Commissioning of a Coupled Earth Tube and Natural Ventilation System at the Design Phase

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ABSTRACT

Natural ventilation airflow rate is generally calculated using indoor and outdoor temperature difference without consideration of thermal interaction between the ventilated air and the room in simple analytical method based on pressure balance. 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 thermal interaction and ventilation to obtain the correct result. Moreover, when there is marked temperature stratification, 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 the 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 (Computational Fluid Dynamics) to simultaneously calculate indoor air flow/temperature distribution and natural ventilation airflow rate. In this paper, at the design phase of an actual coupled earth tube and natural ventilation system in a gymnasium, natural ventilation airflow rate for four outdoor air conditions have been calculated to perform commissioning and several findings were obtained.

KEYWORDS

Earth tube, Natural ventilation, Coupled analytical tool with natural ventilation and CFD

INTRODUCTION

Natural ventilation not only saves energy, but is also a psychologically and physiologically comforTable method of ventilation. Introduction of outdoor air into rooms passing earth tubes can result in a decreased outdoor air heat load, as outdoor air is preheated through heat exchange with soil. Recently, use of natural ventilation systems with earth tubes as a means of introducing outdoor air is generating a lot of attention in Japan.

For natural ventilation analysis in buildings, the simple analytical method, which is static based on pressure balance without consideration of thermal interaction between the ventilated air and the room, was proposed almost 40 years ago (Ishihara,1969). Several pieces of software have been developed for use in building ventilation analysis based on the airflow network method expanded from the simple analytical method in the Case of multi-zone,. Commonly used software includes COMIS (developed by Annex 23 of IEA (Haas, 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; however, the thermal interaction calculation can not be performed.

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 heat and airflow balances to get the correct calculation result. Therefore, coupled analysis of COMIS with TRNSYS (Hensen, 1995) and EnergyPlus (Huang, 1999), were developed respectively. Moreover, an airflow analysis model based on airflow network method is included in DeST (Jiang, 2005), which is an energy simulation program of building.

NETS (developed by Okuyama, 1998) is ventilation analysis software based on the airflow network theory. When the 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. Unlike using CFD, which is based on heat, movement, and continuity equation of fluid, ventilation calculations carried out using NETS are essentially calculations of total pressure. Thus, NETS is not appropriate for use in the prediction of indoor airflow and temperature distribution.

As a result, the ventilation calculation tool mentioned above cannot reproduce the driving force of the buoyancy ventilation which originates from indoor temperature stratification because each room or sub-zone is handled as one node. Therefore, a ventilation analysis tool that considers the indoor vertical temperature distribution is needed. Li (2002) studied natural ventilation with consideration of indoor vertical air temperature distribution. According to the calculation comparison with CFD and multi-zone analysis model when the room is divided to several spaces along the height, Li pointed out that it is necessary to provide the vertical temperature distribution obtained from experiment or prior experience since the multi-zone analysis model cannot be applied directly.

Furthermore, Li (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 a ventilation model based on CFD model with an algorithm of adaptive convection in indoor surface and airflow network model to energy simulation program ESP-r and constructed a dynamic energy simulation by which it is able to simultaneously calculate indoor air temperature distribution and natural ventilation airflow rate. Although this method is able to calculate the yearly energy consumption of a natural ventilation system, the calculation time will be hugely increased.

The purpose of the research presented in this paper is to develop a commissioning support tool in design phase to forecast the natural ventilation airflow rate of a coupled earth tube and natural ventilation system. A simple analysis tool with low computational intensity is necessary. Therefore, 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 and temperature distribution and natural ventilation airflow rate. In this paper, natural ventilation airflow rate of an actual coupled earth tube and natural ventilation system in a gymnasium was calculated to perform Cx at the design phase.

OUTLINE OF SIMULATION METHOD

The CFD coupled analysis method is composed of two simulation tools which are presented below. Figure 1 shows the calculation flowchart for the simulation method.

