

Coupled Analytical Tool of Ventilation Calculation and CFD in Annexation System of Cool/Heat Tube and Natural Ventilation

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ABSTRACT

Natural ventilation airflow rate is generally calculated using indoor and outdoor temperature difference without consideration of heat balance based on the vertical air temperature distribution in simple analytical method. However, room air temperature is influenced by natural ventilation airflow rate, and airflow rate is influenced by room air temperature, so it is necessary to perform a coupled analysis taking into account both heat balance and ventilation to obtain the correct result. Moreover, when there is marked indoor vertical temperature distribution, as found in large enclosures, or when ventilation airflow rate is small, significant computation error will occur if the set value of room air temperature differs greatly from the actual value.

To solve two problems mentioned above, the authors developed a natural ventilation tool that takes into account indoor vertical temperature distribution and proposed a coupled simulation method using this tool in conjunction with CFD to simultaneously calculate indoor air flow/temperature distribution and natural ventilation airflow rate. In this paper, the difference between this method and the simple analytical method was shown clearly by comparing calculation results of the two methods about an actual annexation system of cool/heat tube and natural ventilation in a gymnasium.

KEYWORDS

cool/heat tube, natural ventilation, coupled analytical tool with natural ventilation and CFD

INTRODUCTION

Natural ventilation not only saves energy, but is a psychologically and physiologically comfort method of ventilation. However, introduction of outdoor air into rooms passing cool/heat tubes can result in a decreasing outdoor air heat load, as outdoor air is preheated through heat exchange with soil. Recently, use of natural ventilation systems with cool/heat tubes as a means of introducing outdoor air is generating a lot of attention.

A simple static method for analysis of natural ventilation in buildings was proposed almost 40 years ago (Ishihara, 1969). This method is based on

an analysis of pressure balance without consideration of heat balance. Several pieces of software have been developed for use in building ventilation analysis, based on a ventilation network method created by applying the simple method to multi-zone scenarios. Commonly used software includes COMIS (developed by Annex23 of IEA (Anne, 2002)) and VENTSIM (developed by Building Research Institute (Utumi, 2005)). By using these ventilation analysis tools, natural ventilation airflow rate can be calculated according to the temperature difference between fixed room air points and the outdoor air, or between adjoining rooms, taking each room as one node, but heat balance calculation can not be performed.

However, room air temperature is influenced by natural ventilation airflow rate, and airflow rate is influenced by room air temperature, so to get the correct calculation result, it is necessary to perform a coupled analysis taking into account heat and airflow balances. Therefore, coupled analysis of TRNSYS (Hensen, 1995) and EnergyPlus (Huang, 1999) with COMIS, respectively were developed. Moreover, a ventilation analysis model based on thermal and ventilation networks is included in DeST (Jiang, 2005), a program for simulating energy consumption in buildings.

NETS(developed by Okuyama, 1998) is a ventilation analysis software based on the airflow network theory. When properties of indoor air temperature distribution and airflow distribution are known roughly, air temperature of division sub-zones and airflow between adjoining division sub-zones can be calculated simultaneously by using NETS depended on the appropriate division sub-zones of indoor and outdoor space. CFD is based on heat/movement and continuity equation of air, however ventilation calculations carried out using NETS are essentially calculations of total pressure, and thus NETS is not appropriate for use in the prediction of airflow and temperature distribution of indoor.

As each room is handled as one node, the ventilation calculation tool mentioned above cannot reproduce the driving force of buoyancy ventilation originating from indoor vertical temperature distribution. Therefore, there is a necessity for a

ventilation analysis tool which considers the indoor vertical temperature distribution. Li (2002) carried out research into natural ventilation analysis that considers indoor vertical air temperature distribution. It was pointed out that it is necessary to give the tool that is in use the vertical temperature distribution as known from experiment or previous experience, as the multi-zone analysis model cannot be applied directly, based on the calculation comparison with multi-zone and CFD when the room is divided into several spaces according to height.

