Method for Evaluating an Air-Conditioning System with Natural Ventilation by Coupled Analysis of a Building Energy Simulation Tool and Computational Fluid Dynamics

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ABSTRACT

In office buildings, an air-conditioning system with natural ventilation can reduce cooling loads and create a comfortable indoor environment. However, it is difficult to predict the performance of such systems and there is concern that the natural ventilation will create an uneven indoor thermal environment. In this paper, we propose a method for evaluating the performance of a natural-ventilation air-conditioning system by coupling a building energy simulation tool and computational fluid dynamics. In addition, we analysed the office building in which the system was installed and verified the prediction accuracy of the proposed method by comparing the simulation results with actual measurements. It was confirmed that the proposed method has sufficient accuracy.

KEYWORDS

Natural ventilation, Office building, Building energy simulation tool, CFD, Coupled analysis

1 INTRODUCTION

In recent years, air-conditioning (A/C) systems that incorporate natural ventilation to reduce cooling loads and achieve a comfortable indoor environment have attracted increasing attention. However, because the amount of natural ventilation is greatly affected by weather conditions, it is difficult to predict quantitatively, and there is concern that the natural ventilation will create an uneven indoor thermal environment. In addition, no uniform performance evaluation method for such systems has been established. Building energy simulation (BES) tools have attracted attention as a comprehensive analysis tool for evaluating the performance of buildings. However, such tools represent the physical quantity of the room as a single node and cannot consider the non-uniformity of the room environment.

Therefore, in this paper, we propose a method for evaluating the performance of an A/C system that considers the heterogeneity of the indoor environment by coupling the BES tool and computational fluid dynamics (CFD). In addition, we analysed a real office building in which the system was installed and verified the prediction accuracy of the proposed method by comparing the simulation results with actual measurements.

2 BUILDING CASE STUDY

In the office building targeted in this study (Fig. 1), outdoor air is introduced through inlets capable of supplying a constant airflow. These inlets are situated at the northern and southern ends of the workspace. The air travels through a shaft in the centre of the workspace and exits through the northern and southern outlets in the upper part of the shaft (Fig. 2). A building energy management system (BEMS) is installed in the building, through which automatic control of the indoor environment, equipment, and facilities is carried out based on sensor information collected both inside and outside the building. The determination of whether natural ventilation is effective or not is made based on the conditions shown in Table 1, and if all conditions are met, the mechanism for natural ventilation will be activated.