Natural ventilation analysis tool for ventilation airflow rate calculation

Airflow rate and airflow direction for each aperture can be obtained based on a pressure balance. This requires known (or assumed) initial conditions for the indoor vertical temperature distribution, outdoor air temperature, wind direction, wind speed, area /number/height of each aperture etc., The results of this calculation is then used as the input data of CFD analysis.

CFD analysis tool for indoor airflow and air temperature distribution

Airflow rate and airflow direction for each aperture are required inputs to the CFD. Additional input 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. Indoor air temperature distribution is calculated with CFD by selecting turbulence model, finite different scheme and convergence judgment standard.

Convergence calculation

ε_0, ε_1, ε_2 are convergence criteria for the pressure balance, natural ventilation airflow rate, and vertical air temperature distribution, respectively. As shown in Figure 1, the airflow rate/direction of each aperture and the vertical air temperature distribution are obtained by iterative calculations of natural ventilation and CFD.

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. A coupled earth tube and natural ventilation system is shown in Figure 2. The concept of the natural ventilation plan in this facility is to obtain pleasant indoor environment without HVAC energy consumption duo to preheating effect by introducing outdoor air from earth tube. For the gym's natural ventilation system of gym (the second floor of the building) outdoor air is introduced from outdoor inlet, to supply air to the room from the second floor aperture via a tube buried in the outdoor earth, the first floor underground pit, the first floor air supply shaft, and the second floor pit, and to flow out from the balanced sash installed in the upper parts of the south wall and the north wall.

Table 1 Outline of object building

Usage	elementary school gymnasium
Location	TOYAMA Province, Japan
Construction	Reinforced Concrete made, 4 floors above ground
Floor height	14 [m]
Floor area of gym	840 [m^2]

Table 2 Outline of natural ventilation apertures

	Area[m^2]	number	height[m]
Floor aperture 2(south)	4.4×0.105	4	4.0
Floor aperture 2(north)	23×0.105	1	4.0
Wall aperture 3(south)	3.6×0.9	2	17.1
Wall aperture 3(north)	3.6×0.9 2.4×0.9	1 4	17.1 17.1

