Function Relationship Between Minimum Fresh Air Volume and Personnel Density Meeting the Standard Value of CO₂ in Working Area

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Abstract. Reasonable fresh air volume can effectively improve indoor air quality and reduce building energy consumption. In order to achieve the comfortable and energy saving operation of air conditioning and ventilation system, the standard $k-\varepsilon$ turbulence model combined with wall function method is used to simulate and analyze the indoor velocity field, temperature field and CO₂ concentration field under different fresh air volume by simulation software. The results show that increasing fresh air volume can improve indoor ventilation efficiency and reduce CO₂ concentration; and based on the CO₂ concentration, the function between the minimum fresh air volume and the density of indoor personnel is fitted to meet the requirement of comfort and health in indoor working area. The function is $y = 5.980\exp(x/0.343) - 3.999$.

1. Introduction
At present, many scholars have studied different air distribution, which shows that reasonable air distribution can effectively improve indoor air quality and comfort[1-7]. Shang Min et al. Proposed that the indoor CO₂ concentration increases exponentially, and the outdoor air system can effectively control the indoor CO₂ concentration, the critical fresh air volume (the minimum fresh air volume required to meet the CO₂ standard) is linearly related to the number of indoor personnel[8]. Zhang Peng et al. studied the fresh air volume needed when the CO₂ concentration in the respiratory area reached the warning value of 900 ppm, and fitted the functional relationship between the fresh air volume and the indoor personnel density for the upper and upper return airflow[9]. In this paper, the indoor velocity field, temperature field and CO₂ concentration are analyzed under different fresh air flow rates, and the function relationship between the minimum fresh air volume to meet the good air quality in the working area and indoor personnel density is found by taking the CO₂ concentration as the index, which provides a reference for energy-saving and comfortable operation of air conditioning and ventilation system.

2. Theoretical approach
According to the theory of total ventilation, it is assumed that the indoor CO₂ concentration is ideal and fully mixed at any time, and that the room is airtight and there is no air leakage from doors and windows, then the theoretical CO₂ concentration can be obtained by formula derivation, as formula (1), the left side of the equal sign is the variation of indoor CO₂, the first item on the right side of the equal
sign is the amount of CO₂ exhaled by the human body, and the second item is the difference between the amount of CO₂ delivered into the room by the fresh air system and the amount of CO₂ diffused to the outdoor.

\[ V_{\text{diff}} = NQ + V_0(\text{C}_0 - \text{C}) \]  

(1)

In the formula: \( V_0 \)—room volume, m³; \( C \) is indoor CO₂ concentration, ml·m⁻³; \( C_0 \)—outdoor CO₂ concentration, ml·m⁻³; \( N \)—number of people in the room; \( Q \)—the amount of CO₂ exhaled by human body, ml·p⁻¹·h⁻¹; \( V_1 \)—Fresh air volume, m³·h⁻¹.

It can be obtained by integrating the two ends of equation (1):

\[ C = \frac{NQ}{V_1} + C_0 - \frac{NQ}{V_1 + C_0 - C} \exp \left( \frac{V_1}{V_0} \right) \]  

(2)

It can be seen from formula (2), the indoor CO₂ concentration satisfies the functional relationship:

\[ y = a + be^{kt} \]. In the formula, \( a = \frac{NQ}{V_1} + C_0 \), \( b = \frac{NQ}{V_1 + C_0 - C} \), \( k = -\frac{V_1}{V_0} \).

When the fresh air is fully mixed with the indoor air, that is, assuming \( t \to \infty \), the indoor CO₂ concentration \( C = a \). If the indoor CO₂ concentration is known or expected, the required fresh air volume can be obtained.

\[ V_1 = \frac{\frac{NQ}{C - C_0}}{C_0} \]  

(3)

3. Model introduction

3.1. Physical model

Figure 1. Room layout

Figure number represents the physical model as follows: 1-air outlet, 2-air outlet, 3-top lamp, 4-human heat source, 5-table, 6-door, 7-wall, 8-nose. The research model of this paper is a summer office, the geometric parameters of the room are: length 6m, width 5m, height 2.8m. The room is equipped with an air inlet, an outlet, a desk, two top lights. But the real indoor layout and object structure are very complex, if not simplified, the simulation will be very difficult and unnecessary. Therefore, the simulation is simplified as follows:

1) Simplification of human heat source: simplify human body to a cuboid of 0.4m×0.3m×1.2m.

2) Simplification of human nose: because this paper studies CO₂ gas, human is the main source of release, so the human nose is simplified to: 0.3m×0.3 m square.

