Commissioning of a Coupled Earth Tube and Natural Ventilation System at the Post-Acceptance Step

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ABSTRACT

In this paper, the environment and energy performance of an actual coupled earth tube and natural ventilation system in a gymnasium was measured during the post-acceptance step in two operation states: no ventilation and natural ventilation. From the measurement result, the authors conducted the commissioning for this system. By the use of the CFD (Computational Fluid Dynamics) coupled analysis with natural ventilation method, the natural ventilation air volume and the indoor temperature in summer and autumn while windless have been calculated. Several findings were obtained and informed to the operator.

INTRODUCTION

Recently, even though coupled earth tubes and natural ventilation systems are often used in Japan, the amount of basic information based on actual measurements and simulations is limited. Furthermore, design methods and optimal operation policy have yet to be clarified. When commissioning of a coupled earth tube and natural ventilation system is performed at the post-acceptance step, the following questions must be answered clearly:

1) What commissioning items must be considered?
2) What points should be measured for each commissioning item?
3) What simulation tools should be adopted?
4) What should be simulated?

The purpose of this paper is to clarify the commissioning method and processes for this type of system. As part of that effort, the authors reviewed previous research efforts and existing simulation tools used for coupled earth tube and natural ventilation systems and then developed a natural ventilation simulation tool that considers vertical air temperature distribution and coupled the CFD analysis method with this simulation tool (Pan, 2007a; Zheng, 2007). Using this CFD coupled analysis method, the authors performed the commissioning of an actual system at the plan/design phase (Pan, 2007b; 2007c). The commissioning results of four items, energy conservation performance, air temperature of the occupied section, natural ventilation air volume, and airflow velocity through the floor apertures, are reported. After the actual system was built, the authors conducted commissioning before acceptance through measurement made in Feb., 2008 and simulation with CFD coupled analysis method (Pan, 2008a; 2008b; Zheng, 2008).

In this paper, we report the commissioning results at post-acceptance step through measurement made in Aug., 2008 and simulation with CFD coupled analysis method.

OUTLINE OF THE COUPLED EARTH TUBE WITH NATURAL VENTILATION SYSTEM

An outline of the building and the coupled earth tube with natural ventilation system is shown in Table 1 and 2, respectively. The building is the indoor gymnasium of an elementary school. The ventilation system consists of rotary natural ventilation windows near the ceiling of the north and south walls, floor apertures, under-floor pits and the outdoor earth tube. Outside air is introduced from inlets and supplied to the room by means of seven south floor apertures(1〜6, 13) and six north floor apertures(7〜12), as shown in Figure 1, after the air flows through ①the outdoor air introduce tower, ②the route from the outdoor earth tube to the inlet of south vertical shaft of under-floor pits, ③the route from the inlet of south vertical shaft of under-floor pits to the inlet of north vertical shaft, ④the route from the north outdoor vertical shaft to the north under-floor space of gymnasium, and ⑤the route from the south indoor vertical shaft to the south under-floor space of gymnasium. Furthermore, forced ventilation is performed by means of two supply fans installed at the inlet of the under-floor pits and the two exhaust fans installed near ceiling of the north outside wall. And, no-ventilation operation (natural room temperature state) can easily be achieved by closing all the floor apertures.

Table 1 Outline of the building

Usage	Elementary school gymnasium
Location	Toyama Province, Japan
Floor height	12.5 [m]
Floor area of gym	840 [m^2]

COMMISSIONING ITEM AND MEASUREMENT CASE

Commissioning items at post-acceptance step

The purpose of commissioning at the post-acceptance step is to verify if the function/performance of system built can satisfy the owner's requirement. It is very important to set the commissioning items to achieve the purpose. In this research, the authors thought out the following commissioning items.

(1)Comparing the thermal environment in residential region with and without natural ventilation

Through the comparison of measurement data, the improving effect of natural ventilation for thermal environment should be confirmed.

(2)Verifying the energy saving effect of earth tube

The sensible cooling heat gain from earth tube could be calculated with equation (1).

$$Q = c_p \times \gamma \times (\theta_O - \theta_S) \times G_t / 3.6 \quad (1)$$

(3)Verifying the natural ventilation air volume and air temperature of residential region at design outdoor air condition and windless state

The natural ventilation air volume at design outdoor air condition and windless state should be calculated with the CFD coupled simulation method and used to verify if it can satisfy the necessary ventilation air volume for 40 or 600 person.

(4)Verifying air velocity of area used for sports

The air velocity of area used for sports should be verified by CFD if it is lower than the allowable air velocity (0.2m/s) in sports such as badminton or table tennis.

Measurement CASE/item/equipment

Measurement for two operation states was planned as shown in Table 3. For a general natural ventilation system, it is sufficient to measure indoor vertical temperatures and the distribution and natural ventilation air volume of each aperture in the room, but when a coupled earth tube with natural ventilation system is under consideration, it is also necessary to measure the air temperature and humidity at the inlet and outlet of earth tube, as well as the airflow volume from the floor apertures, because the air temperature of the floor apertures is higher in winter and lower in summer than the outdoor temperature. The measurement items and equipment are shown in Table 4. The position of each measurement point is shown in Figures 1 and 2 a).