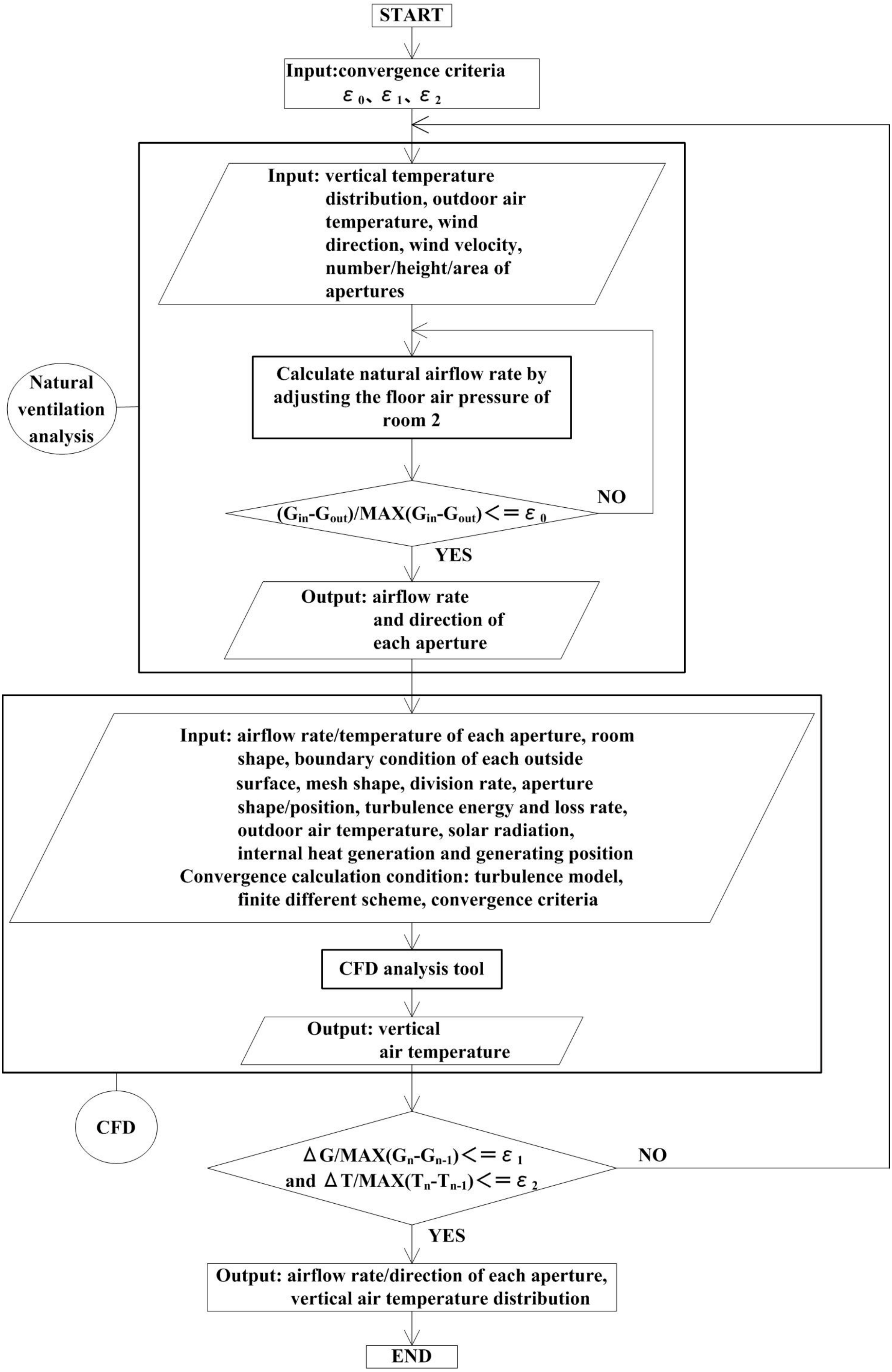


Figure 1 Calculation flow of CFD coupled analysis method

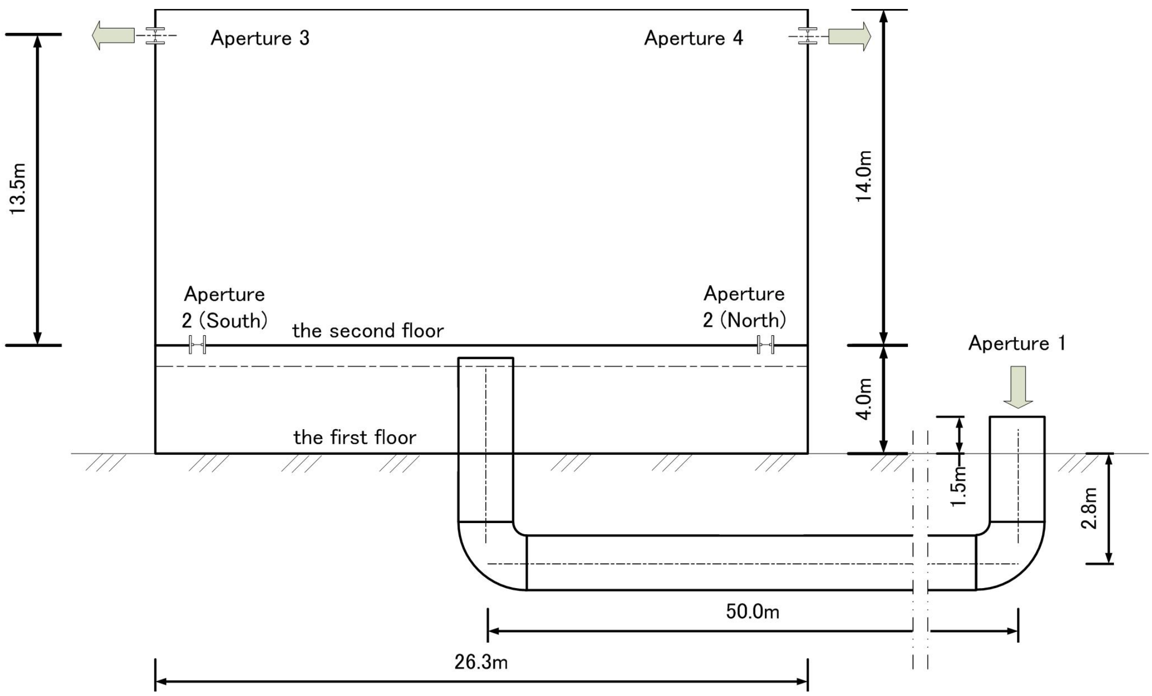


Figure 2 A coupled earth tube and natural ventilation system

COUPLED ANALYTICAL MODEL OF THE OBJECT SYSTEM

Simplification of simulation model

Although the actual ventilation route passes six spaces (i.e., ①outdoor air inlet, ② outdoor tube, ③the first floor underground pit, ④the first floor air supply shaft, ⑤the second floor pit, and ⑥indoor sports ground,) a simplified model was developed. In this research project, a computation model was constructed with an assumption: room (room 1), having two apertures, and a large enclosures (room 2), having three apertures.

The outdoor air is heated or cooled in a earth tube. Therefore, it is necessary to consider temperature difference between inlet and outlet of the earth tube in the ventilation analysis for large enclosures. Mei (1991) proposed a simulation model based on heat transfer balance at the earth tube, taking into account changes in the soil temperature, physical properties of the soil, tube material, fluid nature and time. By analyzing the transmission model of various heat mediums, Benkert (1997) proposed the GATE model in which air temperature in the length direction along the tubes can be calculated with a high level of accuracy. Mihalakakou (1994) proposed a model by which length, radius, air wind speed and depth of the tube underground could be considered at the same time, and proposed a total performance calculation of ATEHE (air-to-earth heat exchanger). Yoon(2006) developed the simulation model of heat and moisture movement between tube and soil and verified it with measurements.

Furthermore, although outlet air temperature of the earth tube should be obtained from the calculation of ATEHE (air-to-earth heat exchanger), it is assumed to be 4 ℃ (summer), 2 ℃ (winter), and 1 ℃ (swing season) in this paper by referencing the past study (Yoon, 2006).

Determination of outdoor wind speed and wind direction at each aperture

Wind direction of each aperture is defined using the average monthly wind direction according to information recently published on the Web (Anonymous). As the height at which wind direction was measured was 20m off the ground, the speed of the wind in each aperture in the object building was calculated with equation (1). Note: Nomenclature for all equations is presented at the end of this paper.

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

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).

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

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

$$\Delta P_{m2} = \xi \frac{V_m^2}{2} \gamma_m \tag{4}$$

$$\Delta P_m = \Delta P_{m1} + \Delta P_{m2} \tag{5}$$

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.

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

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

$$G = \alpha A \sqrt{2\gamma_{o2} |\Delta P|} \tag{7}$$

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

$$P = C \frac{\gamma_o}{2} v^2 \tag{8}$$

Indoor and outdoor air pressure difference of aperture 1 with the consideration of friction loss of outdoor air introduction route and temperature change in earth tube is calculated by expression (9). When backflow occurs in earth tube, ΔPm is treated as a negative value.

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

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

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

COMMISSIONING VERIFICATION TASKS

The following verification tasks are necessary for commissioning the coupled earth tube and natural ventilation system.

