Comparative Study of Numerical Simulation of Indoor Thermal Environment in the Pattern of Personalized Ventilation and Stratum Ventilation

Taishun Liua, Zeqin Liuab,c,*, Ge Lia, Zhenjun Zuoa

*aKey Laboratory of Tianjin Refrigeration Technology, Tianjin, China
bEngineering Research Center of the Ministry of Education of Refrigeration Technology, Tianjin, China
cEngineering Center of Tianjin Refrigeration Technology, Tianjin University of Commerce, Tianjin, China

Abstract

The air distribution of air-conditioned room in the pattern of personalized ventilation and stratum ventilation was simulated respectively with the Fluent airpak numerical simulation software in this paper. And the indoor thermal environment of the two ventilation modes was comparative studied. The following conclusions could be obtained. Obvious draft sensation wouldn’t be produced, as long as the air velocity of the two ventilation modes was controlled in a certain range. The value of air velocity around body was met the ISO7730 regulations. The mean age of air of human breathing zone in the pattern of personalized ventilation was less than that in the pattern of stratum ventilation. However, the mean age of air in the plane of human breathing zone (y=1.1m) was less. The temperature difference between head and foot of personalized ventilation was less than that of stratum ventilation. In the pattern of personalized ventilation, the temperature distribution was better as well as thermal comfort.

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Keywords: Personalized ventilation; stratum ventilation; numerical simulation; mean age of air; thermal comfort

* Corresponding author. Tel.: +86-22-60170565; fax: +86-22-26675724.
E-mail address: liuzq@tjcu.edu.cn
1. Introduction

Nowadays, the energy consumption problem has attracted extensive attention. How to realize the energy saving purpose is the social focus. As the large energy consumer in the construction industry, refrigeration and air conditioning industry is facing greater pressure. In order to realize the purpose of energy saving and still guarantee the thermal comfort of air conditioned room, all kinds of new type of air conditioning modes gradually appear, which include personalized ventilation mode and stratum ventilation mode[1]. The pattern of personalized ventilation is designed to provide improved air quality and better thermal comfort, which also is designed to realize personalized control in each occupied zone. In the pattern of stratum ventilation, the fresh air is transported through the air inlets that are at 1.2m from the ground to the occupied zone [2]. In the two patterns of ventilation, energy saving is achieved by increasing the supply air temperature and reducing the scope of environment control zone. And better air quality of the human breathing zone is ensured because the air inlets of the two ventilation modes are closed to the human breathing zone. Personalized ventilation was proposed by Fanger to provide people with better air quality [3]. Michal Veselý reached the conclusion that personalized ventilation had good energy saving effect through collection and study [4]. Stratum ventilation was proposed by Lin [5]. By means of a series of study on stratum ventilation, he concluded that the energy saving effect could be ensured as well as the thermal comfort and air quality in the pattern of stratum ventilation [6]. Yin investigated the indoor environment of stratum ventilation mode of an office in Lanzhou and compared the indoor environment with that of hybrid ventilation and displacement ventilation. He concluded that the stratum ventilation had better thermal comfort and energy saving effect than the hybrid ventilation and displacement ventilation [7]. Then he also studied the influence of the different position of air outlet on the indoor pollutant distribution in the pattern of stratum ventilation by numerical simulation. The results were showed that better pollutant discharge effect and higher ventilation efficiency could be obtained when the air outlet was arranged in the upper room [8]. The above two kinds of ventilation modes has been lucubrated and promoted in practical application because of the better air quality and energy saving effect. However, the study on the comparison of the two ventilation modes was difficult to find. In this paper, the indoor thermal environment of air conditioned room of personalized ventilation mode and stratum ventilation mode was respectively studied by means of computational fluid dynamics (CFD) numerical simulation. The air distribution of the two ventilation modes was explored; the thermal environment, mean age of air and thermal comfort were calculated. Then the results were comparatively analyzed.