VERIFICATION OF SYSTEM PERFORMANCE BY MEASUREMENT

Meteorological situations during measurement period

The outdoor temperature and humidity in measurement period are shown in Fig.3 and Fig.4. Outdoor temperature and relative humidity on Aug.11 varied between 34.1~37.7 °C, and 41~51%, separately. On the other hand, outdoor temperature, relative humidity Aug. 14 varied between 28.3~37.1 °C, 44~79%. Due to approximate 1 hour raining until 9:20 am on Aug 14, outdoor temperature in the morning was significantly lower (the relative humidity was significantly higher) on Aug. 14 than that on Aug. 11.

Indoor vertical temperature distribution and residential region temperature

The measurement results of indoor vertical temperature distribution of two measurement date were shown in Fig. 5 and Fig 6. The following points were noted based on the result.

1) Regardless whether there is natural ventilation or not, indoor vertical temperature distribution showed intensive temperature stratification distribution. And drastic increase of temperature was noted from above 11m above-floor. It was caused by the lights on the ceiling.

2) In the case of without natural ventilation, due to the shutting of south/north ventilation window, air temperature on the above was gradually increasing all through the day until 41.7 °C. On the other hand, in the case of natural ventilation, the maximal value of air temperature on the above was 40.4 °C, which was 1.3 °C lower than that of without natural ventilation. It was because that outdoor air was flown in through the ventilation window on the above, whereas high-temperature air was flown out.

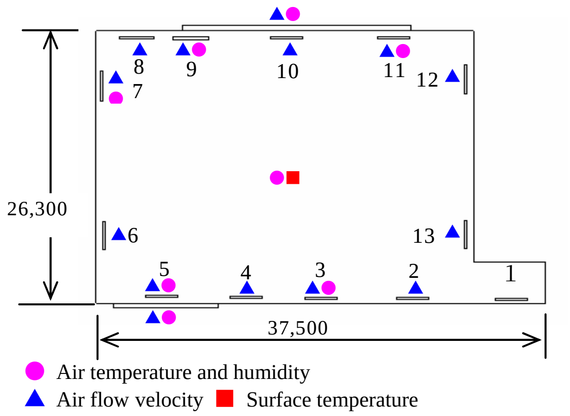


Figure 1 Floor aperture and measurement points

Table 3 Measurement Case

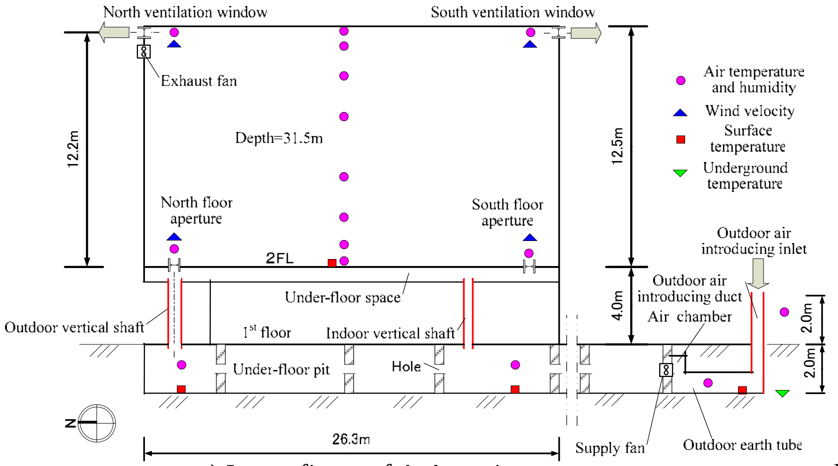
	Measurement date	Case	Floor aperture
Case-A	10:00-14:00 on Aug.11	No ventilation	Close
Case-B	10:00-14:00 on Aug.14	Natural ventilation	Open

Table 2 Outline of the coupled earth with natural ventilation system

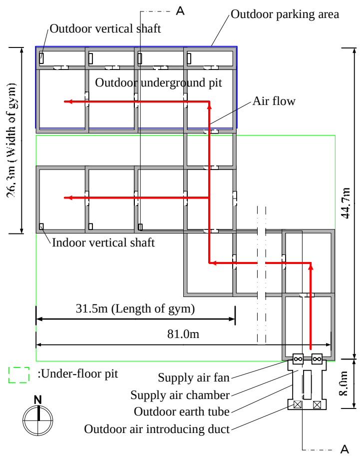
Height and rotation angle of south and north ventilation windows [m]	12.2, 45°
Area of south and north ventilation window [m^2]	6.76, 12.79
Total effective area of the floor aperture [m^2]	1.43
Total length of the outdoor earth tube and the under-floor pits [m]	130.0
Cross-sectional area of outdoor earth tube and the under-floor pits [m^2]	2.25, 14.4
Cross-sectional area [m^2] and height [m] of indoor south vertical shaft	1.47, 4.0
Cross-sectional area [m^2] and height [m] of outdoor north vertical shaft	1.84, 4.0
Height [m] and area of outdoor air introducing inlet [m^2]	4.0, 2.25
Cross-sectional area of hole in the under-floor pits [m^2]	0.28×3
Rated air volume [m^3] and power [W] of the supply fan	3,600, 198
Rated air volume [m^3] and power [W] of the exhaust fan	5,800, 390