1) Verify that the natural ventilation airflow rate satisfies requirements or not under various outdoor air temperature, wind speed and direction of each season.
2) Verify that the speed of the air entering the room is in the permissible range for comfort or not.
3) Verify how much has the indoor thermal environment improved by the adoption of earth tube.
4) Verify the energy conservation effect of earth tube. The natural ventilation airflow rate will be decreased due to friction resistance in the tube. So neither the improvement of the thermal environment nor energy conservation effect might be achieved.

CALCULATION CONDITIONS AND CASES

In general, because the object building is the gymnasium in a public elementary school, air conditioning equipment is not installed. Therefore, the natural ventilation system in the object building is assumed to be used throughout the year. And three calculations have been performed for no-wind conditions: summer, winter and swing season. Table 3 shows the outdoor air design condition and outlet air temperature of earth tube for each season. Conditions for the surface load and internal heat generation rate for CFD are shown in Table 4 and Table 5 respectively. The common calculation condition of each case is shown in Table 6. 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 with a comparatively coarse grid (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, the convergence criterion for the simultaneous linear equations is 0.01, and the convergence criterion for the pressure correction is 1.0E-4.

CONSIDERATION OF CALCULATION RESULTS WITH EARTH TUBE

Calculation results of four Cases are shown in Table 7～10. The air temperature and flow speed distribution in vertical section of Case 1 are shown in Figure 3 and 4. The commissioning result for the coupled earth tube and natural ventilation system based on these calculation results is shown as follows.

Table 3 Outdoor air temperature and set point of outlet air temperature of earth tube

		Summer (Aug.)	Winter (Jan.)	Swing season(Apr.)
Outdoor air temperature[℃]		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

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

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 [℃]	Summer	34.9	31.5	34.9	31.5	45.0
	Winter	-1.2	9.4	-1.2	9.4	-1.2
	Swing season	27.8	27.8	27.8	27.8	35.0

Table 6 Common calculation condition of each Case

Aperture	1	3	4
Height [m]	1.5	18.05	18.05
Input wind speed (Case 1) [m]	1.18	2.71	2.71
Area A [m^2]	2.25	6.48	15.12
Wind pressure coefficient	0.5	0.8	−0.55
Aperture shape	mosquito net	Pivoted window 80°	Pivoted window 80°
Airflow rate coefficient α	0.33	0.5	0.5
α・A	0.73	3.24	7.56
Outside surface wind pressure (Case 1) [Pa]	0.4	3.36	−2.31

Table 7 Calculation result of Case 1

Aperture	1	3	4
ΔP [Pa]	-1.24	-4.67	1.0
Airflow rate [m^3/h]	2,641	33,292	35,933
Airflow direction	in	in	out
Pressure difference from Aperture 3 or 4 to 1 [Pa]			2.24
Friction lose on the tube ΔP_m [Pa]			0.67
Airflow speed at the aperture 2 [m/s]			0.17

Table 8 Calculation result of Case 2

Aperture	1	3	4
ΔP [Pa]	-0.61	0.001	0.001
Airflow rate [m^3/h]	1,846	554	1,292
Airflow direction	in	out	out
Pressure difference from Aperture 3 or 4 to 1 [Pa]			0.61
Friction lose on the tube ΔP_m [Pa]			0.33
Airflow speed at the aperture 2 [m/s]			0.12

Table 9 Calculation result of Case 3

Aperture	1	3	4
ΔP [Pa]	-5.41	0.01	0.01
Airflow rate [m^3/h]	5,187	1,556	3,631
Airflow direction	in	out	out
Pressure difference from Aperture 3 or 4 to 1 [Pa]			5.42
Friction lose on the tube ΔP_m [Pa]			2.89
Airflow speed at the aperture 2 [m/s]			0.34

