Thermal environment characteristics of large space building
with stratified air conditioning based on Block-Gebhart model
during the cooling season

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Abstract. The thermal environment of large space building with stratified air distribution is characterized
by its obvious gradient of vertical temperature, and the stratified air conditioning load (SACL) is closely
related to the thermal environment. The Block-Gebhart (B-G) model in summer is established for an actual
large space building which has two stratified air distribution (STRAD) systems. One system is the air supply
nozzles (ASN) arranged at middle sidewall, the other is the half-cylinder diffusers (HCD) arranged at low
sidewall. In order to quickly calculate the air temperature of unoccupied zone (ATUZ), two regression
equations for the air temperature gradient under the conditions of two STRAD systems were proposed.
Considering six factors, the B-G model was used to calculate 648 cases and the two equations were obtained
by multiple regression analysis. Through the field measurement in summer, in three cases of ASN system,
the mean absolute error (MAE) between predicted and experimental values of ATUZ was 1.71°C, and the
mean absolute percentage error (MAPE) was 4.5%; in three cases of HCD system, the MAE was 1.0°C and
the MAPE was 3.0%. The results of this study establish the foundation for the calculation of SACL.

1 Introduction

Large space buildings often use stratified air conditioning
to reduce energy consumption [1-3]. Previous studies
have shown that the thermal environment of large space
buildings with stratified air distribution is characterized
by its obvious gradient of vertical temperature [4-6]. And
the stratified air conditioning load (SACL) is susceptible
to the thermal environment [7-9].

Mathematical models are often used to predict the
indoor thermal environment. Among them, the earlier
ones include the zonal model [10] and the nodal model
[11]. The principles of the both two models are to divide
the object space into several regions or nodes in the
vertical direction. Togari [12] proposed the Block model
based on the zonal model to study the indoor thermal
environment. At present, the Block model has developed
into the Block-Gebhart (B-G) model [13, 14], in which the
air temperature and the inner wall temperature are
calculated synchronously by combining the Block model
with the Gebhart radiation model. Wang [15] predicted
the vertical air temperature distribution in three hybrid
ventilation scenarios based on the B-G model. The results
of field measurements showed that the average deviations
of air temperature were 0.85°C (in summer), 0.80°C (in
summer), 0.32°C (in winter).

Through the above study, it was found feasible and
accurate to use the B-G model to predict the thermal
environment of the actual large space buildings, but the
model was still complicated in engineering applications.

2 B-G model

2.1 Block model

The B-G model divides the space into several regions in
vertical direction. The indoor air temperatures can be
calculated by establishing the mass and energy balance
equations for each region. The schematic diagram of
Block model is shown as Fig. 1. The energy balance
equation of Block i is as expressed in Eq. (1).

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\[
\sum_{i=1}^{\infty} \left[ C_p M_\infty \right] (i,k) T_a(i,k) - C_p M_\infty \right] (i,k) T(i) \\
+ C_p M_i (i+1) T(i+1) - C_p M_i (i) T(i) + C_p M T_i \\
- C_p M T_a - C_p M_a T + C_p M T_a - C_p M T_a + C_p M T_a + C_p M T_a \\
+ C_p A_k [T(i+1) - T(i)] \\
+ C_p A_k [T(i+1) - T(i)] + h A_k [\theta - T(N)] \\
+ h_j A_j [\theta - T(i)] + \beta_{\text{conv}} Q_n (i) = 0 \\
\]

where \( i \) is the index of Block; \( m \) is the number of wall divisions in Block \( i \); \( C_p \) is the specific heat capacity of the air, \( V/(kg \cdot ^\circ C) \); \( M_\infty (i,k) \) is the mass flow rate from wall surface airflow \( k \) to Block \( i \) (kg/s); \( T_m (i,k) \) is the temperature of wall surface airflow \( k \) in Block \( i \) (\(^\circ C\)); \( M_\infty (i,k) \) is the mass flow rate from Block \( i \) to wall surface airflow \( k \) (kg/s); \( T(i) \) is the air temperature in Block \( i \), \( 1 \sim N \) in bracket means Block \( 1 \sim N \) (\(^\circ C\)); \( M(i+1) \) is the is the is the is the is the is the is the is the is the is the is the vertical mass flow rate from Block \( i + 1 \) to \( i \) (kg/s); \( M_a, M_e, M_s, M_r, M_k \) are the mass flow rates of air supply, return, exhaust and entrainment (kg/s); \( T_m, T_n, T_e, T_s \) are the temperature of air supply, return, exhaust and entrainment (\(^\circ C\); \( C_k \) is the temperature difference heat transfer factor [W/(m\(^2\)\(^\circ\)C)]; \( A_b \) is the area of the interface between the Blocks (m\(^2\)); \( h_c, h_r \) are the convective heat transfer coefficient of the ceiling and floor [W/(m\(^2\)\(^\circ\)C)]; \( A_c, A_f \) are the area of the ceiling and floor (m\(^2\)); \( \theta, \theta \) are the inner wall temperature of the ceiling and floor (\(^\circ C\)); \( \beta_{\text{conv}} (i) \) is the convective fraction of internal heat sources in Block \( i \), the recommended values are given in Ref [16]; \( Q_n (i) \) is the internal heat source in Block \( i \) (W).