Furthermore, Ji (2007) verified the effectiveness of CFD for natural ventilation analysis when vertical temperature distribution exists by comparing the measurement and the calculation result, which is obtained by specifying the pressure boundary condition of natural ventilation aperture.

Beausoleil(2001) added ventilation analysis model based on ventilation networks and CFD model with the adaptive convection algorithm to an energy simulation program ESP-r, and thereby constructed a dynamic energy simulation that simultaneously calculates indoor air temperature distribution and natural ventilation air volume. Thus solving both of the two problems mentioned before, by the use of this new program, will be possible to perform a simulation of the yearly energy consumption of a natural ventilation system, however data entry time and calculation volume will increase.

The purpose of this research was to develop a Cx support tool for use in the design step to forecast the natural ventilation air volume of an annexation system comprised of a cool/heat tube and natural ventilation system, so static analysis tool with small calculation capacity is necessary. Therefore, in the course of this research, a simple ventilation analysis tool that considers indoor vertical temperature distribution was developed, and a coupled analytical method using the simple tool with CFD currently available on the market was proposed. The difference between this method and the simple analytical method was shown clearly by the comparison of calculation results of them from a cool/heat tube annexation system and natural ventilation in a gymnasium.

OUTLINE OF SIMULATION

The CFD coupled analysis method is composed by two simulation tools as shown in the following. Figure 1 shows the calculation flow.

Natural ventilation analysis tool for ventilation airflow rate calculation

When present indoor vertical temperature distribution (at the first calculation step, optional assumption value) is assumed to be input data, by the use of calculation condition such as outdoor air temperature, wind direction, wind velocity, area

/number/height of each aperture etc., airflow rate and air flow direction of each aperture could be obtained based on pressure balance and be used as the input data of CFD analysis.

CFD analysis tool for indoor airflow and air temperature distribution

Airflow rate and direction of each aperture are settled as input of CFD and calculation conditions include room shape, boundary condition of each outside surface, mesh shape, division rate, aperture shape and position, air temperature in each aperture, turbulence energy and loss rate, outdoor air temperature, solar radiation, internal heat generation and generating position etc. By the selection of turbulence model, finite different scheme and convergence judgment standard, CFD is performed to calculate indoor air temperature distribution.

Coupled method

ϵ_0 is convergence judgment standard of pressure balance. ϵ_1, ϵ_2 are convergence judgment standard of natural ventilation airflow rate and vertical temperature distribution respectively. As shown in Figure 1, by the repetitive calculation of natural ventilation and CFD, if the relative error of pressure difference, natural ventilation airflow rate difference and vertical temperature difference between the two neighboring calculation results satisfy the convergence judgment standard ϵ_0, ϵ_1 and ϵ_2 (in this paper, 3%) together, the calculation process will be stopped and the airflow rate/direction of each aperture and vertical temperature distribution will be outputted.

OUTLINE OF THE OBJECT BUILDING AND NATURAL VENTILATION APERTURES

The outline of the object building and natural ventilation apertures are shown in Table 1 and Table 2, respectively. Annexation system of cool/ heat tube and natural ventilation is shown in Figure 2. The concept of the natural ventilation plan in this facility is to obtain pleasant indoor environment without

Table 1 Outline of object building

Usage	gymnasium of elementary school
Location	TOYAMA Province
Construction	RC made, 4F above ground
Floor height	14 [m]
Floor area of gym	840 [m ²]

Table 2 Outline of natural ventilation apertures

	Area[m]	number	height[m]	α
Floor aperture 2(south)	4.4×0.105	4	2FL+0	0.33
Floor aperture 2(north)	23×0.105	1	2FL+0	0.33
Wall aperture 3(south)	3.6×0.9	2	2FL+13.1	0.5
Wall aperture 3(north)	3.6×0.9 2.4×0.9	1 4	2FL+13.1 2FL+13.1	0.5 0.5

