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Study on the character of indoor air in house with displacement ventilation system

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Abstract

Applying the method of computational fluid dynamics, velocity and temperature fields of three-dimensional displacement ventilation system with double heat sources are numerically simulated. Comparisons of computational results with experimental data are made. The velocity and temperature distribution of indoor air in houses with displacement ventilation system with single and double heat sources were studied. Two different cases of heat source are analyzed and compared. The results show that there are three layers in vertical temperature fields of displacement ventilation system with single or double heat sources, and the vertical temperature distribution of single heat sources is different from that of double heat sources. Furthermore, under the condition of two heat sources, the displacement ventilation parameters can't be simply computed according to single heat sources inlet parameters, therefore the interaction between heat sources should be considered.

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Keywords: Indoor air quality; displacement ventilation; heat comfort; numerical simulation

1. Introduction

Today, reasonable and high efficiency ventilation is very important to energy conservation in building. With the gradual progress in human society, people more and more concern the quality of indoor air. Although the traditional mixing systems have poor ventilation efficiency and are less energy efficient, they still occupy a large portion of the market. When displacement ventilation (DV) was first introduced almost three decades ago, it seemed at the time to be a promising ventilation concept due to its high ventilation efficiency and stratification principle [1]-[5]. In practice, DV system is a complex system that many pollution sources dynamic exist simultaneously. In this mixed system, there exist interaction among pollution heat sources and limitation of thermodynamic concentration diffusion among different pollution air. So, it's greatly significant to engage in research of DV with multi heat sources. In this paper, distribution of velocity and temperature in displacement ventilation system are investigated by using computational fluid dynamics.

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2. Mathematical models

2.1Physics model

Three-dimensional physical model is built (3.0m ×3.0m × 3.0m) shown in figure. 1. A primary pollution heat source (0.4m×0.4m) is located at the bottom of room and an accessory heat source (0.1m×0.4m) located nearby. A return air outlet is installed near a ceiling in the opposite wall side. In this study, four representative dots (A, B, C, D) which distributed around heat source are selected to analyze the whole temperature distribution in room shown in figure.2.

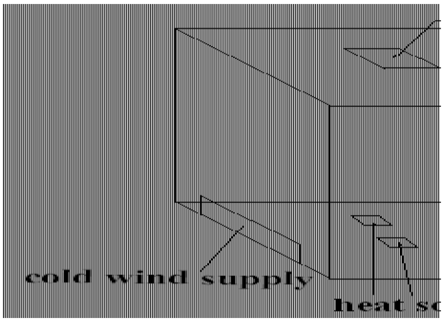


Figure 1. Model of simulated room

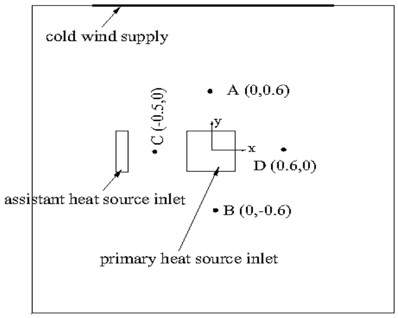


Figure 2. Distribution of four dots

2.2Mathematics model

The finite volume method is employed to solve the time-averaged Navier-Stokes equations with a collocated variable arrangement. The SIP solver is used to solve the set of algebraic equations. A conventional turbulent $k-\varepsilon$ model with wall functions is adopted. The semi-implicit method for pressure-linked equations (SIMPLE) is used to reach a convergent solution set. The CFD program is self-written in FORTRAN language. The calculated velocity and temperature fields are visualized by TECPLOT9.0. It is assumed that flow is steady, turbulent, Newtonian and incompressible with constant physical properties. The continuity, momentum, energy conservation and $k-\varepsilon$ equations are expressed as

$$\frac{\partial}{\partial x_j} u_j = 0 \tag{1}$$

$$\rho \frac{\partial}{\partial x_j} u_i u_j = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \mu (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) - \frac{\partial}{\partial x_j} \rho (u_i' u_j') + F_i \tag{2}$$

$$\rho C_P \frac{\partial}{\partial x_j} T u_j = \frac{\partial}{\partial x_j} (-k \frac{\partial T}{\partial x_j}) + \frac{\partial}{\partial x_j} \rho C_P (u_j' T') + \Phi \tag{3}$$

$$\rho \frac{\partial k}{\partial t} + \rho u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} [(\eta + \frac{\eta_t}{\sigma_k}) \frac{\partial k}{\partial x_j}] + \eta_t (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) \frac{\partial u_i}{\partial x_j} - \rho \varepsilon \tag{4}$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} [(\eta + \frac{\eta_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j}] + \frac{c_1 \varepsilon}{k} \eta_t (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) \frac{\partial u_i}{\partial x_j} - \frac{c_2 \rho \varepsilon^2}{k} \tag{5}$$