For a specific Block, the constituent elements such as air supply, air return, air exhaust and air entrainment are added or deducted according to the real condition.

2.2 Gebhart model

Gebhart model [17] is a theoretical model that can calculate the radiant heat transfer between inner wall surfaces. The energy balance equation of each inner wall surfaces is established to achieve the temperature distribution of the inner wall surfaces as shown in Eq. (2):

\[
\frac{1}{K_i} \left[ t_{i,k} - \theta_i \right] + q_{i,k} = 0 \\
\]

where \( K_i \) is the convective heat transfer coefficient of surface \( k \) (W/(m\(^2\)\(^\circ\)C)); \( \theta, \theta \) are the inner wall temperature of surface \( j \) and \( k \) (\(^\circ C\)); \( T_m \) is the area-weighted average temperature of the inner wall surface (\(^\circ C\)); \( \varepsilon_k \) is the emittance of surface \( k \); \( \sigma \) is Stephen-Boltzmann constant, \( 5.67 \times 10^{-8} \) [W/(m\(^2\)\(^\circ\)C\(^4\)]; \( j \) is the index of wall surface in the horizontal direction; \( G_k \) is the Gebhart absorption factor from surface \( j \) to surface \( k \); \( K_s \) is the envelope heat transfer coefficient of wall \( k \) [W/(m\(^2\)\(^\circ\)C)]; \( q_{i,k} \) is the sol-air temperature of wall \( k \) (\(^\circ C\)); \( q_{i,k} \) is the radiant heat emitted by all internal heat sources to the wall \( k \) (W/m\(^2\)).

2.3 B-G model

For the Block model, we can calculate the indoor air temperatures by the known inner wall temperatures. In the same way, for the Gebhart model, we can also calculate the wall temperatures by the known air temperatures. Therefore, the B-G model is to combine the Block model with Gebhart model to synchronously calculate the air and wall temperatures. There is a coupling relationship between the air and wall temperatures, so the iterative method is adopted. The details of B-G model can be found in the previous study [14].

3 Methodology

3.1 Research object

The research object of this paper is a large space computerized numerical control (CNC) machine zone. It has two stratified air distribution (STRAD) systems. One system is the air supply nozzles (ASN) arranged at middle sidewall, the other is the half-cylinder diffusers (HCD) arranged at low sidewall. Eight nozzles are installed at a height of 5.5 m on the east wall, with the same diameter of 373 mm. The height of each half-cylinder diffuser is 1.5 m and the diameter is 1.0 m. The air return vent is installed at a height of 0.5 m with a size of 3 m×2 m. And the exhaust devices are installed at the top of the building.

When establishing the B-G model of the research object, the building with slope roof is simplified into a cuboid building according to the principle of equal volume, and the equivalent height is 10.8 m. The vertical direction is divided into 6 Blocks. The specific Block division of HCD system is shown as Fig. 2. The Block division of ASN system is 2.6 m, 2.9 m, 1.5 m, 1.5 m, 1.5 m and 0.8 m from bottom to top.

3.2 Experimental scheme

The arrangement of vertical temperature measuring points is shown as Fig. 3. The air temperatures in the space above 3 m were measured by the PT1000 temperature sensors (an accuracy of ±0.2 \(^\circ\)C) fixed on the vertical measuring lines. The air temperatures below 3 m were measured by Testo 174T (an accuracy of ±0.5 \(^\circ\)C) at line A, C, E, I, K.
Experimental conditions are shown in Table 1, in which A1–A3 are the cases of ASN system, B1–B3 are the cases of HCD system, and the parameters in the table are the experimentally measured values.

### Table 1. Experimental conditions

| Case | Supply air temperature (°C) | Outdoor temperature (°C) | Supply air volume (m³/h) | Horizontal irradiance (W/m²) | Internal heat source (W) |
|------|---------------------------|--------------------------|------------------------|-----------------------------|-------------------------|
| A1   | 16.1                      | 32.2                     | 22030                  | 156                         | 11410                   |
| A2   | 15.4                      | 33.0                     | 18764                  | 675                         | 280                     |
| A3   | 17.6                      | 37.4                     | 21613                  | 670                         | 280                     |
| B1   | 18.9                      | 33.8                     | 25297                  | 517                         | 17290                   |
| B2   | 17.7                      | 36.0                     | 22117                  | 427                         | 17220                   |
| B3   | 17.7                      | 35.8                     | 21576                  | 328                         | 20220                   |

### 4 Results and analysis

#### 4.1 Calculation conditions

Six factors that may affect the thermal environment are comprehensively considered, and the indoor vertical air temperature gradient $V_l$ under different conditions are calculated by changing each factor. The air temperature gradient $V_l$ is as expressed in Eq. (3). The design temperature of the occupied zone is a known parameter. After obtaining $V_l$ according to the influencing factors, the air temperature of unoccupied zone (ATUZ) can be quickly calculated according to Eq. (3).

$$ V_l = \frac{(T_{uo} - T_o)}{\Delta h} \tag{3} $$

where $V_l$ is the vertical air temperature gradient (°C/m), $T_{uo}$, $T_o$ are the air temperature of unoccupied zone and occupied zone (°C), $\Delta h$ is the height difference between the unoccupied zone and occupied zone (m).