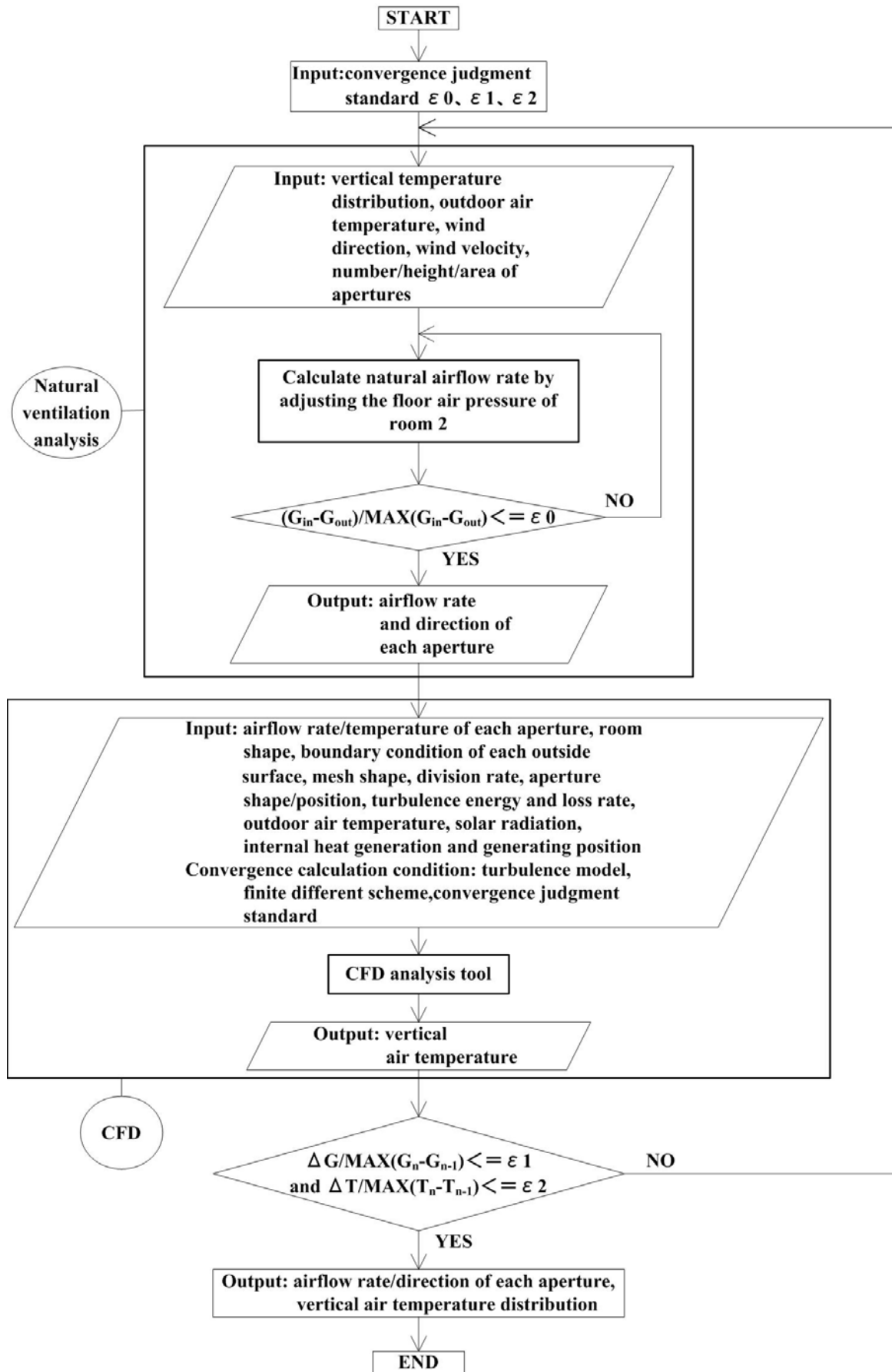


Figure 1 Calculation flow of CFD coupled analysis method

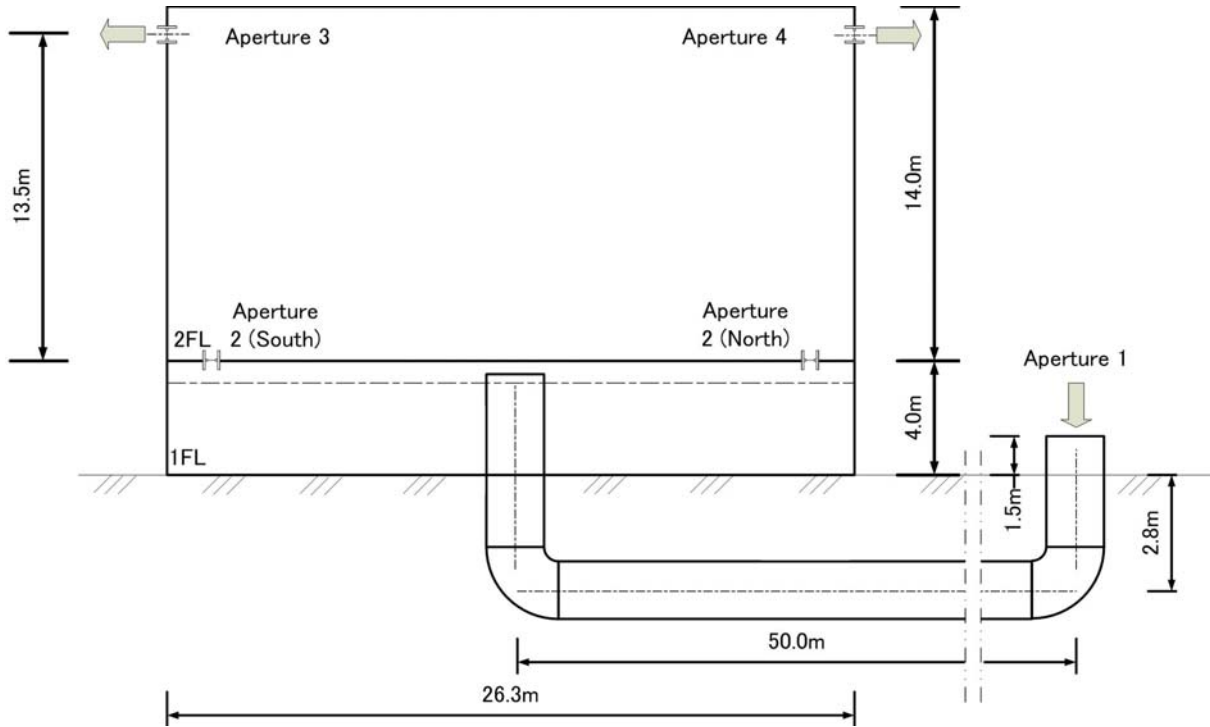


Figure 2 Annexation system of cool/heat tube and natural ventilation

HVAC energy consumption due to preheating effect by introducing outdoor air from cool/heat tube. In this natural ventilation system of gym in 2F of the building, outdoor air is introduced from outdoor inlet, to supply air to the room from 2F floor aperture via a tube buried in the outdoor earth, 1F underground pit, 1F air supply shaft, and 2F floor pit, and to exhaust from the balanced sash installed in the upper parts of the south wall and the north wall.

COUPLED ANALYTICAL MODEL

Simplification of simulation model

Although the actual ventilation route passes six spaces such as ① outdoor air inlet, ② outdoor tube, ③ 1F underground pit, ④ 1F air supply shaft, ⑤ 2F floor pit, and ⑥ indoor sports ground, in this research, based on the following assumptions, a computation model with an assumption room (room 1), having two apertures, and an large enclosures (room 2), having three apertures, was constructed. Furthermore, although outlet air temperature of cool/heat tube should be obtained from the calculation of ATEHE (air-to-earth heat exchanger), it is assumed to be 4°C (summer), 2°C (winter), and 1°C (middle season) in this paper by referencing the past study (Yoon, 2006).