Table 10 Calculation result of Case 4

Aperture	1	3	4
ΔP [Pa]	-0.22	0.0004	0.0004
Airflow rate [m^3/h]	1,077	323	754
Airflow direction	in	out	out
Pressure difference from Aperture 3 or 4 to 1 [Pa]			0.22
Friction lose on the tube ΔP_m [Pa]			0.12
Airflow speed at the aperture 2 [m/s]			0.07

1) The friction losses in the earth tube are less than 54% of the pressure difference between the inlet aperture and the exhaust air aperture on upper part of the wall in the gymnasium, thus natural ventilation would be available to some extent, although the airflow rate is decreased by comparing to the state when there is no earth tube.
2) When there is the wind in front of the south wall aperture in summer (Case-1), the driving force of natural ventilation is chiefly wind power. The air flows into the gymnasium from the earth tube and the aperture in the upper part of the south wall and flows out through the aperture in the upper part in north wall. Much of the natural ventilation airflow that enters through the upper aperture in the south wall attaches to the ceiling before flowing out through north wall aperture, as shown in Figure 4. That means the contribution of the wind-driven ventilation to the natural ventilation in the occupied region is small. Thus air temperature at 1.5 m above the floor is high (33.5 ℃) and just 1.4 ℃ lower than outdoor air temperature.
3) When outdoor wind speed is zero, natural ventilation airflow in the room occurs only from the earth tube, and airflows out through the upper north and south wall apertures. The driving force of natural ventilation is buoyancy only; the ventilation airflow rate depends on the vertical indoor air temperature difference and the indoor-outdoor air temperature difference. The natural ventilation airflow rates in summer, winter and the swing season are 1,846 m^3/h, 5,187 m^3/h, and 1,077 m^3/h respectively. All exceed the ventilation airflow rate required for human occupancy (40 person × 25 m^3/h･person＝1,000 m^3/h) and the avoidance of sick building syndrome. The air change rate is 0.09～0.44 times/h.
4) Because the airflow speed of the floor aperture of each Case is less than 0.34 m/s and is below the permissible speed(0.5 m/s), it can be confirmed that the air movement will not produce discomfort.

EFFECT VERIFICATION OF INTRODUCTION OF EARTH TUBE

To verify the improvement of the indoor thermal environment and the effect of energy conservation of earth tube, the natural ventilation airflow rate and the indoor vertical air temperature distribution without earth tube were calculated. A comparison of calculation results with and without the earth tube is shown in Table 11. Indoor vertical air temperature distribution for Cases 1～4 are shown in Figure 5～Figure 8, respectively. To asses the energy savings due to the earth tube, the set-point of the indoor air temperature with air-conditioning at each season was assumed to be 30℃(summer), 20℃(winter) and 25℃(swing season.) and the virtual air conditioner load to maintain the air temperature of the occupied region, from floor level to 2.0m height, at the set-point was calculated using Equation 11. The virtual cooling/heating load of each case is also shown in Table 11.

$$Q = c_p \cdot \gamma_2 \cdot (\theta_2 - \theta_s) \cdot G_A/3.6 \qquad (11)$$

The following findings are obtained from Table 11, and Figure 5～Figure 8.

1) When there is the wind in front of aperture in summer, there is only a small indoor vertical air temperature difference. This is the Case even though the natural ventilation airflow rate from aperture 2 with the earth tube is only 60% of the one without the earth tube. The reason is that natural ventilation airflow rate from aperture 2 is only about 8% of the airflow rate from aperture 3.

2) When wind speed is zero, the presence of the earth tube has a substantial effect on the indoor vertical air temperature distribution in summer (Case-2) and winter (Case-3) and almost has no effect in the swing season. The reason is that the presence of the earth tube influenced the supply air temperature of aperture 2 greatly in summer and winter. In the swing season, the outlet air temperature of the earth tube is only 1℃ lower than the outdoor air temperature, so the influence on the natural ventilation airflow rate and indoor vertical air temperature distribution is small.