3) Simplification of tuyere: the tuyere is simplified as a rectangular tuyere, and the air supply speed is vertical to the wall.

3.2. Control equations

The air supply speed of the air-conditioned room is low, and the indoor air flow is mainly natural convection in this simulation, at present, the standard \( k-\varepsilon \) model is used in the calculation of air flow in air-conditioned rooms. Since \( k-\varepsilon \) two-equation turbulence model is suitable for high Reynolds number turbulent flow, the standard wall function method is applied to the near wall surface, the following
assumptions are made:

(1) The fluid in the room is constant and low speed, it can be regarded as incompressible fluid.

(2) According to Boussinesq hypothesis, it is considered that the indoor fluid density only affects the buoyancy.

(3) Ignoring the energy dissipation caused by viscous action in the energy equation of fluid dynamics.

(4) Ignoring thermal radiation between solid walls.

(5) Ignoring air leakage.

Based on the above assumption and simplification, a set of closed equations including continuous equation, momentum equation, turbulent flow energy equation, turbulent flow energy dissipation equation, energy equation and component transport equation are established.

\[
\frac{\partial (\rho \vartheta)}{\partial t} + \text{div}(\rho \bar{u} \vartheta) = \text{div}(\Gamma \text{grad} \vartheta) + S_\vartheta
\]  

In the formula: \( \frac{\partial (\rho \vartheta)}{\partial t} \) —Transient term; \( \text{div}(\rho \bar{u} \vartheta) \) —Convective term; \( \text{div}(\Gamma \text{grad} \vartheta) \) —Diffusion term; \( \bar{u}, \bar{v} \) and \( \bar{w} \) —The component of velocity \( \bar{u} \) on the \( x, y, z \); \( \vartheta \) —The general variable can represent the dependent variable and the fluid parameters such as velocity, temperature and volume concentration; \( \Gamma \) —The generalized diffusion coefficient of the general equation; \( S_\vartheta \) —The generalized source term of the general equation can be expressed as the internal heat source of the fluid and the mass parameter of the component produced by the chemical reaction per unit volume within the system.

3.3. Boundary conditions

(1) The given temperature of wall and floor is 299k, and the table is adiabatic boundary.

(2) The second boundary condition is adopted for human body and ceiling lamp. The heat flux density is 75W·m\(^{-2}\) and 210W·m\(^{-2}\) respectively.

(3) The air supply outlet adopts velocity inlet, defines turbulence intensity and hydraulic diameter, and air supply temperature \( T=291K \); The exhaust outlet should be fully developed.

(4) CO\(_2\) volume fraction of the gas exhaled by the human body is 5\%, the CO\(_2\) temperature is 34\(^\circ\)C, and the exhaled volume per person in the room is about 0.0173 m\(^3\)·h\(^{-1}\); The initial CO\(_2\) concentration of air supply is 440ppm.

3.4 Grid division and solution setting

(1) ICEM was used to mesh the model. Tetrahedral mesh was used and the global mesh size was set to 0.1, the heat source of human body is set with boundary layer, and the nose is locally encrypted. The quality are above 0.3, it can be considered that the mesh quality meets the simulation requirements.

(2) The SIMPLE algorithm and the second-order upwind scheme are used to improve the accuracy; The convergence standard of energy residual value is e-6, and the convergence standard of other variables is e-3.

4. Simulation results analysis

According to the indoor air quality standard issued by China, the upper limit of indoor CO\(_2\) concentration is set as 1000ppm. For office areas such as offices, according to the relevant standards of CO\(_2\) concentration control, the standard value of indoor CO\(_2\) concentration is set as 700ppm. Table 1 lists the effects of different indoor concentration CO\(_2\) on personnel. The breathing area is defined as the space of 1 m~1.1 m and the working area is 0.1 m~1.2 m during human sitting.

| Volume fraction(%) | Physiological reaction of personnel |
|--------------------|-----------------------------------|
| 0.03               | Outdoor normal air, most people in the room can not detect |
| 0.07               | A small number of sensitive personnel in the room have been detected |
| 0.1                | Most people feel uncomfortable |
1. The faster the breathing rate, there is no obvious effect on the learning efficiency.
2. Headache, drowsiness, mild hearing loss, decreased computational efficiency.
4. Unable to breathe normally, work efficiency are greatly affected.
6. Headache is very serious, vomiting, neurological disorders, manic state.
7-9. In about ten minutes, there was a state of unconsciousness.