Fixation of outdoor wind velocity and wind direction at each aperture

Wind direction of each aperture is adopted the average monthly wind direction according to information released in recent years on the Web (Anonymity). As the height at which wind direction was measured was 20m off the ground, the velocity

of the wind in each aperture in the object building was calculated with equation (1).

$$\frac{V}{V_{ob}} = \left(\frac{h}{h_{ob}} \right)^{\frac{1}{3}} k \quad (1)$$

Frictional resistance of outdoor air introduction route

The frictional resistance of the outdoor air introduction route consists of frictional resistance of straight part and of the bend in the duct (SHASE, 2001).

$$\Delta P_{m1} = \lambda \frac{l}{d} \times \frac{V_m^2}{2} \gamma_m \quad (2)$$

$$\lambda = 0.055 \left\{ 1 + \left(2000 \frac{\varepsilon}{d} + \frac{10^6}{Re} \right)^{1/3} \right\} \quad (3)$$

$$\Delta P_{m2} = \xi \frac{V_m^2}{2} \gamma_m \quad (4)$$

$$\Delta P_m = \Delta P_{m1} + \Delta P_{m2} \quad (5)$$

Natural ventilation analytical equation with consideration of vertical indoor air temperature distribution

For room 2, Aperture 1 and 2 are in series, so the two apertures are synthesized to one aperture with the following equation (Ishihara, 1969) and the analysis object becomes room 2 only.

$$\left(\frac{1}{\alpha A}\right)^2 = \left(\frac{1}{\alpha_1 A_1}\right)^2 + \left(\frac{1}{\alpha_2 A_2}\right)^2 \frac{T_1}{T_0} \quad (6)$$

Airflow rate at each aperture is calculated with equation (7).

$$G = \alpha A \sqrt{2\gamma_o 2|\Delta P|} \quad (7)$$

Air pressure at each aperture is calculated with equation (8)

$$P = C \frac{\gamma_o - \nu}{2} v^2 \quad (8)$$

Indoor and outdoor air pressure difference of aperture 1 with the consideration of friction loss of outdoor air introduction route and temperature change in cool/heat tube is calculated by expression (9). When backflow occur in cool/heat tube, ΔP_m is treated as minus value.

$$\Delta P_1 = \{x_2 - (P_1 - \Delta P_m)\} + \gamma_o H_1 - \gamma_1 H_1 \quad (9)$$

Because the driving force of the buoyancy ventilation by the indoor vertical temperature distribution is not considered, the indoor and outdoor temperature difference is set to calculate natural ventilation airflow rate in simple analytical method may make the result incorrect. Therefore, in this research, authors induced equation (10) based on Bernoulli's theorem(Zhou,1994) to calculate indoor and outdoor air pressure difference considering indoor vertical air temperature distribution (The inducement process is described in the appendix).

$$\Delta P = (x_2 - P) + \gamma_o H - \int_1^H \gamma_{ih} g dh \quad (10)$$

Calculation condition

In general, because the object building is the gymnasium in a public elementary school, the air conditioning equipment is not set up. Therefore, the natural ventilation system in the object building is assumed to be used all the year, and three kinds of calculation when there is no wind in summer, winter and middle season have been performed. Table 3 shows the outdoor air design condition and outlet air temperature of cool/heat tube for each season. Set condition of surface load and internal heat generation rate for CFD is shown in table 4 and table 5 respectively. A 3-D computational fluid analysis program based on the standard k-ε model was used for CFD analysis with which the solution could be obtained in comparatively rough division (Kato, 1997, 1998). The main analysis conditions related to convergence of CFD calculation are set as the following. Mesh number is 57(x) × 30(y) × 20(z) in unequal interval. Convergence judgment constant of simultaneous linear equations is 0.01. Convergence

judgment condition of pressure correction is 1.0E-4.

