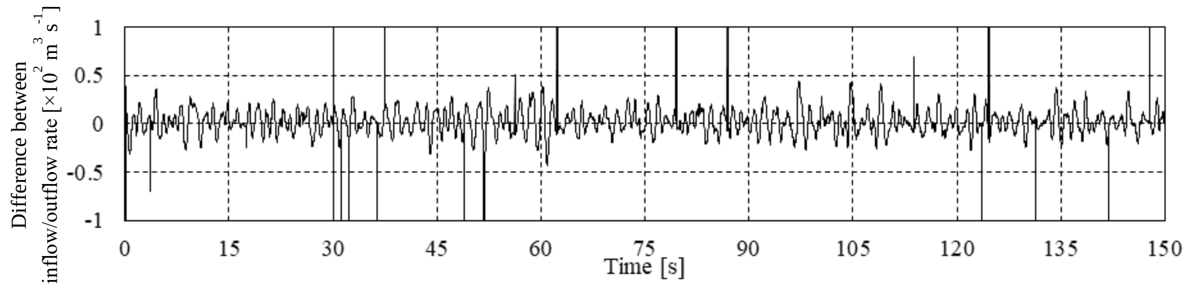


Figure 5: Difference between inflow/outflow rate by method 1 (Outflow was defined to be positive)

Air pressure inside the room at floor level calculated by method 1 and air pressure calculated by the result of airflow rate in method 2 are shown in Figure 6, where air pressure P of method 2 was calculated with the following equation based on the assumption of mass conservation, i.e. the assumption that the air is incompressible and the density is constant:

$$P = \left(\frac{F}{C_D A}\right)^2 \frac{\rho}{2} sign(F) + C_w \frac{1}{2} \rho V_o^2 \tag{10}$$

where P [Pa] is the pressure, F [m^3 s^{-1}] is the airflow rate, $C_D A$ [m^2] is the effective area of the opening (Op-R), ρ [kg m^{-3}] is the density, C_w [-] is the wind pressure coefficient of the corresponding opening, and V_o [m^3] is the outside wind velocity [m s^{-1}].
The results of air pressure obtained by two methods were correspond to each other. Thus, the calculation results of air pressure also were reasonable. Therefore, it was expected that method 1 can be applied to the calculation for more complicated building flow network model, e.g. the room with several openings so the airflow direction is difficult to be determined. Air pressure varied around -12 [Pa] in both method 1 and 2, due to the negative wind pressure coefficient outside the openings.