Figure 1: Building exterior

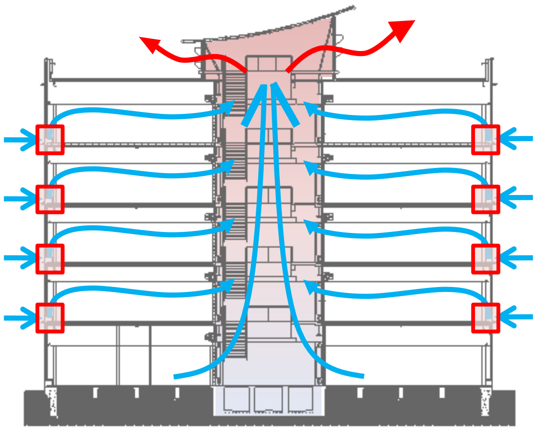

Figure 2: North-south vertical cross section

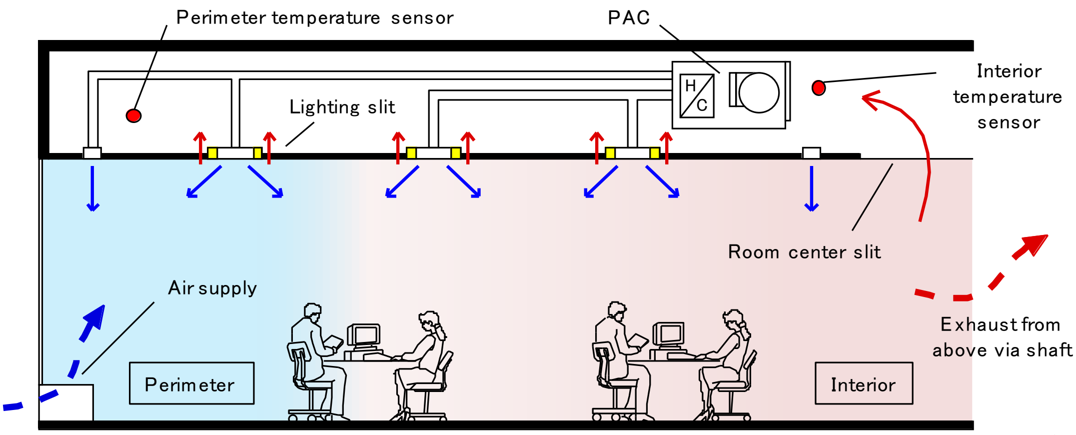

Figure 3: A/C system using natural ventilation

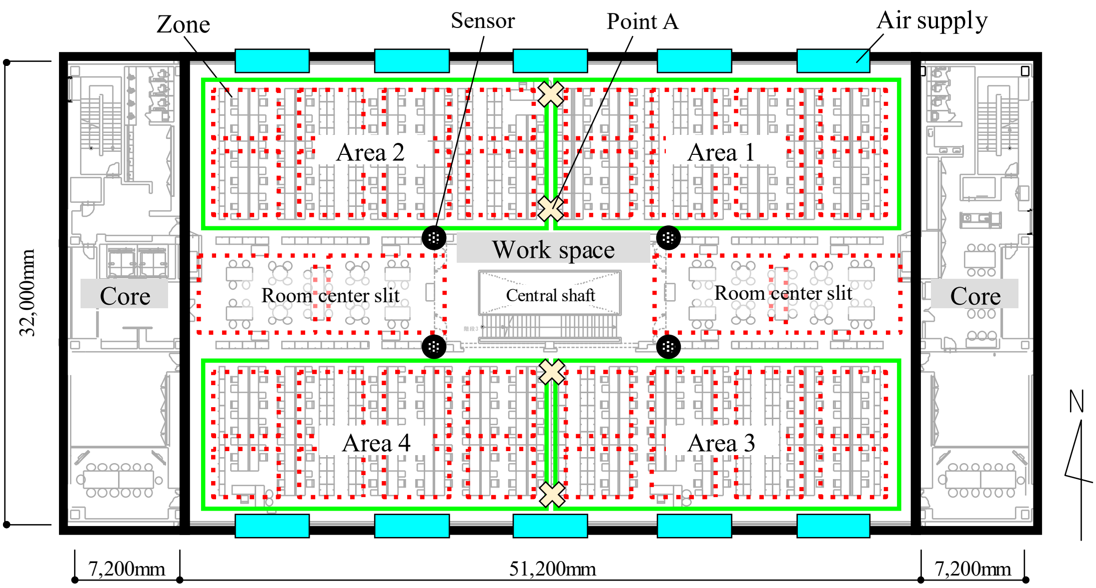

Figure 4: Floor plan

Table 1: Conditions for natural ventilation effectiveness

1. Enthalpy	Outdoor enthalpy < Indoor enthalpy
2. Outside temperature	16 °C < Outdoor temperature < 26 °C
3. Humidity	5 °C DP < Dew point (DP) < 16 °C DP
4. Indoor temp	Indoor temperature setting – 4 °C < Indoor temperature

3 MEASUREMENT

3.1 Overview of measurements

Measurements were performed for one month, from May 1 to 31, and the items for which data were collected are shown in Table 2. The estimated ventilation rate was calculated by multiplying the area of each air supply outlet by the wind speed value at the centre point of each air supply outlet. The accuracy of the estimation method was verified and correction methods were determined in advance based on preliminary measurements[1)]. The heat generated by the equipment and lighting was estimated from the power consumption data of the BEMS. The solar load was measured by monitoring the amount of solar radiation on the north–south vertical surfaces on the third floor. In addition, the CO_2 concentration was used to estimate the human heat load. The vertical temperature distribution on the third floor was measured at 0.1, 0.6, 1.1, 1.6, 2.2, and 2.8 m above the floor at each point A (Fig.4).

Table 2: Measured parameters

Natural ventilation	Wind direction/speed
	Outdoor temperature
	Outdoor dew point temperature
	Outdoor/Indoor enthalpy
	Indoor temperature
	Status of supply air vents (open/close)
	Supply air velocity
Heat load	Solar radiation
	Electricity consumption of outlets
	A/C power consumption
Others	Vertical temperature distribution
	CO_2 concentration

3.2 Measurement results

May 10 was selected as the representative day because it had the most suitable weather conditions for natural ventilation during the measurement period. Figure 5 shows the time series variations of outdoor air temperature, outdoor dew point temperature, and heat load due to solar radiation on the third floor for the day. It was confirmed that May 10 was a clear day with an outdoor temperature between 15°C and 20°C, which is suitable for natural ventilation. Figures 6 and 7 respectively show the time series variation of the ventilation rate and internal load on the third floor on the representative day. The heat processed by the A/C system and natural ventilation will be discussed later in conjunction with the analysis results.

