Application of the Gebhart-Block Model for Predicting Vertical Temperature Distribution in a Large Space Building with Natural Ventilation[1]

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Abstract: Based on the Block model for predicting vertical temperature distribution in a large space, this paper describes an improved Gebhart-Block model for predicting vertical temperature distribution of a large space with natural ventilation. In this model, the Gebhart method for calculating interior surface temperature distribution is incorporated into the Block model for predicting vertical temperature distribution. The Gebhart method is put forward for calculating the surface temperature using the Gebhart absorption coefficient of each surface and a heat balance equation for coupled thermal conduction, convection and radiation of the enclosure. In the Gebhart-Block model, the influence of inside heat sources is also calculated. Its convective and radiative terms here are treated separately in the Block model and Gebhart method. The calculated results are compared with the measured data.

Key words: large space; Gebhart absorption coefficient; Block model; vertical temperature distribution; natural ventilation

1. INTRODUCTION

For a large space, it is important to predicting the vertical temperature distribution in designing the thermal environment and air-conditioning system. A simplified model, Block model, for predicting vertical temperature distribution and unsteady-state thermal analysis have been reported in the cases of natural convection, occupied zone cooling and hot air supply in an enclosed test room without inner heat sources[1]. In order to decrease the energy consumption of a large space building, the natural ventilation tends to be widely used to remove the surplus indoor heat during the transit season in the building. The formerly-reported Block model can be used in cases where the interior surface temperatures are given and no heat sources exist in an enclosed building. With this in mind, the authors develop an improved Gebhart-Block model for predicting the vertical temperature distribution of a large space building with natural ventilation and inner heat sources. An outline of this model and the results of a study on its accuracy are presented in this paper.

2. GEBHART-BLOCK MODEL

2.1 Block Model

The Block model proposed by S.Togari et al.[1] is a simplified model for calculating the vertical temperature distribution of large space building. This model assumes that the horizontal temperature distribution tends to be uniform in a large space except for the regions affected by supply air jet or ventilation airflow. Based on this assumption, the space is divided into a number of zones vertically. Descending or ascending natural currents generated by convective heat along walls are evaluated using boundary-layer analysis on a flat plate. Then, the vertical temperature distribution is calculated by solving a heat balance equation and an airflow balance equation of each zone. Fig. 1 indicates the Block model construction of a natural ventilated large space with n vertical zones for general use.

In this model, the measured natural ventilation

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airflow is added into the airflow balance equation of the zones it flows by, and the convective term of the indoor heat is added into the energy balance equation according to the type of heat sources [2].

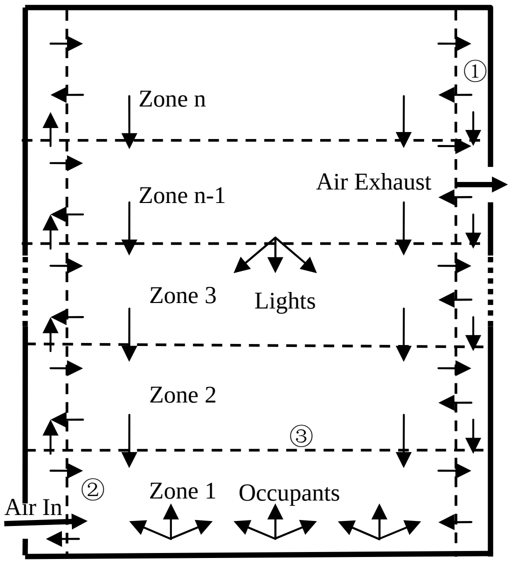

Fig.1 Block model with natural ventilation（n zones）

① wall surface current model
② natural ventilation airflow model
③ heat transfer by temperature difference between adjacent zones

2.2 Calculation of Interior Surface Temperature with Gebhart Method[3]

The thermal conduction, convection and radiation couple occurred on the walls in a large space. In addition, the radiation heat exchange between the interior surfaces is also be affected by the air temperature and the radiation of inner heat resources, such as lighting and equipments. Since the heat transfer through the walls is rather complicated, a heat balance equation for coupled thermal conduction, convection and radiation is necessary to predict the wall surface temperature affected by both outdoor and indoor conditions.

The radiative heat exchanges between interior surfaces actually include the direct radiation and indirect radiation. The indirect radiation includes one-time reflective radiation and multiple reflective radiations. The Gebhart absorption coefficient is a radio of the radiation heat surface *j* gains from surface *i* to the entire radiation energy of surface *i*. Here, the direct radiation and one-time reflection radiation are taken into account. Generally, one-time reflection radiation is enough to describe the heat exchange situation, for the radiation heat exchange between the interior surfaces is long-wave radiation. Assuming that the heat conduction is in a steady state, and the indoor heat sources are radiative flat plates, the heat balance equation of surface *i* can be represented as follows:

$$q_{\lambda i}+\alpha_i\cdot(t_i-\theta_i)-4T_m^3\cdot\varepsilon_i\cdot\sigma\sum G_{ij}\cdot(\theta_i-\theta_j)$$
$$+G_{Ui}q_{LfUi}+G_{Di}q_{LfDi}=0 \qquad (1)$$