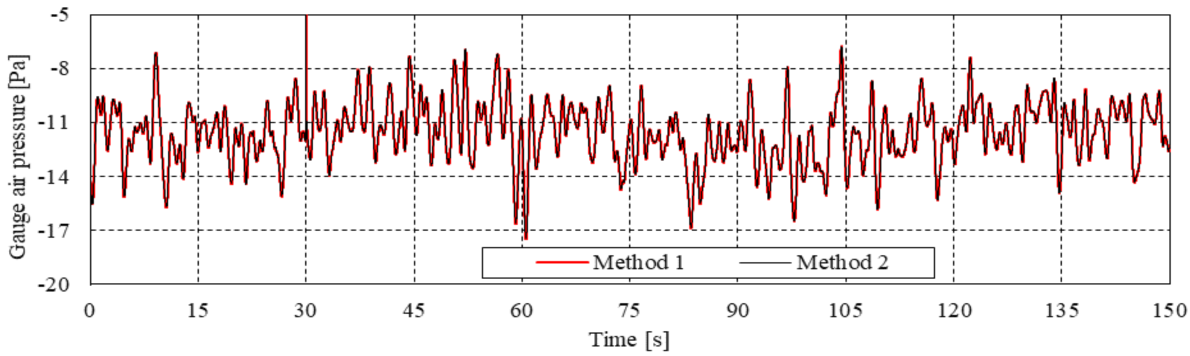


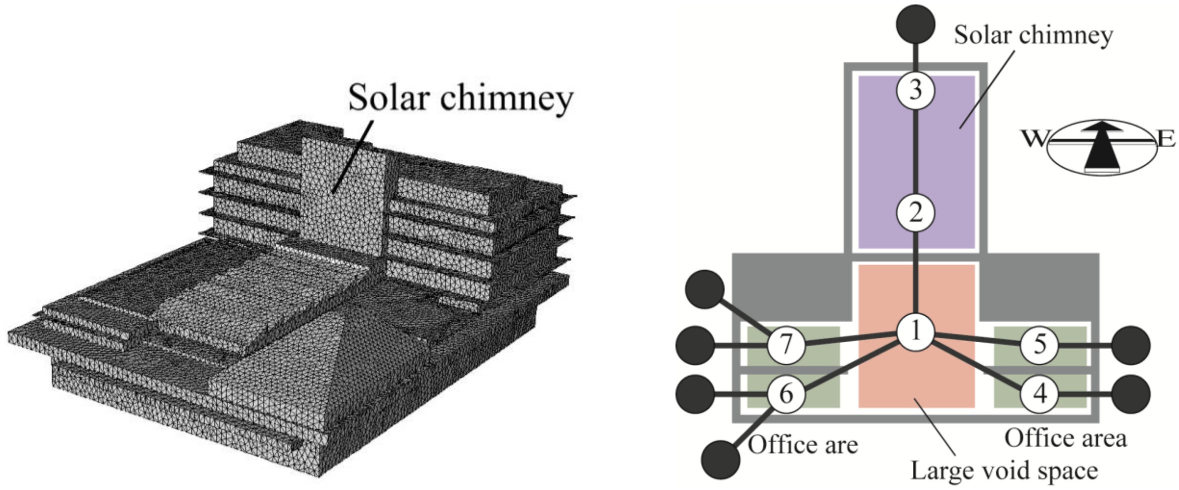
Figure 6: Gauge Air pressure at floor level

4 STEADY STATE CACULATION WITH BUILDING MODEL

A more complicated model, which simulates an actual building, was chosen to verify the validity of the calculation method for actual buildings. Additionally, this calculation is for verifying whether the model properly shows convergence to the steady result, if the boundary conditions are steady, and whether the time-series change correspond to the real phenomenon.

4.1 Calculation method and conditions

The measurement target building in the authors' previous study [16] was chosen to be the calculation target in this study. In order to obtain the wind pressure coefficient of the building, CFD analysis with the shear stress transport (SST) k-ω model was conducted. The CFD model of the target building is shown in Figure 7 (a). To facilitate the successive calculation, the building was simplified to be a model shown in Figure 7 (b). Using the results of wind pressure coefficient obtained from the CFD analysis, the successive calculation was conducted under the condition detailed in Table 3.



(a) Model of CFD analysis (b) Model of calculation

Figure 7: CFD Model and calculation model of Target Building

Table 3: Calculation condition

Programming Language		Fortran
Solution		Explicit
Time step		1.0×10^{-4} [s] (1×10^{7} cycles = 1,000 [s])
Initial Condition	Temperature	outdoor air: 24℃ (Constant), indoor air: 28℃
	Pressure	Gauge pressure: 0 [Pa] (Atmospheric pressure: 101,300 [Pa])
	Density	Calculated by Eq. (9)
Heat generation	Office area	60 [W m^{-2}] × Floor area [m^{2}]
	Solar chimney	500 [W m^{-2}] × Wall (glass) area [m^{2}]

4.2 Result and discussion

Calculation results of air pressure and temperature at each node are shown in Figure 8 and 9, respectively. The airflow rate through each branch are shown in Figure 10. As shown in Figures

8-10, air pressure and airflow rate reached to the steady state soon, while the air temperature took approximately sixteen minutes for reaching the steady state, which also occurs in the real phenomenon, because of the heat capacity of the air. The time-averaged airflow rate through the branches are shown in Table 4. Comparing the airflow rate with the time-series change of the temperature, the node with large airflow rate reached to the steady state more quick than the others, because of the large air change rate. These results show that the proposed calculation method has simulated the real phenomenon properly.