Where u_i, T, and p are the mean components, and u_j', T', and p' are fluctuation components of an instantaneous velocity, temperature and pressure respectively. $\rho(u_i' u_j')$, $\rho C_P (u_j' T')$ in Eqs.(2) and (3) represent additional stress(Reynolds stress) to a fluid element and additional heat flux due to turbulent phenomena. Φ is a mean dissipation term which is not considered in this study due to low velocity scale. F_i is the *i*th component of buoyant force due to temperature difference. Eqs. (4) and (5) is called the $k-\varepsilon$ model. In this model, the eddy viscosity is expressed as

$$\eta_t = c_\mu \rho k^2 / \varepsilon \tag{6}$$

In this study, the Boussinesq approximation is appropriate for the simulation. In region near the wall, no-slip boundary condition and the wall functions are used. The radiative heat transfer of wall is neglected. The wall is adiabatic. Because of the effect of natural convection, a kind of rising thermal current with certain speed will be formed above the solid heat source. We approximately apply the hot air-supply opening to replace the solid heat source in real project, and use to simulate the hot rising stream above the solid heat sources [6]. The approximation may result in certain difference between the simulation and the real project, but this kind of simplification won't have great influence on the study of the characteristics of DV systems.

3. Model verification

The model is verified by experimental data [4]. Fig.1 shows the experimental room (1.8m×1.2m×1.5m) has two heat pollution heat sources (S=0.4m). Supply air enters from a wall-mounted, low-velocity diffuser with velocity of 0.11m/s and temperature of 24.1℃. The temperature of heat sources is 48.5℃. Fig.3 shows the trend of temperature change of dot A along the height (0.125m-1.125m) of the room. It is observed that simulation results are almost consistent with experimental data. The maximum relative error is 2%, which proves that the mathematical model built in this paper is right and the hypothesis is reasonable.

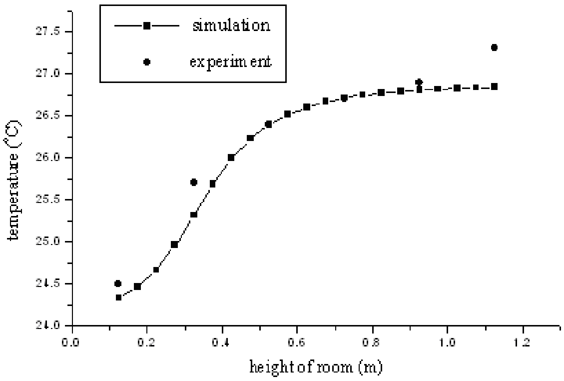
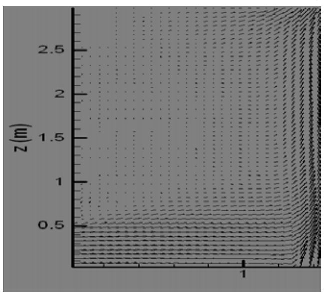


Figure 3. Comparison of experiment and simulation

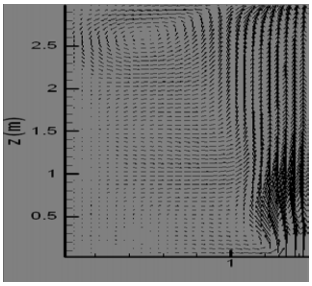
4. Results and discussion

4.1Single heat source

The assistant heat source is turned off and the whole heat flux is kept to be consistent. In the DV with single heat source, the size of the heat source inlet is 0.4 m×0.4 m. Entering air's temperature is 40℃ and speed is 0.35m/s. Supply air enters with a velocity of 0.2m/s and a temperature of 21℃. Mass flux of single heat source is the same as that with double heat sources. From the Fig.4, we can make out some characteristics of displacement ventilation flow field. The whole air indoors flows at low speed and the whole velocity field is almost calm except for the strong updraft above the heat source. That is to say, there is no strong air flow but nearly laminar flow in the personnel workaround. Furthermore, the updraft above the heat source is oblique as a result of influence of the supply air speed.