Table 4 Measurement items and equipment

Measurement items	Measurement position	Measurement equipment
Vertical air temperature and humidity	Center of indoor gymnasium (8 points)	Thermo recorder
Air temperature and humidity of the floor aperture	Floor apertures of No. 3, 5, 7, 9, 11 (5 points)	Thermo recorder
Air temperature and humidity of south and north ventilation window	South and north ventilation windows (2 points)	Thermo recorder
Air temperature and humidity of outdoor earth tube or under-floor pits	Inlet of outdoor earth tube and outlet of under-floor pits (3 points)	Thermo recorder
Inside surface temperature outdoor earth tube or under-floor pits	Inlet of outdoor earth tube and outlet of under-floor pits (3 points)	Thermography
Outdoor air temperature and humidity	Outdoor Floor + 1.5 m (1 point)	Thermo recorder
Soil temperature	Outdoor underground 2.0 m (1 point)	Thermocouple
Floor surface temperature	Center in 2nd Floor of the gymnasium (1 point)	Thermo recorder
Airflow velocity of floor aperture	Each floor aperture (12 point)	Climomaster (single channel)
Airflow velocity of south window	South ventilation window (4 points)	Anemometer (multi channel)
Airflow velocity of north window	North ventilation window (4 points)	Anemometer (multi channel)



a) Image figure of A-A section



b) Plane figure of under-floor pits

Figure 2 Imagine figures of the coupled earth tube and natural ventilation system and measurement points

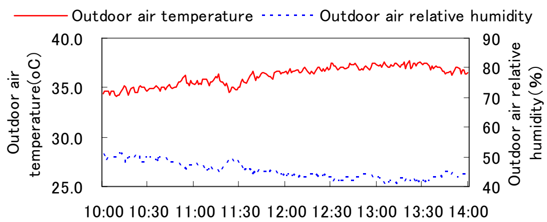


Figure 3 Outdoor air temperature/humidity (Aug.11)

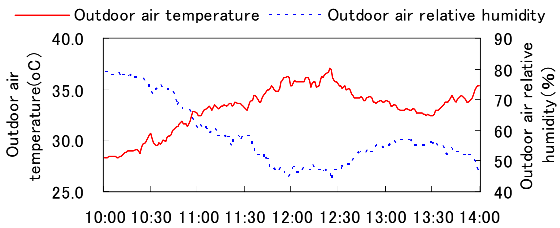


Figure 4 Outdoor air temperature/humidity (Aug.14)

3) During the measuring time period of 10 am~ 12 am, regardless of whether there is natural ventilation, the average air temperature of residential region was nearly 31.9 ^{o}C. On the other hand, after 12 am, average air temperature in the residential region in the case of natural ventilation was 33.1 ^{o}C, 0.4 ^{o}C higher than that of without natural ventilation, which was 32.7 ^{o}C. The reason was thought to be that in-door air temperature within 11m above-floor was in complete mixing state, because out-door wind velocity was above 3.3 m/s after 12 am on Aug. 14 (refer to Fig. 4), and natural ventilation air volume flown in through ventilation window on the north was 21,000 m^3/h (refer to 4.3). Besides, during natural ventilation, the temperature of introduced outdoor air from aperture of floor was approximate 32.0 ^{o}C. While it was lower than the air temperature in the residential region, the diffused air volume from aperture of floor were low. That was thought to be one of the reasons that it has few effects on the residential air temperature.

Natural ventilation air volume and airflow direction of each aperture

The air temperature close to south/north ventilation window and the measurement result of natural ventilation volume of each aperture during natural ventilation on Aug. 14 were shown in Fig 7. and Fig. 8, separately. The following points were understood based on the result.

1) The airflow direction was understood by comparison of the air temperature of south/north ventilation window, since the air temperature on the above was nearly high than that of outdoor air temperature during the measuring period. That is, the ventilation window on the side of lower temperature was the flow-in side. Refer to Fig. 7, during the

period of 10:00 am~10:48 am, because the air temperature of south ventilation window was lower than that of the north one, it was noted that the outdoor air was flown in through south ventilation window, then high-temperature air was flown out though north ventilation window successively. On the other hand, the airflow direction adversely changed during the period of 10:49 am~12:44 am. Furthermore, during the period of 12:45 am~14:30 am, the airflow direction changed frequently.