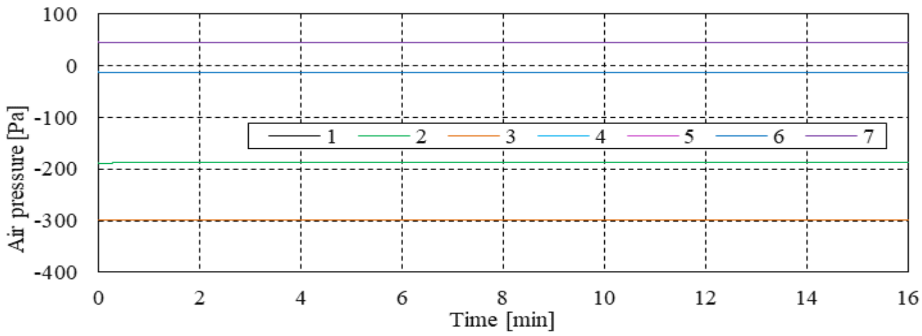


Figure 8: Air pressure at each node

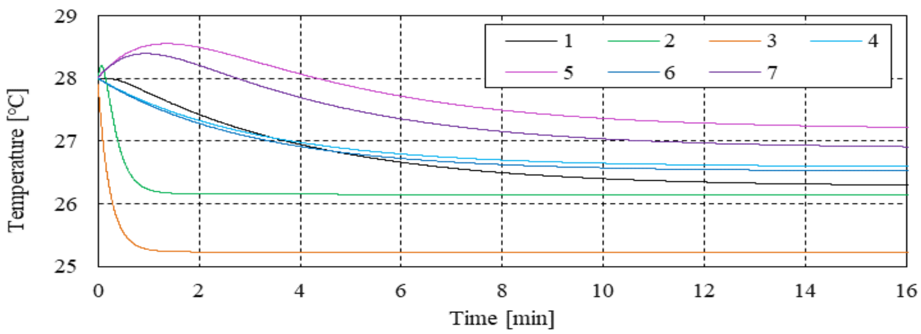


Figure 9: Air temperature at each node

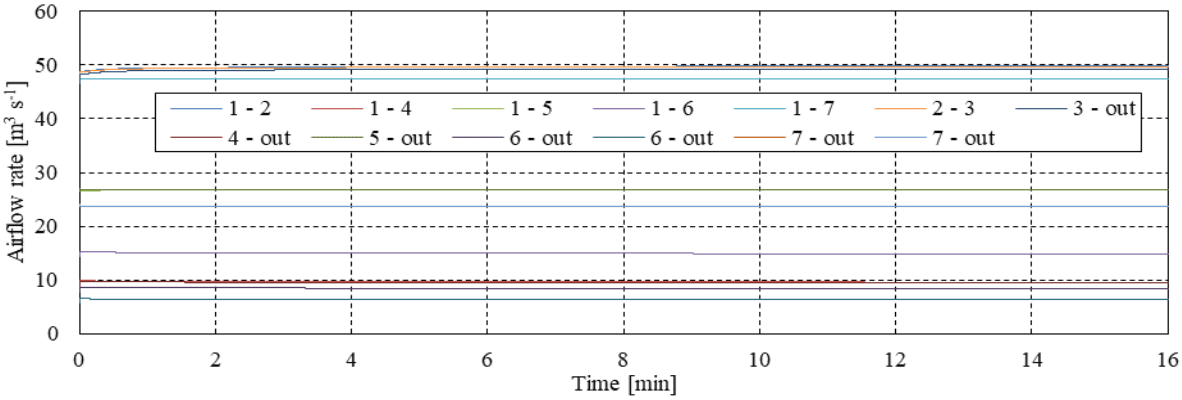


Figure 10: Airflow rate through each branch

Table 4: Averaged airflow rate through branches and difference between inflow/outflow at each node [$m^3 s^{-1}$]

Averaged airflow rate										
1 – 2	**1 - 4**	**1 - 5**	**1 - 6**	**1 - 7**	**2 - 3**	**3 - out**	**4 - out**	**5 - out**	**6 – out**	**7 - out**
49.7	9.6	26.7	15.0	47.5	49.6	49.2	9.5	26.8	14.8	47.5
Difference between inflow/outflow rate at each node (outflow was defined to be positive)										
		1			**2**	**3**	**4**	**5**	**6**	**7**

-0.0795	0.0990	0.3896	0.0925	0.0664	0.1403	0.0694

5 CONCLUSIONS

The theory of the "Successive Indoor Air Pressure Calculation Method" was explained, and two types of the calculation model was analyzed in this paper. One is the simple model to verify the applicability for the calculation with time-varying boundary condition, and the other is the complicated model for the actual buildings.

The main knowledge obtained in this study is summarized as follows:

- In a simple model with one node and two branches, the model calculation was conducted with transient condition with time-series change data of the wind pressure coefficient. However, there was no heat generation, thus the environment kept isothermal.

- By taking small time step, the vibration of the result was avoided, and it was confirmed that the model is able to calculate the time-series change of the pressure and airflow rate with the time-varying boundary condition.

- In a relatively complicated model, which is simulated by an actual NV building, the model calculation was conducted with steady state. However, there was heat generation, so the temperature time-series change of the air temperature was obtained.

- The result showed that the temperature took longer time for reaching the steady state, compared to the air pressure and airflow rate, due to the heat capacity, and it shows that the model has well simulated the real phenomenon.

The calculation result of this study showed the possibility of the calculation model to simulate the real phenomenon. The comparison between the calculation and experimental results is required as future prospects.

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