3) Although natural ventilation airflow rate is decreased by introducing the earth tube, thermal environment of residential region in each Case is improved as 0.8 ℃, 2.0 ℃, 1.8 ℃, 0.2 ℃, respectively and the virtual air conditioner load is reduced by 7～36 %.

Table 11 Comparison of system performance with and without tube

Case	Tube	1	2	3	4
Airflow rate [m^3/h]	With	2,641	1,846	5,187	1,077
	Without	4,377	4,140	6,749	1,666
Residential region	With	33.5	31.6	6.7	27.7
	Without	34.3	33.6	4.9	27.9
Upper part air	With	35.4	46.4	11.3	35.6
	Without	35.5	44.1	8.8	35.6
virtual AHU	With	3.025	1.980	-7.517	1.500
	Without	3.465	3.080	-8.534	1.612
Load reduce rate [%]		13	36	12	7

Annotation: The negative value indicates a heating load.

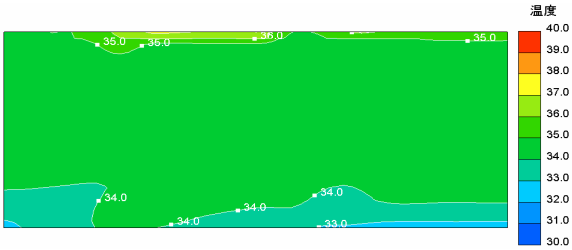


Figure 3 Vertical section air temperature distribution of Case-1(with earth tube)

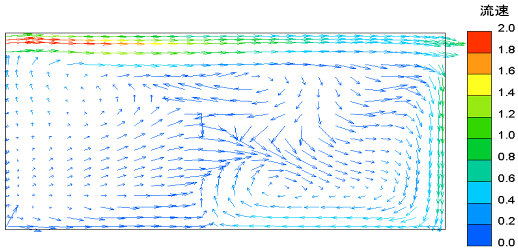


Figure 4 Vertical section airflow speed distribution of Case-1(with earth tube)

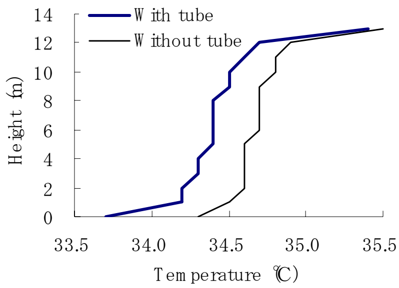


Figure 5 Vertical air temperature distribution of Case-1

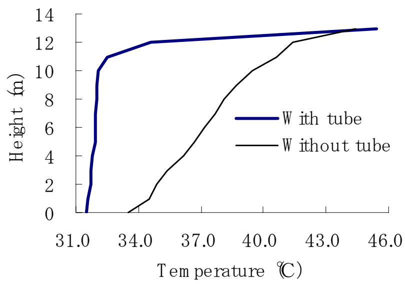


Figure 6 Vertical air temperature distribution of Case-2

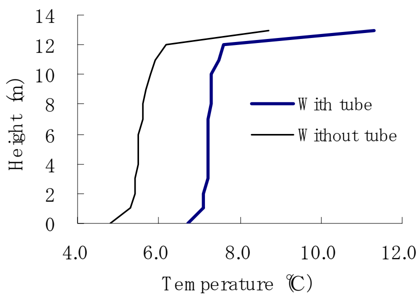


Figure 7 Vertical air temperature distribution of Case-3

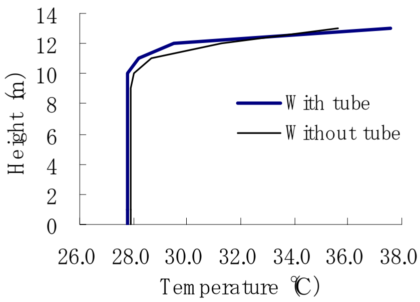


Figure 8 Vertical air temperature distribution of Case-4

CONCLUSION

In this paper, a natural ventilation analysis tool that takes into account indoor vertical air temperature distribution was developed, and the CFD coupled analysis method with this tool was proposed to perform the Cx work of the coupled earth tube and natural ventilation system. Using this method, authors performed the commissioning for an actual system at design phase. The findings obtained are as follows.