2)The average value of flow-in air volume from south ventilation window, and flow-out air volume from north ventilation window during the period of 10:00am~10:48am was 13,740 m^3/h and -10,453m^3/h, separately, which was only 70% of the average value of flow-in air volume from south ventilation window (-19,704 m^3/h), and 50% flow-out air volume from north ventilation window (21,000 m^3/h) during the period of 10:49am~14:00am.

3) The average diffused wind volume from floor aperture during the two time periods was 306 m/s and 169m/s, separately. And it was affected by the outdoor wind velocity and predominant wind direction. It was thought that the average outdoor temperature during the two time period was 29.5 °C and 34.1 °C, the buoyancy ventilation driving force during 10:00am~10:48am was higher that that of the period thereafter. However, the average diffused wind volume from floor aperture during the two time period was only 2.2% and 0.8% of that of flow-in air volume into the indoor gymnasium. Therefore, the provided cold/heat gain had extremely low effect on the indoor thermal environment.

Verification of the energy conservation effect by Earth Tube

The Outdoor air temperature, the air temperature of each measuring point in the introduction path of outdoor air, and the time variation of the diffused temperature from the floor apertures in the case of natural ventilation on Aug. 14 was shown in Fig. 9. The average air temperature of each measuring point in the introduction path of outdoor air and sensible heat gain/loss of each place were shown in Fig. 10. The following points were noted based on the result.

1) During the measuring period, the average outdoor temperature was 33.1 °C, varied considerably within the range of 28.3~37.1 °C. Meanwhile, the air temperature at the entrance of outdoor Earth Tube was averagely 26.5 °C, varied narrowly within the range of 26.3~27.2 °C. It was suggested that outdoor air tower had sufficient cooling capacity due to that introduced outdoor air volume from floor aperture was extremely lower as mentioned above.

2) In comparison of the air temperature at the inlet of the outdoor earth tube with that at the inlet of the south vertical shaft, it was shown that the introduced outdoor air was even cooled down by 1.9 °C evenly compared with that in the introduction route②.

3) Concerning the outdoor air introduction route③, until 11:51am, the air temperature at the entrance of north vertical shaft was 0.8 °C lower than that at the entrance of south vertical shaft, averagely. However, the temperature of the former was high than that of the latter, and the temperature variation was affected by outdoor air temperature then. It was thought that outdoor air entered inside through the outdoor underground pit, which was the entrance for the purpose of maintenance.

4) During the measuring period, the floor surface temperature of the gymnasium was maintained at a high level, 32.5 °C averagely. And the floor material was made of inefficient thermal insulation wood. It was easily supposed that the air temperature was high in the space of under-floor on the second floor. At first, the introduced outdoor air was cooled down by the outdoor Earth Tube and the under-floor pit on the 1F. On the contrary, it was heated after passing the air introduction route ④ and ⑤. As a result, the average temperature at the south/north floor aperture during the measuring period was 31.5 °C and 31.2 °C, that was 6.9 °C or 6.5 °C higher than that at the inlet of south/north vertical shaft, separately.

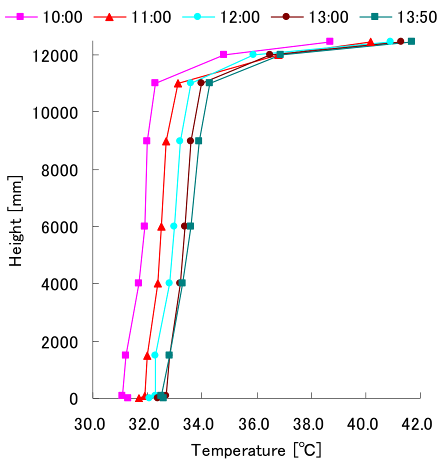


Figure 5 Indoor vertical air temperature distribution on Aug.11 (without natural ventilation)

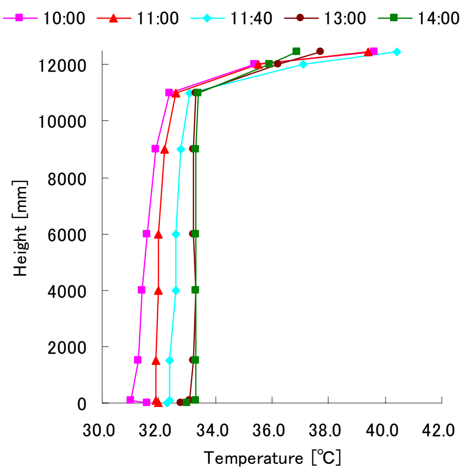


Figure 6 Indoor vertical air temperature distribution on Aug.14 (natural ventilation)