Where $q_{\lambda i}$ is the heat conduction per area, W/m^2, α_i the convective heat transfer coefficient, W/(m^2·℃), t_i the zone *i* air temperature, ℃, θ_i the temperature of surface *i*, ℃, T_m the mean surface temperature according to area, ℃, ε_i the radiation coefficient, it is supposed to be 1 for radiation heat source plate, σ the Stefan-boltzmann constant, σ=5.67×10^{-8} W/(m^2·K^4), *Gij* the Gebhart absorption coefficient from surface *i* to surface *j*, G_{Ui} the Gebhart absorption coefficient from the upper side of radiation source to surface *i*, G_{Di} the Gebhart absorption coefficient from the down side of radiation source to surface *i*, q_{LfUi} the radiation heat plate releases to the upper surfaces per area, and q_{LfDi} is the radiation heat plate releases to the lower surfaces per area.

2.3 Gebhart-Block Model

Based on the outdoor conditions and the Gebhart absorption coefficient of the surfaces, the surface temperature can be calculated as the boundary conditions for the Block model calculation. In order to predict the vertical temperature and the surface temperature that influents each other, either needs the iterative calculation circulation.

2.4 Calculation Procedure

Firstly, with the assumed wall temperature distribution, the air temperature can be solved through the iterated calculation circulations with the Block Model. The calculated air temperature can be assigned into the heat balance equation for predicting the surface temperature. The calculation ends until the deviation of both wall temperature and air temperature is less than allowable error. (see Fig.2)

3. CALCULATION EXAMPLE OF GEBHART-BLOCK MODEL

3.1 Zone Division

The example building is a gymnastic centre with a huge dome 8 meters high. The auditorium 12 meters high and the occupied zone are treated as zone 1. Then the upper space is equally divided into 7 zones with a height of 2 meters each. (see Fig. 3)

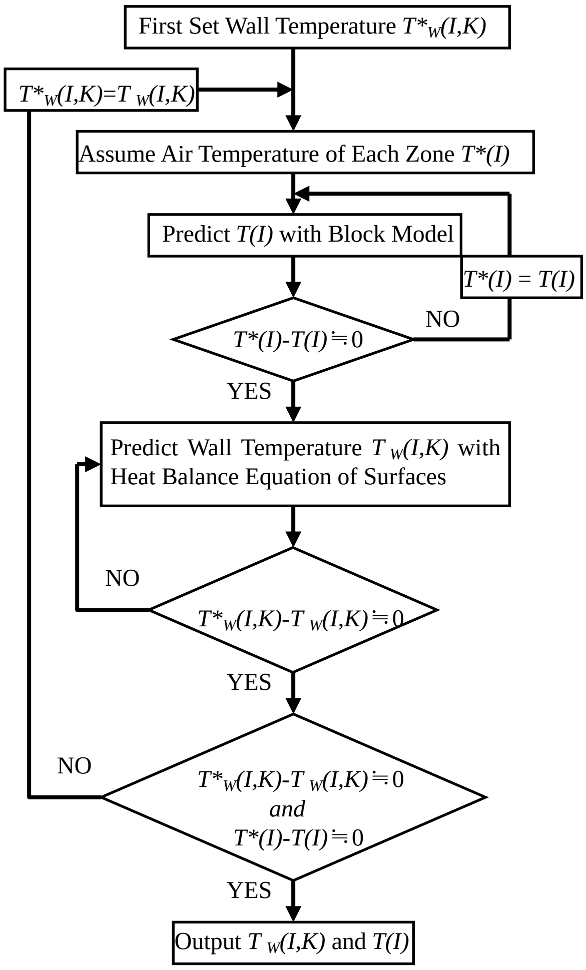

Fig.2 Calculation procedure

3.2 Calculation Conditions

The indoor convective heat transfer coefficient used here can be evaluated as follow:

$$\alpha_i = A[t_w(i) - t(i)]^B \quad (2)$$

Where, for ceiling, A=3.0, B=0.0; for floor, α_i =9.0 W/(m^2·); for vertical walls, A=1.5, B=1/3.[4] Thermal conduction via the walls is calculated with the one dimensional steady-state method. The outdoor temperature used for the floor and the interior walls is the outdoor dry-bulb temperature at the same height and for the ceiling and the walls affected by the solar energy is the solar air temperature. The heat conductivity of floor, interior walls, exterior walls and ceiling are 2.21W/(m^2·K), 2.59 W/(m^2·K), 2.48 W/(m^2·K), and 2.75 W/(m^2·K).

The value used for the heat transfer factor C_B (a parameter for heat transfer due to temperature difference between upper and lower zones) is recommended as 2.3 W/(m^2·)[1] .