Table 3 Outdoor air temperature and set point of outlet air temperature of cool/heat tube

		Summer (Aug.)	Winter (Jan.)	Middle season(Apr.)
Outdoor air temperature[°C]		34.9	-1.2	27.8
Outlet air temperature of tube [°C]	With tube	30.9	0.8	26.8
	Without tube	34.9	-1.2	27.8

Table 4 Internal heat generation rate and set height of heat generator

heat gain	human	lighting
Heat generation rate [W]	3,160	8,398
Height of heat generator [m]	0.5~1.0	13.5~14.0

Setting of analytical case

When the simple analytical method is used, it is necessary to set the indoor and outdoor air temperature difference. To consider the influence which the values set exerted on the natural ventilation airflow rate calculation results, these values were set at 1°C(CASE ①) and 5°C(CASE ②) respectively. In the CFD coupled analysis of CASE ③, indoor vertical temperature distribution was calculated using the heat balance of indoor heat generation, heat load of each wall and ventilation load.

COMPARISON AND CONSIDERATION OF THE CALCULATION METHODS

The indoor vertical temperature distribution calculation results are shown in Figure 3~ Figure 5. The natural ventilation airflow rate of each CASE is shown in Table 6. The following findings were obtained from these figures and tables.

1)When indoor and outdoor temperature difference is assumed to be 1°C, results using the simple analytical method are smaller than those when using the CFD coupled analysis method in summer and winter and are bigger in the middle season. From Figure 3~Figure 5, in winter, indoor air temperature set value using the simple analytical method is lower than air temperature as calculated using CFD, and the opposite result was found for the middle period. Put simply, the natural ventilation airflow rate increases when room temperature rises. However, in summer, the natural ventilation airflow rate calculated using the CFD coupled analysis method is larger than that of simple analytical method; although air temperature obtained using CFD (32.5°C) is lower than set point of the simple analytical method (35.9°C). This means that the simple analytical method cannot reproduce the driving force of the buoyancy ventilation which originates from the difference in indoor vertical air temperature.

2) In summer and the middle season, when indoor and outdoor air temperature difference is assumed to

be 5°C, the natural ventilation airflow rate calculated with the simple analytical method is larger than that calculated with CFD coupled analysis method. For winter, this volume is smaller. The reason for this is similar to that mentioned in 1).

3) Natural ventilation airflow rate calculated by the simple analytical method increases with increasing indoor and outdoor air temperature, almost regardless of the season. However, it must be pointed out that the influence of indoor and outdoor air temperature difference is on the contrary when considering heat balance. On the other hand, use of the CFD coupled analysis method seems to give a better result, as the indoor vertical air temperature distribution could be taken into account.

CONCLUSION

In this paper, a natural ventilation analysis tool that takes into account indoor vertical air temperature distribution was developed, and a CFD coupled analysis method for calculation of airflow rate using this tool was proposed. Calculation results using the CFD coupled analysis method were compared with those obtained using the simple analytical method. When using the simple analytical method, the heat balance of the room is not calculated, thus the simple analytical method can be used to understand the influence which the indoor and outdoor air temperature difference has on the natural ventilation airflow rate, but it will not give accurate final calculation values. However, the CFD coupled analysis method gives an appropriate natural

ventilation airflow rate, as airflow rate and indoor vertical air temperature distribution are calculated at the simultaneously by considering heat balance and airflow rate balance in the room.

After the gymnasium considered in this study has been built, the CFD coupled analysis tool developed in this paper will be verified by comparing calculation results with measurements, and commissioning will be performed at the post-acceptance step of the object natural ventilation and cool/heat tube annexation system.