Six influencing factors and the value ranges are shown in Table 2 [18]. A total of 648 calculation conditions are designed, and there are 324 calculation conditions for ASN system and HCD system respectively. In all the calculation cases, only the values of six influencing factors are changed. The outdoor parameters are selected in Shanghai [18]. The design temperature of the occupied zone is 26°C. It assumes that the air is exhausted at the top of the unoccupied zone. The exhaust ratio $\beta_e = \frac{M_{ex}}{M_e}$.

#### 4.2 Multiple regression analysis

The indoor vertical air temperatures of 648 cases were calculated based on the B-G model, and two regression equations for the air temperature gradient under the conditions of two STRAD systems were proposed by the multiple regression method. The temperature gradient has a high correlation with $q_1$, $q_2$, $\beta_e$ and $H$, but has a low correlation with $L$ and $W$. In the multiple regression, $L$ and $W$ are eliminated, and the first-order polynomial regression equations for temperature gradient are obtained. The equations are shown as Eq. (4) and Eq. (5).

$$ V_l = 0.016 q_1 + 0.037 q_2 - 0.441 n_{e0} + 2.912 \times 0.861 n_{ex} + 0.102 \tag{4} $$

$$ \beta_e = 0.004 L + 0.047 L - 0.431 n_{e0} + 4.006 \times 0.870 n_{ex} + 0.201 \tag{5} $$

where $n_{e0}$ is the air exhaust per hour in unoccupied zone (h⁻¹). $n_{ex}=M_{ex}/V_2$, $V_2$ is the volume of unoccupied zone (m³). Since the exhaust ratio $\beta_e$ is difficult to obtain in the design stage, $n_{ex}$ is used to describe the air exhaust.

Fig. 4 shows the relative error of $T_{uo}$ between the results obtained from B-G model and Eq.(4),(5). It can be seen that the relative error is basically within ±10%. The applicable ranges of two regression equations are: $q_1<150W/m^3$, $q_2<80W/m^3$, $n_{ex}<4$ h⁻¹, $H<55m$.
4.3 Experimental validation

According to the experimental scheme in Section 3.2, the ATUZ $T_{wo}$ under six experimental conditions were obtained. The regression equations proposed in this paper can also be used to calculate the ATUZ $T_{wo}$. The calculated values of the ATUZ $T_{wo}$ were compared with the experimental values as shown in Table 3. It could be seen that in the three cases of ASN system, the MAE between the experimental and calculated values was $1.4 \degree C$, and the MAPE was $4.5\%$. In the three cases of HCD system, the MAE was $1.0 \degree C$ and the MAPE was $3.0\%$. It indicates that the two regression equations proposed in this paper can be used to predict the vertical air temperature gradient and the ATUZ $T_{wo}$ of the actual large space buildings.

| Case | Experimental value (°C) | Calculated value (°C) | Absolute error (°C) | Relative error |
|------|--------------------------|-----------------------|---------------------|----------------|
| A1   | 29.2                     | 31.0                  | 1.8                 | 6.1%           |
| A2   | 30.0                     | 31.8                  | 1.8                 | 6.0%           |
| A3   | 33.1                     | 33.6                  | 0.5                 | 1.5%           |
| A1–A3 | MAE (°C)                | MAPE                  |                      |                |
| B1   | 33.1                     | 34.0                  | 0.9                 | 2.6%           |
| B2   | 34.8                     | 33.9                  | -0.9                | -2.6%          |
| B3   | 33.0                     | 34.3                  | 1.3                 | 3.8%           |
| B1–B3 | MAE (°C)                | MAPE                  | 1.4                 | 4.5%           |
|      |                          |                       | 1.0                 | 3.0%           |

5 Conclusion

In this paper, a thermal environment experiment was carried out in a large space CNC machine zone. Two B-G models were established for two STRAD systems. Considering six factors, 648 cases were calculated based on B-G model. Then two equations for $V_i$ were proposed by multiple regression analysis, and the ATUZ $T_{wo}$ can also be calculated. Finally, the regression equations proposed in this paper were experimentally verified according to the six experimental cases. The results showed that in the three cases of ASN system, the MAE was $1.4 \degree C$, and the MAPE was $4.5\%$. In the three cases of HCD system, the MAE was $1.0 \degree C$, and the MAPE was $3.0\%$.

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