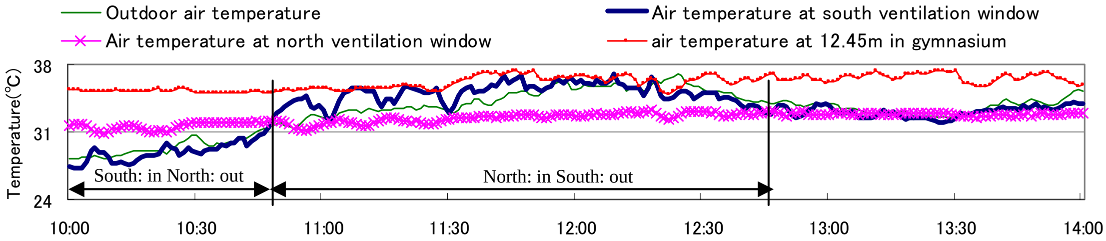


Figure 7 Outdoor air temperature, air temperature at south/north ventilation window and at 12.45m in gymnasium (Aug.14, natural ventilation)

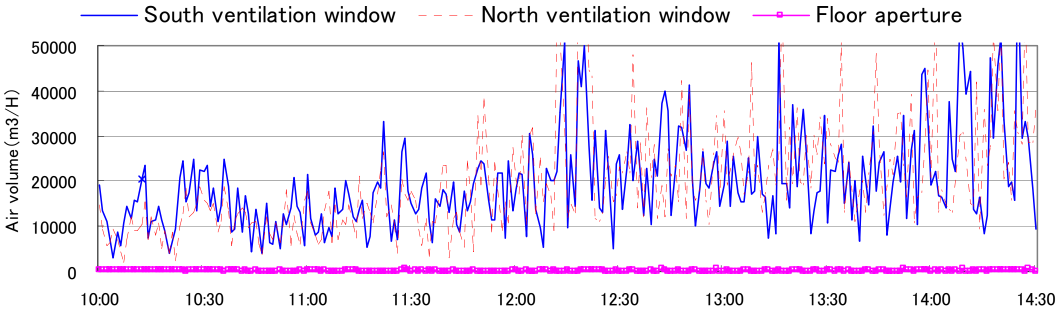


Figure 8 Natural ventilation air volume of each aperture (Aug.14, natural ventilation)

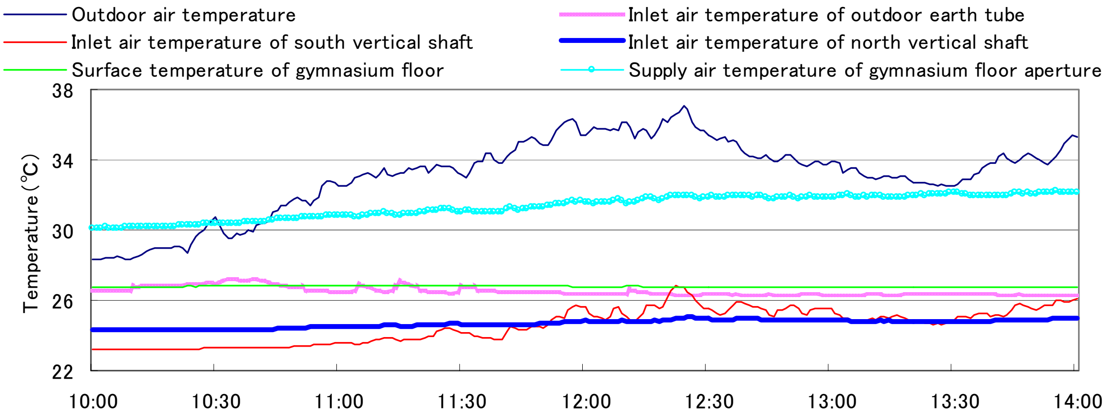


Figure 9 Outdoor air temperature, air temperature at each measurement point in air introduce route and floor surface temperature of gymnasium (Aug.14, natural ventilation)

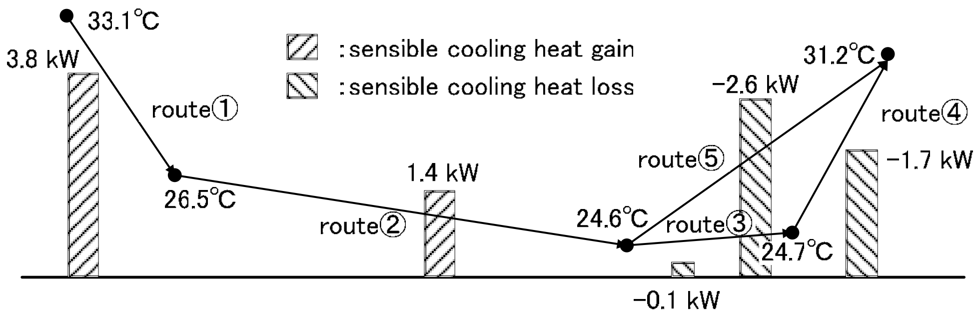


Figure 10 Air temperature at each measurement point and sensible cooling heat gain/loss in air introduce route

5) By using average air temperature of each measuring points, and outdoor air introduction volume of each section in the outdoor air introduction route during the measuring time period, average gain/loss sensible cold/heat gain of each section on the outdoor air introduction route was calculated by formula (1) and shown in Table 5. The introduced outdoor air acquired 3.8 kW and 1.4kW cold/heat gain from route ① and ②, separately. However, it was adversely heated at the route of ③-⑤. Therefore, there were 0.1 kW, 2.6 kW, and 1.7kW cold/heat gain lost up to the aperture of south/north floor, separately. As a result, the sensible cold/heat gain acquired by the outdoor air introduction route of the object system summed up to be just 0.8 kW.