APPENDIX

The inducement of driving force equation of buoyancy ventilation which originates in indoor vertical temperature difference is shown in Appendix Figure 1. In general, driving force of buoyancy ventilation in a room with 2 apertures as shown in Appendix Figure 1 should be calculated using equation (1').

$$\Delta P_g = (P_0 - x) + (P_i' - P_o') \tag{1'}$$

Here, ΔP_g : driving force of buoyancy ventilation
 P_0 : pressure at aperture ①, P_o' : outdoor air pressure at aperture ②, x : air pressure at floor surface, P_i' : indoor air pressure at aperture ② H : height difference from floor to aperture ②

In general, it is thought that the outdoor air temperature near aperture ① is equal to that near aperture ②, and the outdoor at the height of aperture

Table 5 Calculation condition of heat load of each wall

	Outside wall	Inside wall	Window	Floor	Roof	
Heat transfer coefficient [W/m ² · K]	0.13	3.8	1.7	3.0	0.4	
Outside surface temperature [°C]	Summer	34.9	31.5	34.9	31.5	45.0
	Winter	-1.2	9.4	-1.2	9.4	-1.2
	Middle season	27.8	27.8	27.8	27.8	35.0

Table 6 Calculation result comparison of natural ventilation airflow rate in each case [m³/h]

	Analytical method	Outdoor and indoor air temperature difference	Summer	Winter	Middle season
①	Simple analytical method	$\Delta t=1^\circ\text{C}$	1,737	1,850	1,757
②	Simple analytical method	$\Delta t=5^\circ\text{C}$	3,882	4,127	3,926
③	CFD coupled method	—	1,846	5,187	1,077
Average air temperature of CFD coupled method [°C]			32.5	7.1	28.5

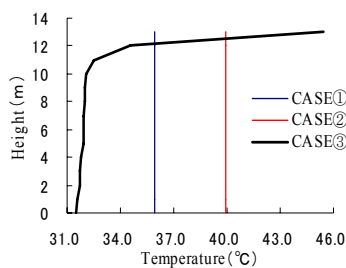


Figure 3 Calculation condition or result of indoor air temperature(Summer)

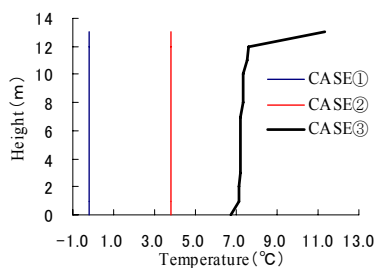


Figure 4 Calculation condition or result of indoor air temperature(Winter)

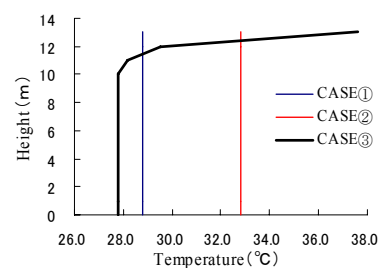


Figure 5 Calculation condition or result of indoor air temperature(Middle season)

② is represented in $P_o' = P_o - \gamma_o H$. When there is no vertical indoor air temperature difference, indoor air pressure at the height of aperture ② is represented in $P_i' = x - \gamma_i H$. These can be substituted for equation (1'), and equation (2') can be obtained to calculate the driving force of the buoyancy ventilation when there is no indoor vertical air temperature difference.

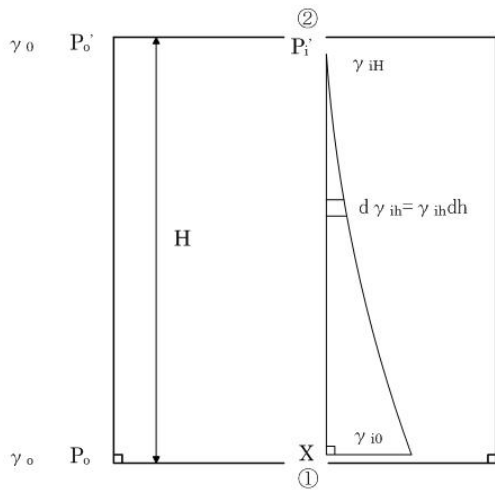
$$\Delta P_g = \gamma_o H - \gamma_i H \quad (2')$$