In this paper, the indoor velocity field, temperature field and CO₂ concentration field under different fresh air volume are analyzed by taking indoor number of six people as an example. For public buildings such as offices, the code for design of heating, ventilation and air conditioning of civil buildings stipulates that the minimum fresh air volume per person is 30m³·h⁻¹, the fresh air volume is 180m³·h⁻¹, meanwhile, 210m³·h⁻¹ was taken for comparative analysis.

4.1 Calculation results and analysis of indoor velocity field

![Distribution of indoor velocity](image)

(a) $V=180$ m³·h⁻¹ (Y=3 Section)  (b) $V=210$ m³·h⁻¹ (Y=3 Section)

Figure 2. Distribution of indoor velocity

(1) As shown in Figure 2, due to the low temperature and high relative density of fresh air, the air is sent into the room and diffused on the ground to form a layer of "cold air lake". The fresh air diffuses slowly in the lower floor of the room, absorbs heat near the heat source of human body, and then rises slowly in the form of natural convection due to the effect of thermal buoyancy. In the process of rising, the air around the heat source is continuously sucked in, so the air flow velocity around and above the heat source is larger.

(2) After the low temperature air is sent into the room from one side of the room, it directly blows to the human body and decays rapidly. When it meets the human body, it forms a disturbance flow. However, due to the low air supply position, the return area is small, the residual air flows upward under the influence of buoyancy, and the air speed decreases gradually until it is discharged from the upper exhaust outlet. Under the two kinds of fresh air volume, the air speed on the back of human body on the side of air supply outlet is larger, ranging from 0.1m/s to 0.5m/s; the air speed in the front of the human body and most of the indoor areas is below 0.2m/s, and the air speed in the whole working area is low, so it can be considered that there is no sense of blowing.

4.2 Calculation results and analysis of indoor temperature field

![Distribution of indoor temperature](image)

(c) $V=180$ m³·h⁻¹ (Y=3 Section)  (d) $V=210$ m³·h⁻¹ (Y=3 Section)

Figure 3. Distribution of indoor temperature
1) As shown in Figure 3, the indoor temperature distribution has obvious stratification phenomenon, the temperature in the upper region is higher and relatively stable, and the temperature gradient is small; the temperature in the lower area is lower and the temperature gradient is larger.

2) When $V=180\text{m}^3\cdot\text{h}^{-1}$, the air temperature above the ankle of the air supply outlet side is between 24°C and 28°C, and the vertical temperature difference is large; the air temperature around the human body on the other side of the room is between 26°C~28°C, and the vertical temperature difference is small, but the temperature is higher.

3) The upper room temperature is still higher at the $V=210\text{m}^3\cdot\text{h}^{-1}$, but the overall temperature of the room is lower than $V=180\text{m}^3\cdot\text{h}^{-1}$, because as the fresh air volume increases, the fresh air can take away more heat generated by the heat source.

4) Ventilation efficiency $\eta$ is an index of the ability of the ventilation system to remove waste heat and dirty gas. The greater $\eta$ is, the higher the efficiency of energy utilization is. It is defined as:

$$\eta = \frac{t_p - t_0}{t_n - t_0}$$  \hspace{1cm} (5)

In the formula: $t_p$—Exhaust air temperature, °C; $t_0$—Supply air temperature, °C; $t_n$—Average temperature of working area (in this paper, the average temperature of $Z=0.5$ section is taken), °C.

| Exhaust air temperature | Supply air temperature | Average temperature of working area | Ventilation efficiency $\eta$ |
|------------------------|-----------------------|-------------------------------------|-----------------------------|
| $V=180\text{m}^3\cdot\text{h}^{-1}$ | 28.8                  | 17                                  | 26.8                        | 1.204                       |
| $V=210\text{m}^3\cdot\text{h}^{-1}$ | 28.4                  | 17                                  | 26.1                        | 1.253                       |

4.3 Results and analysis of indoor concentration field

1) It can be seen from Figure 4 and Figure 5 that the indoor CO$_2$ distribution under the two fresh air rates is obvious, with high concentration and small gradient in the upper layer; low concentration and large gradient in the lower layer, the human body is in a region of relatively good air quality. This is because the fresh air is sent out from the air outlet at the bottom of the room, and the human body acts as the heat source to generate the thermal buoyancy lift, so that the fresh air with lower temperature at the lower part flows from bottom to top through the thermal buoyancy lift force, forming a "displacement" effect, so as to eliminate the CO$_2$ around the human body. Because of the air supply distance, the replacement effect of one side without tuyere is not obvious.