Table 5 sensible cooling heat gain/loss of each outdoor air introduction route

Route	①	②	③	④	⑤	sum
sensible cooling heat gain[kW]	3.8	1.4	-0.1	-2.6	-1.7	0.8

Note: [-] means the cooling heat loss.

Air velocity of area used for sports

Simulated air velocity of area used for sports by CFD was shown in Fig.11. From Fig.11, it is verified that air velocity of area used for sports is almost lower than the allowable air velocity (0.2m/s).

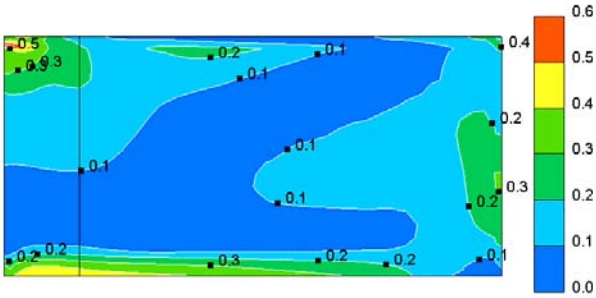


Figure 11 Air velocity distribution of center section

PREDICTION OF NATURAL VENTILATION AIR VOLUME AT WINDLESS STATE

During the measurement, the measurement value during windless period could not be acquired. Therefore, it is necessary to predict and verify the natural ventilation volume and indoor thermal environment during windless period of summer and intermediate season by the developed CFD coupled simulation method.

Calculation equation of natural ventilation

(1)Wind velocity/direction at each aperture
Wind direction of each aperture is defined using the average monthly wind direction according to the Web (Anonymous). As the height at which wind direction was measured was 20m off the ground, the wind velocity in each aperture should be calculated with equation (2).

$$\frac{V}{V_{ob}} = \left(\frac{h}{h_{ob}}\right)^{\frac{1}{3}} k \qquad (2)$$

(2)Frictional resistance of 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.

$$\Delta P_{m1} = \lambda \frac{l}{d} \times \frac{V_m^2}{2} \gamma_m \qquad (3)$$

$$\lambda = \begin{cases} \dfrac{C}{R_e} & ,R_e < 4\times10^3 \\ 0.055[1+(2000\dfrac{\varepsilon}{d}+\dfrac{10^6}{R_e})^{1/3}], & R_e = 4\times10^3 \sim 10^7 \end{cases} \qquad (4)$$

$$\Delta P_{m2} = \xi \frac{V_m^2}{2} \gamma_m \qquad (5)$$

$$\Delta P_m = \Delta P_{m1} + \Delta P_{m2} \qquad (6)$$

(3)Natural ventilation calculation equation
Airflow rate at each aperture and pressure could be calculated with equation (7), (8) respectively. Pressure difference between North/South ventilation window and floor could be calculated with equation (9), while Pressure difference between outdoor air inlet and floor with the consideration of Frictional resistance of air introduction route could be calculated with equation (10).

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

$$P = C \frac{\gamma_o}{2} v^2 \qquad (8)$$

$$\Delta P_{3,4} = (x_2 - P_{3,4}) + \gamma_o H_2 - \int_1^{H_2} \gamma_{ih} g dh \qquad (9)$$

$$\Delta P_1 = \{x_2 - (P_1 - \Delta P_m)\} + \gamma_o H_1 - \gamma_1 H_1 \qquad (10)$$

(4) Calculation of infiltration air flow
Infiltration air flow of window or door is calculated by equation (11).

$$G = aL(\Delta P)^{1/n} \qquad (11)$$

CFD coupled simulation case

In order to predict the performance of the system by CFD coupled simulation method, it is necessary to verify the repeatability of the method firstly. The measurement data at 11:29, Aug. 14 was used as the repeatability verification data (CASE-1). Secondly, by using the CFD coupled simulation method verified, the natural ventilation volume and indoor air temperature during the windless period when the outdoor air temperature to be -1.2 ^{o}C (CASE-2), 34.9 ^{o}C (CASE-3) and 27.8 ^{o}C (CASE-4) are predicted.