The technique of CFD numerical simulation was applied in the air conditioning research field firstly by Nielsen in 1970 and was proved to be basically reliable [9]. In recent years, the CFD technology has been widely applied in the field of simulating the indoor thermal environment [10]. The Fluent airpak software used in this paper is one of CFD simulation software oriented to the field of heating ventilation air conditioning (HVAC). The software can accurately simulate the physical phenomena such as heat transfer, air flow and pollution in the research object, which has the characteristics that include fast modeling, automatic meshing, unstructured grid technique, variety of models, powerful calculating function, visualization post-processing and design performance evaluation [11].

2. Model

The geometric model of the room in this study was in accordance with the air conditioned office in our school, of which the size was 8.1 m (length) × 4.8 m (width) × 3 m (height). The arrangement of indoor body, equipments and lights were referred to the arrangement in the office. And the design of indoor design parameters was referred to Air Conditioning Engineering[12]. The wall of the model room was assumed to be adiabatic. In the room, there were eight people the sitting height of which was 1.2m. And the heat dissipating capacity of each people was 100W. There were eight computers the power of which was 200W and four fluorescent lights the power of which was 75W. The total cooling load of the room was 2700W; and the indoor design temperature was set to 27°C. The personalized air inlets were arranged at 1.45m from the ground, of which the size was 200 mm × 100 mm. The temperature of supply air was 22°C and the velocity was 0.417 m/s. Upper supply top return ventilation was set to the background ventilation mode. The size of air inlets was 200 mm × 200 mm. The temperature of supply air was 19°C and the velocity was 2.91 m/s. The size of air outlet was 1000 mm × 500 mm. The air inlets of stratum ventilation were arranged at 1.2m from the ground, of which the size was 600 mm × 300 mm. The temperature of supply air was 20°C
and the velocity was 0.44 m/s. The air outlet was arranged at the top of the room, of which the size was 1000 mm × 500 mm. The room models of the two ventilation modes were shown in figure 1.

In this study, Fluent Airpak simulation software was adopted to simulate the air distribution of the air conditioned room, which used the Fluent solver to calculate. In the process of solving, the indoor air was assumed to be ideal gas. The thermal radiation between the heated source and the surrounding environment was considered. RNG k-ε turbulence model was set as flow model, which was similar to the standard k-ε model but more accurate. The impact of low Reynolds number was also considered in this model [13]. Predicted mean vote (PMV) was used to evaluate the thermal comfort. Fanger put forward PMV and worked out the regression formula of the relationship between human thermal sensation and human heat load [14].

3. Analysis of simulated results

The thermal environment of the air conditioned room in the pattern of personalized ventilation and stratum ventilation was numerically simulated respectively. The velocity distribution, the distribution of mean age of air, the temperature distribution and PMV of the two ventilation modes were compared and analyzed.

The velocity vector field of inlet section of the room model in the two patterns of ventilation is shown in figure 2(a) and figure 2(b). With personalized ventilation mode, the fresh air flows to the human breathing zone directly at a lower velocity. The supply air velocity decreases along the jet direction gradually and reduces to 0.16 m/s when closing to the body. With stratum ventilation mode, the fresh air also flows to the human breathing zone at a lower
velocity. The supply air velocity decreases gradually. Part of the air flows to the ground; part bypasses the body at side of the room and flows to the body in the middle of the room. The air velocity around the body is all less than 0.16 m/s. The air velocity of the occupied zone of the two ventilation modes is met ISO7730 regulations [15]. It can be seen that obvious draft sensation won’t be produced as long as the air velocity of the two ventilation modes is controlled in a certain range.