1)When there is outdoor wind in front of aperture on the wall in gymnasium in summer, the natural ventilation airflow rate from earth tube is only about 8% of the one from aperture on the wall so it cannot influence the indoor thermal environment greatly.
2)When the outdoor wind speed equals zero, the driving force of natural ventilation is buoyancy only. The necessary natural ventilation airflow rate is obtained at the calculation condition in this paper although it is decreased by introducing the earth tube.
3)The airflow speed passing the floor outdoor air introduction aperture is 0.5 m/s, which is smaller than the permissible one. In a word, the area of floor aperture designed is appropriate.
4)The thermal environment in the residential region of the object space is improved a little by introducing the earth tube. If the gymnasium is conditioned by HVAC equipment, the energy consumption of HVAC can be saved of 7-36%.

NOMENCLATURE

V : wind speed of aperture at height h [m/s]
V_{ob} : wind speed at height h_{ob} as 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 intake route [Pa]
λ : friction factor for straight sections of cool/heat tube [-]
l : length of straight sections of cool/heat tube [m]
d : equivalent diameter of cool/heat tube [m]
V_m : average wind speed in cool/heat tube [m/s]
γ_m : average density of air in cool/heat tube [kg'/m^3]
ε : absolute roughness of cool/heat tube [m]
R_e : 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 of each aperture [m^2]
$A_{1,2}$: cross-sectional area after series aperture 1 and aperture 2 are synthesized [m^2]
γ_o : density of outdoor air [kg'/m^3]
γ_1 : density of outlet air of cool/heat tube [kg'/m^3]
γ_2 : density of indoor air in the residential region of room 2 [kg'/m^3]
γ_{2up} : density of indoor air at the height of aperture 3 and 4 [kg'/m^3]
γ_{o2} : density of airflow, 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'/m^3]
H : height from floor of room 2 to aperture 3 and 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'/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 : wind pressure at aperture 1 [Pa]
P : wind pressure at each aperture [Pa]
C : wind pressure coefficient of each aperture [-]
v : input wind speed of each aperture [m/s]
θ_s : set point of indoor air temperature with air-conditioning at each season was assumed as 30 °C(summer), 20 °C (winter) and 25 °C (swing season) [℃]
θ_2 : residence region air temperature of room 2 [°C]
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]
Q : assumed AHU load [kW]
c_p : constant-pressure specific heat of air [J/(kg'・K)]
G_A : supply airflow rate of Assumed AHU{= Air volume of residence region at height equal 2m× Air change rate(=1)} [m^3/h]

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').

$$\Delta P_g = (P_0 - x) + (P_i' - P_o') \qquad (1')$$

Where, 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 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 ②is 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.

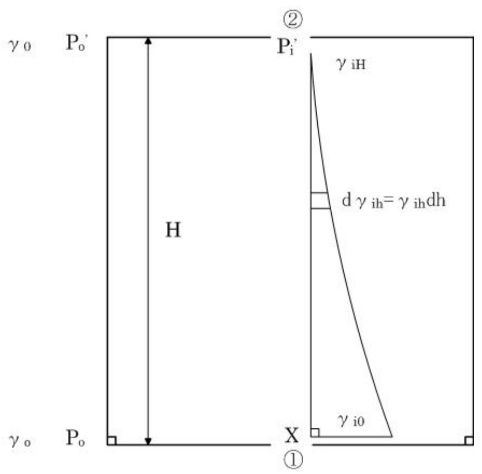
$$\Delta P_g = \gamma_o H - \gamma_i H \quad (2')$$

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

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