CFD coupled simulation condition

The overall thermal transmission of each wall surface and the designated value of out surface temperature for each analysis CASE were shown in Table 6. And the CFD analysis model of each natural ventilation opening and forced ventilation fan in the building was shown in Table 7. The calculation condition and result in each case were shown in Table 8. The solar radiation load was neglected in the analysis model, since the quantity of solar radiation entered inside was lower, which caused by the body structure of the gymnasium. In addition, since there were only 2~3 persons in charge of measurement inside the door during measuring period, only heat generation rate by illumination (21kW) was set as the internal heat generation rate. Since there were spaces existed in the north window, especially in the north outside door and east door, these infiltrations were all modeled in the CFD analysis model and the natural ventilation analysis model. In the case of CFD analysis, 3-dimensions computational fluid analysis program was used based on the standardized k-ε model with data achieved by comparative rough division. Furthermore, in relation to the main analysis conditions involved in convergence of CFD analysis, Mesh number were equal to 57(x)×30(y)×20(z) (nearly at even intervals), and the convergence judgment constant of simultaneous linear equations was set as 0.01. The convergence judgment condition of pressure correction was set as 1.0E-4.

Repeatability of the CFD coupled analysis method

The comparison of CFD analysis value with the measuring data of the indoor vertical temperature distribution in CASE-1 was illustrated in Figure 12a and table 9. From them, it was noted that the error between the measuring data and the calculating data at each measuring point of the indoor vertical temperature distribution in CASE-1 were below 0.7 ^{o}C, expect the air temperature of FL+12m. In addition, in Table 8, it was noted that the error between the calculating data and the measuring data of the south ventilation windows' flow out air volume, the north ventilation windows' flow in air volume, the floor apertures' flow in air volume, and the infiltration's flow in air volume was -10.8%, -8.4%, -40.3%, and 16.9%, separately. That is to say, the CFD coupled analysis method may virtually replicate the vertical air temperature and the natural ventilation air volume from each aperture. Therefore, by the use of the developed CFD analysis method, the indoor vertical air temperature and the natural ventilation volume from each aperture under different operating condition could be predicted simultaneously.

Prediction of the natural ventilation air volume at windless state in summer/intermediate season

The air volume and the vertical air temperature calculated are shown in Table 8 and Figure 12b, respectively. From them, we can obtain the following findings.

(1)In the CFD coupled simulation at design outdoor air temperature and windless state in winter (CASE-2), the air temperature of residential region were calculated to be 6.0 ^{o}C. Added with the infiltration air volume, the supply air volume (4983 m^3/h) to the gymnasium could satisfy the necessary volume (800 m^3/h) when there are 40 persons, but could not when there are 600persons (12000 m^3/h). So it is need to perform the forced ventilation when there are 600 persons in gymnasium.

(2)In the CFD coupled simulation at design outdoor air temperature and windless state in summer (CASE-3), the air temperature of residential region was calculated to be 34.1 ^{o}C. Although there is infiltration air volume, the supply air volume (711m^3/h) to the gymnasium could not satisfy the necessary volume even when there are only 40 persons. So it is necessary to perform the forced ventilation.

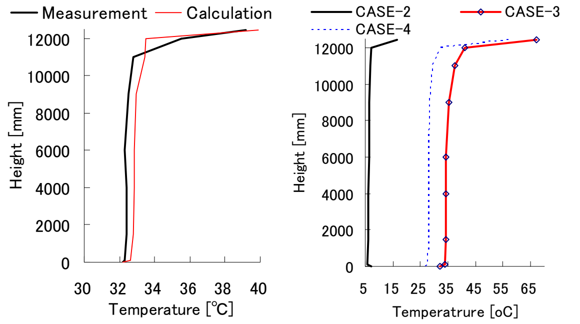
(3)In the CFD coupled simulation at design outdoor air temperature and windless state in intermediate season (CASE-4), the air temperature of residential region were calculated to be 28.1 ^{o}C. Added with the infiltration air volume, the supply air volume (1164 m^3/h) to the gymnasium could satisfy the necessary volume when there are 40 persons, but could not when there are 600persons. As the outdoor air temperature is lower than 27.8 ^{o}C, it is suggested to open the north side door to ventilate than to adapt the forced ventilation when there are 600 persons in gymnasium.

CONCLUSION

In recent years, even though coupled earth tube and natural ventilation systems are often applied, there is no method and support tool reported to perform the commissioning for design and operation policy. In this paper, through measurements of the performance of an actual system in summer and the simulations based on the coupled CFD analysis method, the commissioning at post-acceptance step was performed and the following findings were obtained.

1) Regardless whether there is natural ventilation or not, indoor vertical temperature distribution showed intensive temperature stratification distribution. And drastic increase of temperature was noted from above 11m above-floor.

2) In the case of natural ventilation, since outdoor air flows in through the ventilation window on the above, whereas high-temperature air flows out, air temperature on the above is lower than that in the case of without natural ventilation.



a.Comparison of measurement and calculation (CASE-1) *b.Vertical air temperature (CASE-2, 3,4)*

Figure 12 Calculation result of each CASE

3) In summer, although the supply air temperature from floor aperture is lower than that of residential region, the cooling heat gain for the introduce outdoor air is only 0.8kW due to the small air supply volume and heat loss coming from crack and lack of thermal insulation.

4) In the measurement period, air velocity of area used for sports is almost lower than the allowable air velocity (0.2m/s) and would not effect on wind-susceptible sports like badminton and table tennis etc.