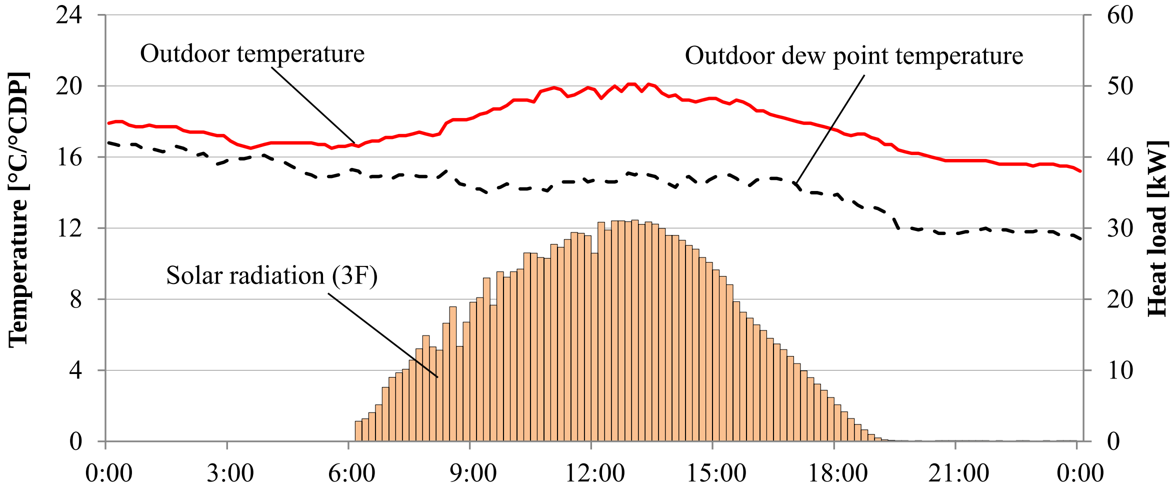

Figure 5: Outdoor temperature/dew point temperature and solar radiation

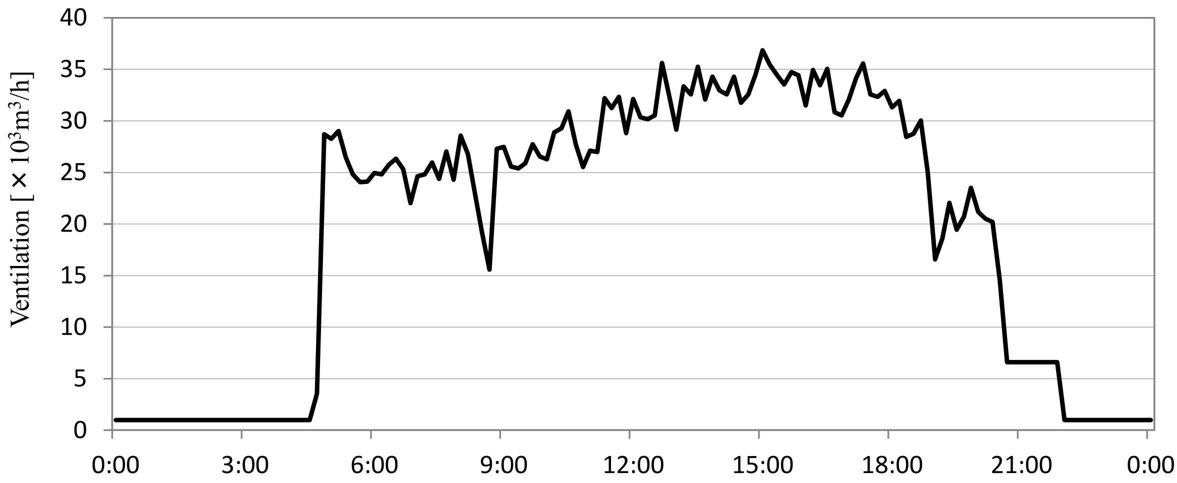

Figure 6: Ventilation volume on the 3rd floor

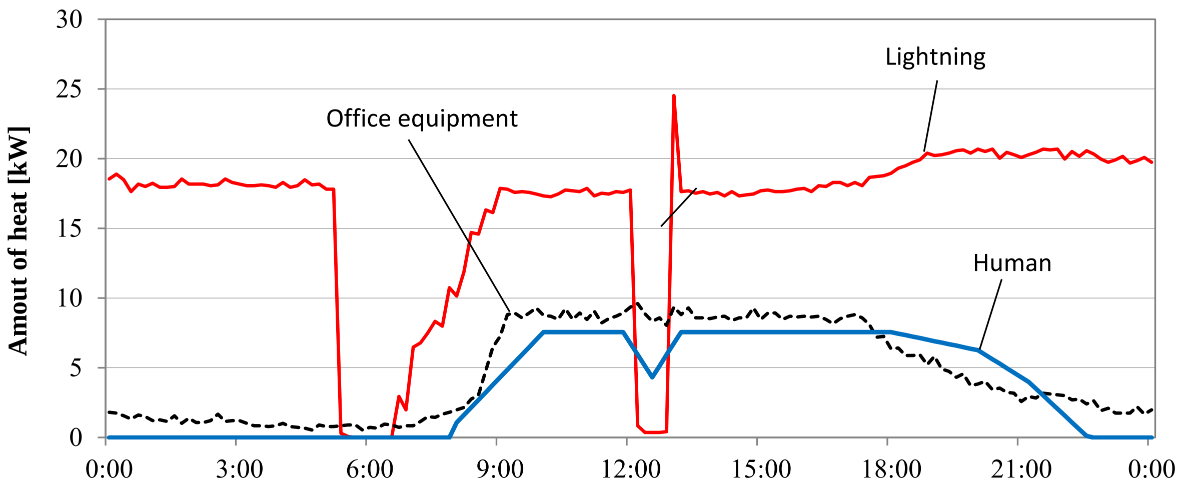

Figure 7: Internal heat load on the 3rd floor

4 ANALYSIS

4.1 Coupling analysis method for the BES tool and CFD

A CFD analysis was performed using the A/C module of BEST[2)], a comprehensives BES tool (Figure 8). BEST creates a model of the A/C system by connecting various modules for the heating source, fans, and other components. We used a newly developed module for connecting CFD that was specifically designed for coupled analysis. In the steady-state analysis, we performed repeated non-steady coupled analyses between BEST and CFD and terminated the calculation when their fluctuations became sufficiently small.