Figure 3(a) and figure 3(b) show the distribution of mean age of air in the plane of human breathing zone (y=1.1m) of the two ventilation modes. Age of air represents the time that air flow into the room and can reflect the freshness of indoor air [16]. The less the age of air is, the better pollutant discharge effect is and the better air quality is. In the pattern of personalized ventilation, the mean age of air in the plane of human breathing zone (y=1.1m) is 602s. However, the mean age of air of human breathing zone (y=1.1, the range is 0–0.1m from the human face) is little, which is in the range of 300s to 400s. This is because the fresh air flowed to human breathing zone directly through the personalized supply air inlets, but the supply air volume is limited and the plane of human breathing zone is far from the background supply air inlets. So the mean age of air in the plane of human breathing zone is high relatively. In the pattern of stratum ventilation, the mean age of air in the plane of human breathing zone is 537s. The mean age of air of human breathing zone is about 500s. This is because the supply air inlets of stratum ventilation mode are arranged at the height of human breathing zone, so more fresh air can flow to human breathing zone faster. It can be seen, the mean age of air of human breathing zone of personalized ventilation mode is less than that of stratum ventilation zone, but the mean age of air in the plane of human breathing zone of stratum ventilation mode is less.

It can be seen from the simulation results of indoor temperature field shown in figure 4(a) and figure 4(b) that temperature stratification phenomenon is generated in the two patterns of ventilation. The temperature of the upper part of the room is in the range of 26°C to 27°C; the temperature of the lower part of the room is in the range of 24°C to 26°C. The reason is that the position of air inlets of the two ventilation modes is relatively low. And the scope of environment control zone is reduced just to ensure the thermal environment of the occupied zone (y=0–1.2m), which provides the possibility for energy saving. The data of temperature and PMV around the body of the two ventilation modes are displayed in figure 5. Due to the thermal layer that is on the surface of the body, the value point is set to 0.05 m from the body. The data points were got respectively from the surroundings of the body at the side of the room(x=5.3, z=3.75) and the surroundings of the body in the middle of the room (x=5.3, z=3.75). In the pattern of personalized ventilation, the range of temperature variation around the body is at 25°C to 26.05°C. And the temperature distribution is relatively uniform. The PMV of the occupied zone is in the range of 0.1 to 0.5, so the thermal comfort is comfortable. In the pattern of stratum ventilation, the temperature difference between head and foot of the body at the side of the room is about 2°C, because the cold air went down so that the temperature of the lower part of body is less than that of the upper part of body. The temperature difference between head and foot of the body in the middle of the room is about 1°C. The PMV of the occupied zone of the body at the side of the room is increased with increasing of the height. There is slight cool feeling in the lower part. The PMV of the occupied zone of the body in the middle of the room is also increased with increasing of the height. The range of the PMV is

![Fig. 4 (a) the temperature distribution of personalized ventilation (Unit: K, x=1.3m)](image)

![Fig. 4 (b) the temperature distribution of stratum ventilation (Unit: K, x=1.3m)](image)
at -0.2 to 0.4. It can be seen that the temperature difference between head and foot of personalized ventilation is less than that of stratum ventilation. And the uniformity of temperature distribution in the occupied zone is better. Therefore, the more comfortable indoor thermal environment is provided by the pattern of personalized ventilation.

![Graph showing temperature and PMV distribution](image)

**Fig. 5.** The temperature and PMV of different height of the two ventilation modes

4. **Experimental verification of the numerical models**

![Diagram showing experimental setup](image)

![Diagram showing point heated sources and temperature measuring points](image)

Fig. 6. The arrangement of the table of stratum ventilation mode

Fig. 7. The arrangement of point heated sources and temperature measuring points

Restricted by the office, the artificial environment comprehensive experimental table was used to verify the correctness of the numerical model in this study. The arrangement of the artificial environment comprehensive experimental test was shown in figure 7. And the position of point heated sources and temperature measuring points of room was shown in figure 8. The temperature measuring point was decorated every 0.2m at the height of 0 to 2m in the vertical direction. The Yokogawa MX100 data acquisition and T-type thermocouple were used to record data. When the temperature of the table reached a steady state, the temperature of each point was collected every 5s and the average temperature of three minutes was calculated.
According to the arrangement of the table, Fluent airpak was adopted to build model with the above numerical model as shown in figure 8. The temperature distribution of measuring points in vertical direction was simulated and compared with the experimental temperature distribution. The results of comparison were shown as figure 9. It can be seen in figure 9 that there is a certain deviation between the simulated data and the experimental data, but all of the deviations are less than 0.7 °C. It is a relatively small value. Moreover, the change tendency of the simulated data and the experimental data is identical basically. With the increase of height, temperature also increases. Therefore, the above numerical model is feasible.