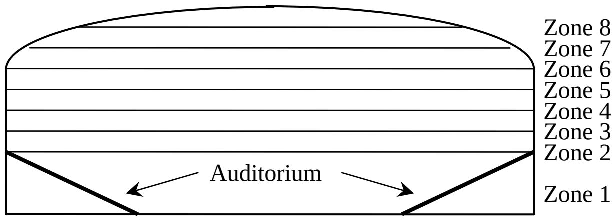

Fig.3 Example model

Tab.1 is the calculation conditions pertaining to heat gain from lighting, occupants, and natural ventilation. According to the type of the heat sources, the convective term of the heat gain was assigned to the heat balance equation of the zone the heat sources located, while the radiative heat was taken into account during the surface temperature calculation with Gebhart method. The measurement was taken while the building was in use with about 3000 audiences watching movies. The lights were nearly turned off when the show was over at about 14:30 while the audiences were almost leaving.

Tab. 1 Calculation conditions

2002-11-11	10:00	13:30	14:00	14:30
Outdoor Temperature/°C	20.3	24.2	24.55	24.2
Occupants/p	3000	3000	3000	30
Light:18kW (in case of 100%)	1%	1%	1%	100%
Equipment:400kW (in case of 100%)	20%	20%	20%	0

3.3 Calculated Results and Analysis

The Calculated vertical temperature distribution for certain time are plotted with measured data in Fig. 4. The calculated vertical temperature was fairly close to measurement data according to Fig. 4.

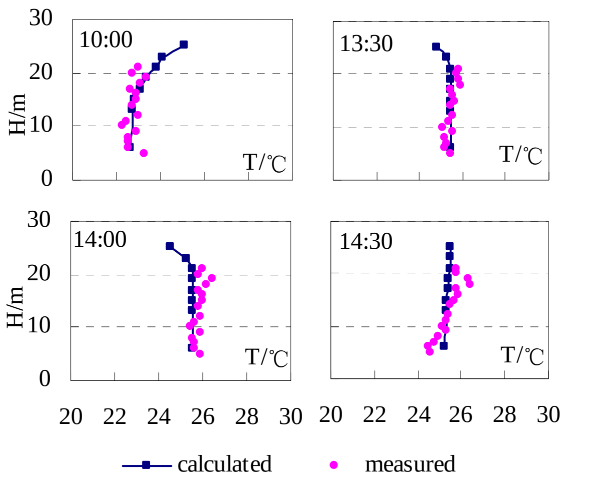

Fig.4 Comparison between calculated and measured vertical temperature distribution

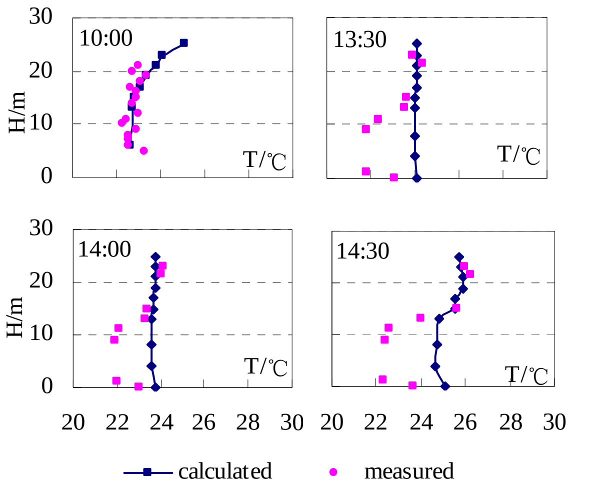

Fig.5 Comparison between calculated and measured surface temperature distribution

For the heat flow of solar energy through the roof was larger than that of occupants at the beginning of the measurement (see 10:00), the temperature of top zones were higher than that of lower zones. Nevertheless, since the heat from the occupants affected the lower zones of the space in the afternoon (see 13:30, 14:00 and 14:30), the top zones temperature was slightly lower than that of lower zones.

Calculated surface temperature distribution compared with measured value is plotted in Fig.5. The calculate temperature of upper zones surfaces agrees well with the measurement data from Fig. 5. Only the calculated surface temperature of lower zones (below 15 meters) was higher than the measured results by about 1~2 ℃. For the lower walls are surrounded by offices with air-conditioning, the walls temperature were affected by the adjacent rooms' temperature. In addition, the heat storage of the walls during the late autumn nights also has an effect on the interior surface temperature distribution.

4. CONCLUSION

In the study described above, a Gebhart-Block model for predicting vertical temperature distribution was applied to an existing gymnastic center with natural ventilation and inner heat sources. The calculated vertical temperature distribution agrees well with the measurements data during transit season. The Gebhart-Block model was found to be capable of predicting the vertical temperature of large space for engineering application. The calculated results can describe the feature that the indoor temperature varies with the outdoor conditions. Further considerations and discussions would still be required during the further research. The value of heat transfer coefficient needs discussing to gain the results correspond to actual situation. The heat store of walls needs considering in the surface temperature distribution calculation.

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