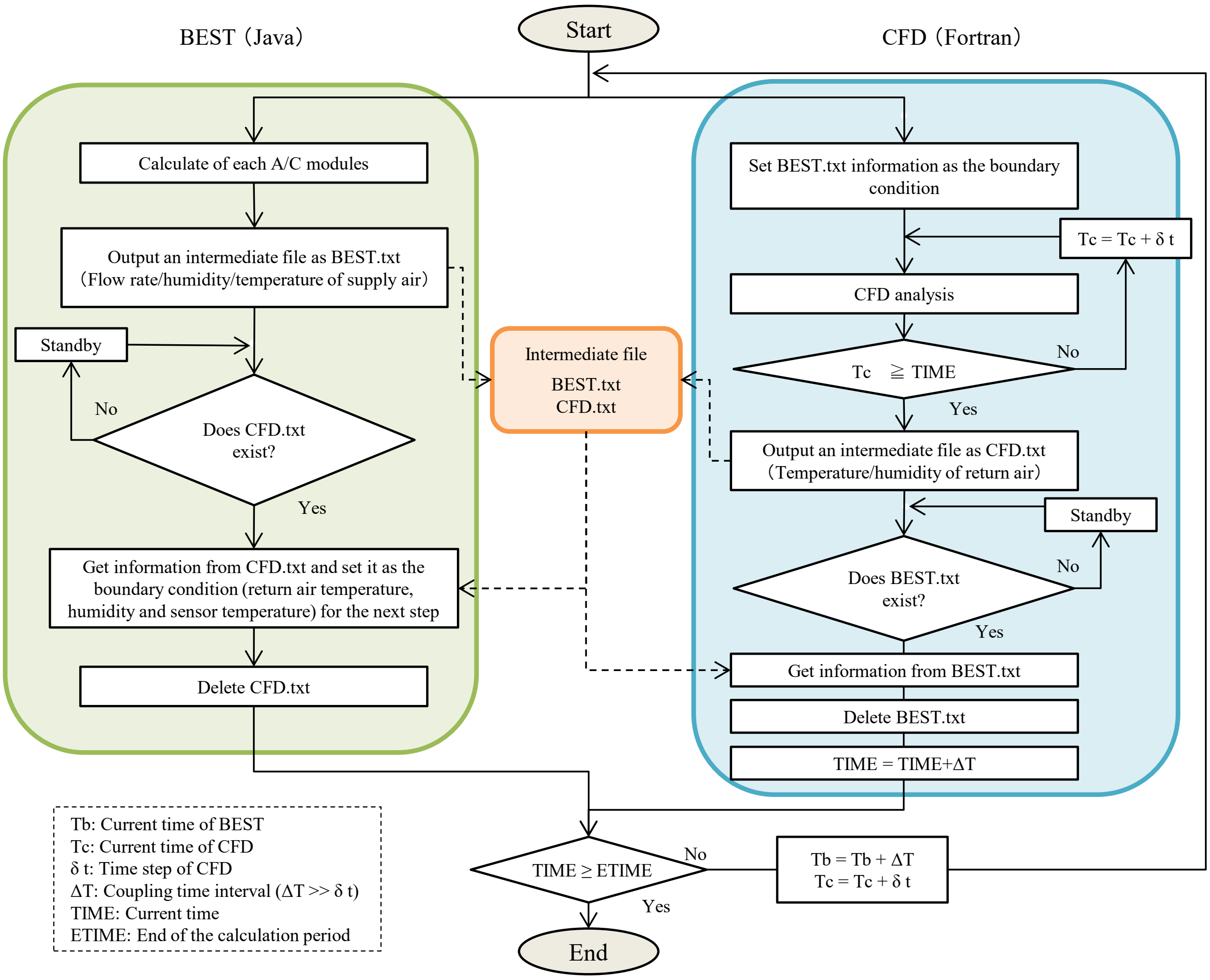

Figure 8: Analysis workflow

4.2 Analysis conditions

The analysis target was the office space on the third floor of the building. Table 3 shows the analysis conditions. Steady-state analyses were performed at five times (9:00, 11:00, 13:00, 15:00, 17:00) each day, and the accuracy of the analysis model was verified by comparing it with the measured values of the indoor A/C heat load and temperature distributions.

Table 3: Analysis conditions

Domain	32.0m(x)×51.2m(y)×4.45m(z)	
Mesh	452(x)×283(y)×39(z) = 4,988,724	
Mesh for radiation	7,291	
Turbulence model	Standard k-ε model	
Inflow conditions	A/C	Temperature: Proportional control Flow rate: 17.5 m^3/min per unit $k_{in}=(U_{in}/10)^2$, $\varepsilon_{in}=C_u^{3/4}k_{in}^{3/2}/\ell_{in}$
	Natural ventilation	Temperature: Outdoor temperature of the BEMS data Flow rate: BEMS data $k_{in}=3/2(U_{in}\times 0.05)^2$, $\varepsilon_{in}=C_u^{3/4}k_{in}^{3/2}/\ell_{in}$
Outflow conditions	A/C	Fixed flow
	Natural ventilation	Fixed static pressure
Wall boundary conditions	Temperature: Fixed convection heat transfer coefficient 4.5 W/m^2K Speed: Generalized logarithmic law	
Outside boundary conditions	South/North: Sol-air temperature, Fixed heat transfer coefficient 23W/m^2K East/West: insulation	
Heating conditions	Lighting/Office equipment/Human/Solar radiation: Measured value	

U_{in}: supply wind speed [m/s]; k_{in}: turbulence energy [m^2/s^2]; ε_{in}: dissipation rate of k_{in}[m^2/s^3]; C_μ: model constant (= 0.09); ℓ_{in}: inlet length

5 RESULT

Table 4 shows the root mean square error (RMSE) value of the vertical temperature distribution for each time and Figure 9 also shows vertical temperature distributions at 9:00 and 15:00. The RMSE value was generally a low value of 1.0°C or less at all time points. Figures 10 and 11 show the measured and analytical values of the A/C heat load and the amount of heat removed by natural ventilation. The maximum error in the amount of heat was also a low value of about 10% at maximum.