However, if there is indoor vertical air temperature difference, not only the indoor air pressure but also the density of air changes with height changes. Assuming driving force of buoyancy resulted by density difference among each minute air space nearby as $d\gamma_{ih}$, equation (3') can be obtained to calculate the driving force of the buoyancy ventilation when there is indoor vertical air temperature distribution by integrating $d\gamma_{ih}$ along height.

$$\gamma_i H = \int_1^H \gamma_{ih} dh \quad (3')$$

When equation (3') is substituted in equation (2'), driving force of buoyancy ventilation in which indoor air temperature distribution is considered can be calculated using equation (4').

$$\Delta P_g = \gamma_o H - \int_1^H \gamma_{ih} dh \quad (4')$$



Appendix Figure 1 calculation model of buoyancy ventilation

NOMENCLATURE

- v : wind velocity of aperture at the height of h [m/s]
- V_{ob} : wind velocity at the height of h_{ob} measured by the meteorological observatory [m/s]
- k : correction value of site condition (0.9 ~ 1.2), assumed to be 1.0 in this paper
- ΔP_{m1} : friction loss of straight parts of cool/heat tube [Pa]
- ΔP_{m2} : friction loss of curved parts of cool/heat tube [Pa]
- ΔP_m : friction loss of outdoor air introduction route [Pa]

- λ : friction factor of straight parts of cool/heat tube
- l : length of straight parts of cool/heat tube [m]
- d : equivalent diameter of cool/heat tube [m]
- V_m : average wind velocity in cool/heat tube [m/s]
- γ_m : average density of air in cool/heat tube [kg^3/m^3]
- ε : absolute roughness of cool/heat tube [m]
- Re : Reynolds value [-]
- ξ : friction factor of curved parts of cool/heat tube [-]
- G : airflow rate of each aperture [kg/s]
- α : airflow rate coefficient of each aperture [-]
- $\alpha_{1,2}$: airflow rate coefficient after series aperture 1 and aperture 2 are synthesized [-]
- A : cross-sectional area after series aperture 1 and aperture 2 are synthesized [m^2]
- $A_{1,2}$: cross-sectional area of each aperture [m^2]
- γ_o : density of outdoor air [kg^3/m^3]
- γ_1 : density of outlet air of cool/heat tube [kg^3/m^3]
- γ_2 : density of indoor air in residential region of room 2 [kg^3/m^3]
- γ_{2up} : density of indoor air at the height of aperture 3 or 4 [kg^3/m^3]
- γ_{o2} : when aperture 1, $\gamma_{o2} = \gamma_2 (\Delta P_1 > 0)$,
 $\gamma_{o2} = \gamma_o (\Delta P_1 < 0)$;
 when aperture 3 or 4, $\gamma_{o2} = \gamma_{2up} (\Delta P > 0)$,
 $\gamma_{o2} = \gamma_o (\Delta P < 0)$ [kg^3/m^3]
- H : height from floor of room 2 to aperture 3(4) [m]
- H_1 : height from outdoor air introduction inlet to floor of room 2 [m]
- γ_{ih} : density of air at the height of h in room 2 [kg^3/m^3]
- ΔP_1 : inside and outside air pressure difference of aperture 1 [Pa]
- ΔP : inside and outside air pressure difference of aperture 3(4) [Pa]
- x_2 : floor pressure of room 2 (unknowns) [Pa]
- P_1 : outside wind pressure of aperture 1 [Pa]
- P : outside wind pressure of each aperture [Pa]
- C : wind pressure coefficient of each aperture [-]
- v : input wind velocity of each aperture [m/s]
- T_o : absolute temperature of outdoor air [K]
- T_1 : absolute temperature of air near aperture 2 of room 1 [K]
- g : Acceleration due to gravity (=9.807) [m/s^2]

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