(2) It can be seen from Figure 4 that the CO$_2$ concentration at the air outlet is the lowest, and the CO$_2$ concentration in the area below the human head is slightly higher than that in the fresh air. The CO$_2$ concentration in human head is the highest, and the velocity of the thermal plume above the human body is larger. The CO$_2$ concentration in the upper part of the human head is gradually diluted.
under the action of the thermal plume.

(3) As shown in Figure 5, with the increase of fresh air volume, the average indoor CO₂ concentration decreases. When \( V = 210 \text{ m}^3 \cdot \text{h}^{-1} \), the CO₂ concentration in the indoor working area is below 700ppm, and the CO₂ concentration above the working area is close to 700ppm, which can satisfy the comfortable and healthy indoor environment; when \( V = 180 \text{ m}^3 \cdot \text{h}^{-1} \), that is, the minimum fresh air volume per person specified in the code for design of heating, ventilation and air conditioning of civil buildings of 30m³·h⁻¹ the CO₂ concentration in the working area is mostly below 700ppm, but the concentration CO₂ human respiratory area is about 700 ppm.

![Figure 5. Distribution of the average concentration CO₂ each indoor plane](image)

5. Relationship between fresh air volume and human density meeting the CO₂ concentration standard in the working area

Under this ventilation system, the indoor CO₂ concentration increases with the increase of indoor height. If the minimum fresh air volume is operated to meet the standard of CO₂ concentration in the respiratory area, it can not only meet the requirements of comfort and health in the working area, but also realize the energy saving operation of the air conditioning system.

Under the same environmental parameters and calculation method, the number of people in the room is changed to simulate the fresh air volume when the CO₂ concentration in the respiratory zone reaches 700pp, the indoor number of people is 4, 5, 6, 7, 8 respectively. At the same time, increasing the fresh air volume will increase the air supply speed. In order to avoid the discomfort of blowing to the human body, this paper does not consider the impact of the change of air supply speed. The size of the air outlet is adjusted appropriately while changing the number of people in the room, as shown in Table 3.

| Number of people in the room | 4   | 5   | 6   | 7   | 8   |
|-----------------------------|-----|-----|-----|-----|-----|
| Personnel density/ (p · m⁻²) | 0.13| 0.17| 0.20| 0.23| 0.27|
| Tuyere Size/m               | 0.3×0.2 | 0.3×0.2 | 0.3×0.2 | 0.3×0.25 | 0.3×0.25 |

The minimum fresh air volume required under different indoor population is shown in Figure 6.
For public buildings with low office density, construction pollution should also be considered. When the number of people in the room is 4, the fresh air volume $V = 144 \text{m}^3 \cdot \text{h}^{-1}$, the ventilation rate $n \approx 2 \text{h}^{-1}$ can be obtained. With the increase of fresh air volume, the air change frequency will increase, which can meet the requirements of indoor sanitation. The relationship between the required fresh air volume per unit area and the density of indoor personnel is obtained by fitting the data in Figure 6:

$$y = 5.980 \times 10^{0.343x} - 3.999$$

In the formula: $y$—Fresh air volume fresh air volume per unit area, $\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$; $x$—Indoor personnel density, $\text{p} \cdot \text{m}^{-2}$. As shown in Figure 7, the fitting degree between the simulated value and the function relation (6) is very good, and the correlation coefficient is $R^2 = 0.996$.

This function relation can provide the basis for the determination of fresh air volume in engineering design. At the same time, for the room with fixed air outlet, in order to avoid the uncomfortable air blowing feeling caused by adjusting the fresh air volume, the air outlet size should be arranged according to the actual situation in the design.

6. Conclusions
(1) Reasonable air conditioning and ventilation system can make the indoor working area meet the requirements of comfortable and healthy environment and obtain higher air quality. At the same time, increasing fresh air volume can improve indoor ventilation efficiency and reduce CO$_2$ concentration.

(2) When operating with the minimum fresh air volume which meets the CO$_2$ concentration standard of 700ppm at breathing area, it can not only meet the comfortable and healthy requirements of the working area, but also realize the energy saving operation. This paper presents a functional relationship between the minimum fresh air volume and the density of indoor personnel: $y = 5.980 \exp(x/0.343) - 3.999$, it can be seen that with the increase of personnel density, the required minimum fresh air volume increases.
exponentially. In engineering design, the fresh air volume can be determined according to the functional relationship, and the fresh air volume can be adjusted in real time according to the personnel density during the operation, so as to realize comfortable and energy-saving operation.

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