The above results indicate that this analysis model has sufficient predictive accuracy, although actual phenomena such as airflow turbulence and unsteadiness due to fluctuations in natural ventilation cannot be reproduced in detail in this analysis.

Table 4: RMSE of vertical temperature distribution

Time	9:00	11:00	13:00	15:00	17:00
RMSE [°C]	0.45	0.66	0.98	0.75	0.97

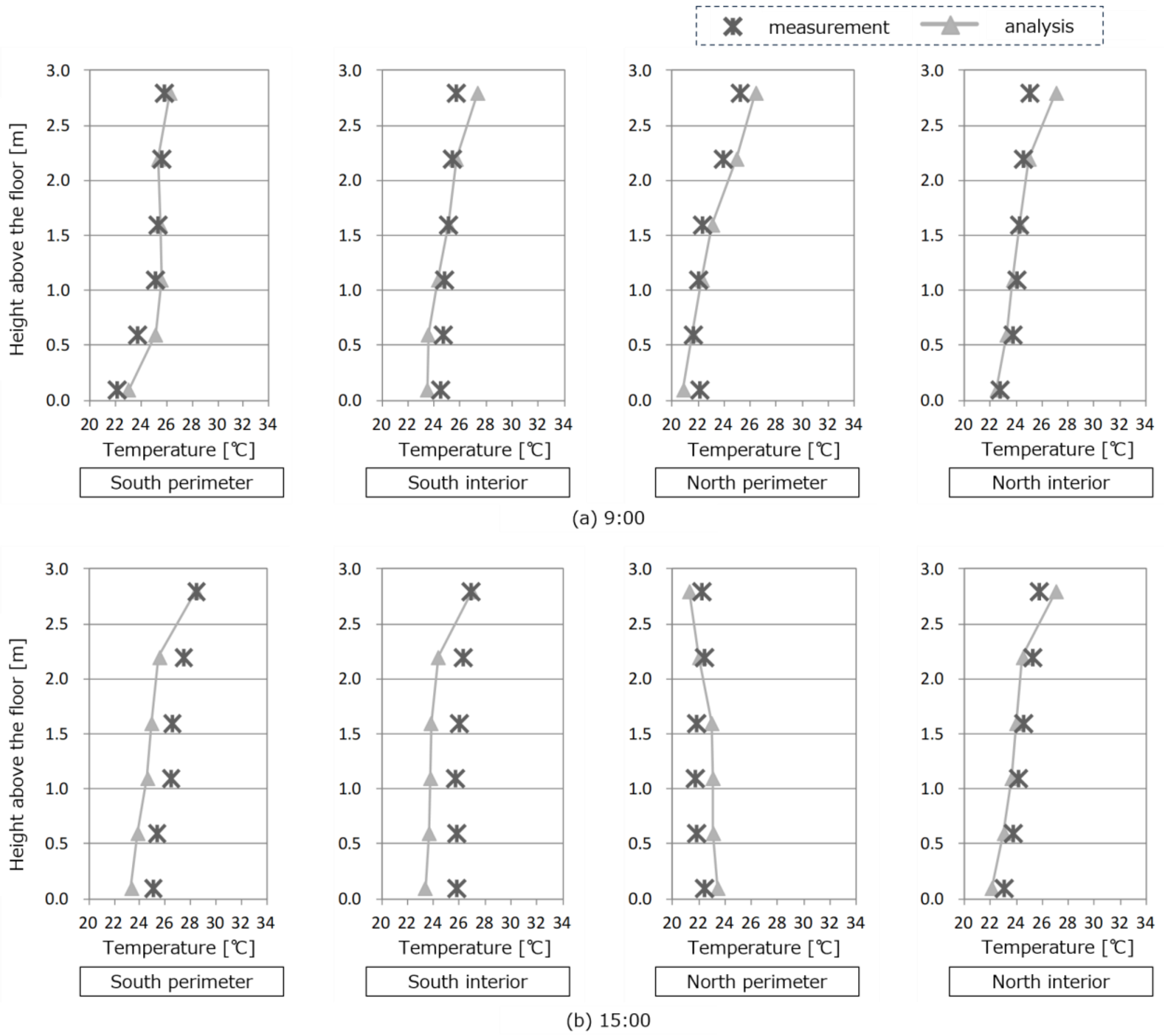

Figure 9: Vertical temperature distribution

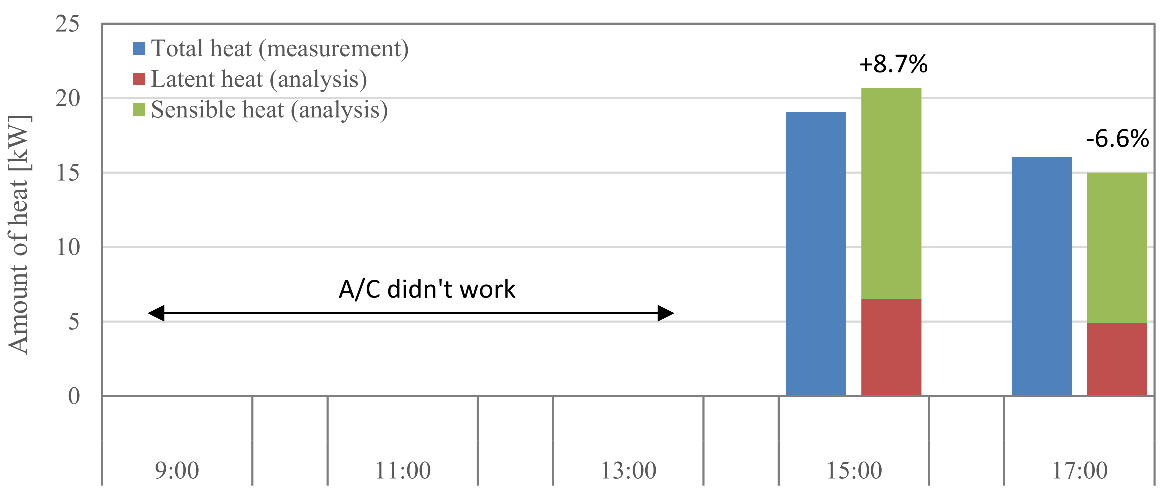

Figure 10: A/C heat load

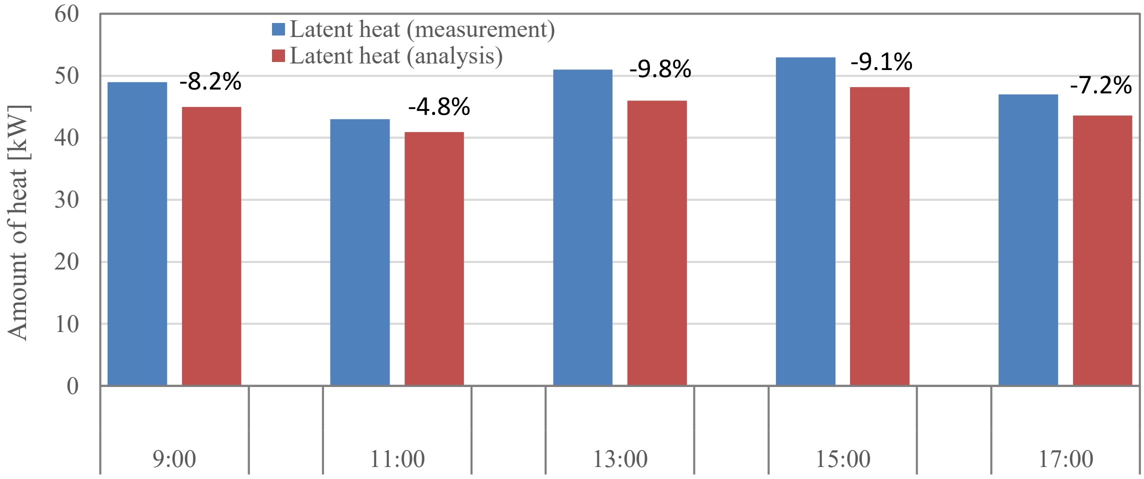

Figure 11: Amount of heat removed by natural ventilation

6 CONCLUSIONS

A method for evaluating the performance of A/C systems involving natural ventilation that combines a BES tool and CFD was proposed. A steady-state analysis was performed based on the proposed method for one floor of an existing office building, and the prediction accuracy of the proposed method was verified by comparing it with the measured values. The results confirmed that the proposed method has sufficient predictive accuracy. In the future, we plan to perform further verification of this analysis model under unsteady conditions and to verify the performance of this building's A/C system as a case study of the method.

7 REFERENCES

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ACKNOWLEDGMENT

This work was supported by JSPSKAKENHI Grant Number 20KK0102.