5. Conclusion

The air distribution of air-conditioned room in the pattern of personalized ventilation and stratum ventilation was simulated respectively with the Fluent airpak numerical simulation software in this paper. The indoor thermal environment of the two ventilation modes was explored; and the results of simulation were comparative studied. The following conclusions could be obtained.

As long as the air velocity of the two ventilation modes was controlled in a certain range, obvious draft sensation wouldn’t be produced. The value of air velocity around body was met the ISO7730 regulations.

The mean age of air of human breathing zone in the pattern of personalized ventilation was less than that in the pattern of stratum ventilation. However, the mean age of air in the plane of human breathing zone (y=1.1m) was less.

The temperature difference between head and foot of personalized ventilation was less than that of stratum ventilation. In the pattern of personalized ventilation, the uniformity of temperature distribution was better as well as thermal comfort.

In conclusion, the indoor thermal environment of such office layout is better in the pattern of personalized ventilation.

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References

[1] N.P. Gao, J.L. Niu, CFD study on micro-environment around human body and personalized ventilation. Building and Environment. 39 (2004) 795-805.
[2] Z.J. Zuo, The indoor thermal environment influenced by stratum ventilation temperature and supply air angle in a typical office, Tianjin University of Commerce, Tianjin, China, 2014.
[3] P.O. Fanger, X.M. Yu, IAQ in the 21st century: search for excellence, HV&AC. 30 (2000) 32-35.
[4] M. Veselý, W. Zeiler, Personalized conditioning and its impact on thermal comfort and energy performance - A review, Renewable and Sustainable Energy Reviews. 34 (2014) 401-408.
[5] Z. Lin, T.T. Chow, C.F. Tsang, Stratum ventilation - a conceptual introduction. In: 10th International Conference on Indoor Air Quality and Climate, Beijing, China, September, 2005, 3260-3264.
[6] Z. Lin, T.T. Chow, C.F. Tsang, L.S. Chan, Stratum ventilation – a potential solution to elevated indoor temperature, Building and Environment. 44 (2009) 2256-2269.
[7] J.F. Yin, Numerical study of office environment under stratum ventilation in Lanzhou, Lanzhou University of Technology, Lanzhou, Gansu, China, 2012.
[8] J.F. Yin, Numerical simulation and analysis of indoor contaminant distribution on four ventilation patterns under stratum ventilation, Refrigeration and air conditioning. 26 (2012) 600-604.
[9] P.V. Nielsen, Flow in air conditioned rooms (English Translation). Technical University of Denmark, Copenhagen, Denmark, 1976.
[10] Zeqin Liu, Ge Li, Chenxiao Zheng, The simulation and calculation of indoor thermal environment and the PPD evaluation index affected by three typical air-conditioning supply modes, HVAC&R Research. 20 (2014) 344-350.
[11] J.S. Wang, The analysis and research on the influence of human thermal comfort in the desktop air supplying system, Hunan University, Changsha, Hunan, China.
[12] X. Huang, Air conditioning engineering. Beijing, China: China Machine Press, 2009.
[13] M.L. Zhang, Three-dimensional simulation of meandering river based on 3-D RNG k-ε turbulence model. Journal of Hydrodynamics. 20 (2008) 448-455.
[14] P.O. Fanger, Thermal comfort. Copenhagen: Danish Technical Press, 1970.
[15] B.W. Olesen, K.C. Parsons, Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730, Energy and Buildings, 34 (2002) 537-548.
[16] X.T. Li, X. Wang, X.F. Li, Y.X. Zhu, Investigation on air age in a ventilated room with tracer gas technique, HV&AC.31 (2001) 79-81.