5) Using the developed CFD coupled analysis method, authors predicted the indoor vertical air temperature and the natural ventilation volume in design outdoor air temperature and windless state in winter, summer and intermediate season. It was found that the natural ventilation volume cannot satisfy the necessary fresh air volume when there are 600 people in gymnasium. So it is suggested to perform the forced ventilation in winter and summer. Otherwise, in intermediate season, it is suggested to open the north side door to ventilate than to adapt the forced ventilation since the outdoor air temperature is lower than 27.8 ^{o}C.

NOMENCLATURE

a : constant by experience
A : cross-sectional area of each aperture [m^2]
C : wind pressure coefficient of each aperture [-]
d : equivalent diameter of earth tube [m]
G : air volume of each aperture [kg/s]
G_t : ventilation air volume from earth tube [m^3/h]
H_1 : height from outdoor air inlet to second floor [m]
H_2 : height from ventilation window to second floor [m]
k : correction value of site condition(0.9～1.2), assumed to be 1.0 in this paper

l : length of straight sections of earth tube [m]
L : length of crack [m]
n : constant.(1～2)
P : wind pressure at each aperture [Pa]
Q : sensible cooling heat gain [W]
R_e : Reynolds value [-]
θ_O : outdoor air temperature [^oC]
θ_S :supply air temperature from floor aperture[^oC]
v : input wind speed of each aperture [m/s]
V : wind speed of aperture at height h [m/s]
V_m : average wind speed in earth tube [m/s]
V_{ob} : wind speed at height h_{ob} as measured by the meteorological observatory [m/s]
x_2 : floor pressure of gymnasium (unknowns) [Pa]
ΔP : inside and outside air pressure difference [Pa]
ΔP_{m1} : friction loss of straight parts of earth tube [Pa]
ΔP_{m2} : friction loss of curved parts of earth tube [Pa]
ΔP_m : friction loss of outdoor air intake route [Pa]
α : airflow rate coefficient of each aperture [-]
c_p : constant-pressure specific heat of air [J/(kg'・K)]
γ : density of airflow of each aperture [kg'/m^3]
γ_{ih} : air density at the height of h in gymnasium[kg'/m^3]
γ_m : average density of air in earth tube [kg'/m^3]
γ_o : density of outdoor air [kg'/m^3]
ε : absolute roughness of earth tube [m]
ξ : friction factor of curved parts of earth tube [-]
λ : friction factor for straight sections of earth tube [-]

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Table 6 Heat transfer coefficient and outside surface temperature 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
Outer surface temperature [oC]	CASE-1(Aug.14)	33.2	31.5	33.2	32.3	45.0
	CASE-2(Winter, windless)	-1.2	2.4	-1.2	8.2	-1.2
	CASE-3(Summer, windless)	34.9	34.5	34.9	33.2	45.0
	CASE-4(Intermediate season, windless)	27.8	27.8	27.8	26.8	35.0

Table 7 CFD simulation condition of each aperture

	Effective area [m^2]	Number	Position	Air flow direction
Floor aperture	0.11	13	2nd Floor	Up (in)
Crack(East door)	0.04	1	1.0 m above the 2nd floor	Horizontal (in)
Crack(North door/window)	0.40	1	3.0 m above the 2nd floor	Horizontal (in)
South ventilation window	4.78	1	11.9 m above the 2nd floor	Horizontal (out/in)
North ventilation window	3.01	3	11.9 m above the 2nd floor	Horizontal (out/in)

Table 8 Simulation condition and result of each case

	CASE -2	CASE -3	CASE -4	CASE-1 (measurement)	CASE-1 (calculation)	Error of measurement and calculation in CASE-1
Air volume of south window [m^3/h]	-1652	-227	-383	-17794	-15870	-10.8%
Air temperature of south window [^oC]	9	53	40	33.4	33.4	0.0 ^oC (absolute error)
Air volume of north window [m^3/h]	-3331	-489	-781	15696	14383	-8.4%
Air temperature of north window [^oC]	8	54	41	32.3	32.3	0.0 ^oC (absolute error)
Air volume from crack [m^3/h]	3384	609	736	1689	1009	-40.3%
Air volume from floor aperture [m^3/h]	1599	102	428	409	478	16.9%
Air temperature of residential region[^oC]	6.0	34.1	28.1	32.4	32.9	0.5 ^oC (absolute error)

Note: [-] mean the air flowing out the room

Table 9: Vertical air temperature comparison of measurement and calculation in CASE-1 [^oC]

Height above 2nd floor	+0.1m	+1.5 m	+4.0 m	+6.0 m	+9.0 m	+11.0 m	+12.0 m	+12.45 m
Measurement	31.2	32.4	32.4	32.3	32.5	32.8	35.5	39.2
Calculation	31.9	32.8	32.9	32.9	33.0	33.4	33.7	40.2
Error	0.7	0.5	0.5	0.6	0.5	0.6	1.8	1.0