(a) y-z section



(b) x-z section

Figure.4 Velocity distribution of single heat source DV

4.2Double heat source

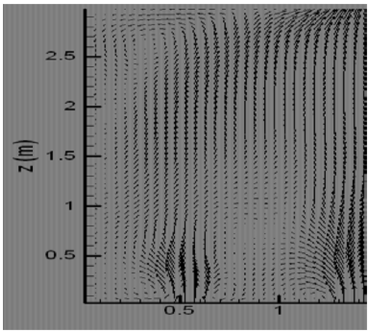


Figure.5 Velocity distribution of double heat sources DV

The air inlet speed at main heat source inlet is 0.28m/s and at the assistant heat source inlet is 0.35m/s. Other parameters are the same as that of the single heat source displacement ventilation system. Fig.5 displays that the velocity distribution of the double heat sources displacement ventilation on the central section (x-z). Due to the updraft from the heat source, two small eddies come into being between and near two heat sources. In the upside area between two heat sources, more updraft is produced because of simultaneously absorbing air of two heat sources, which result in the temperature of this area is lower than that of other areas.

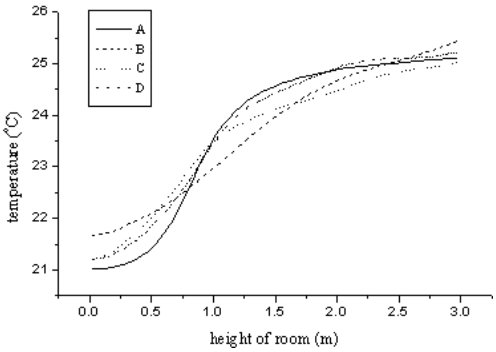


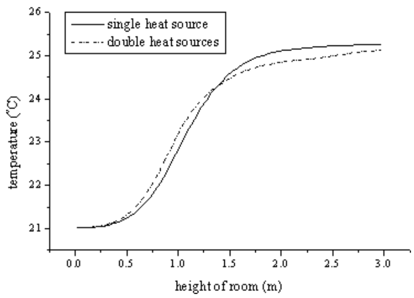
Figure.6 Vertical temperature distribution at four points

From the Fig.6 we can see that double heat sources have a great impact on the distribution of vertical temperature. The upside temperatures of point C located between two heat sources are lower than those of the other three points because more air is absorbed by point C due to the impacts of two heat sources.

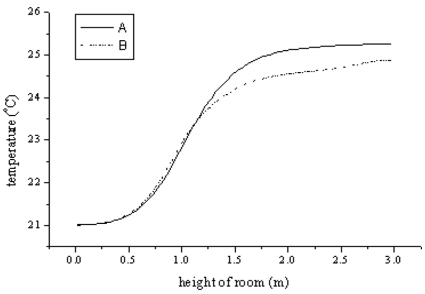
4.3Compare single heat source with double

Fig.7 (a) compares vertical temperature distributions of point A between double and single heat sources. Double heat sources absorb more air so that the upside temperature is lower than that of single heat source. At the same mass flux and temperature of supply air, the temperature of double heat source DV system is higher in the personnel workaround. This will result in augment of vertical temperature gradient between the heights from 0.1m to 1.1m. The vertical temperature gradient is decreasing with the increasing of supply air, which is nearly nothing with the temperature of supply air [6].

Fig.7 (b) shows that the line A denotes the changes of vertical temperature of single heat source, and line B denotes the one of double heat sources when speed of cold supply air is increased from 0.2m/s to 0.22m/s. It is should be mentioned that, between height from 0.1m to1.1m, the temperature gradient and temperature changes of the dispersed double heat sources are nearly the same as those of the centralized single heat source.



(a) Before change parameter



(b) After change parameter

Figure.7 Vertical temperature distribution comparison between single and double heat sources

5. Conclusions

When the distance between heat sources is long, people's requirement for comfort can be satisfied easily. Under the condition simulated in this paper, when the distance was more than 0.8m, the temperature distribution tend to be average and steady, and it will not change as the distance changing. At the same time, the thermal stratification characteristic exists in the temperature field indoors.

The temperature of the thermal current has great influence on the indoor temperature. The rising of the thermal current temperature makes the vertical temperature gradient in the room increase. The upper temperature of the room becomes higher, and also the height of the high temperate air level which lies in the upper part of the room rise.

Both the heat loss of surrounding structure and the change of outdoor temperature have great influence on the indoor temperature. But it will not influence the thermal stratification characteristic of displacement ventilation. Only one has changed is the thermal stratification height.

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