

The destructive time of temperature stratification during human movement and the recovery time after the human movement in the displacement ventilation system

Lu Feng¹, Ruibin Li¹, Yi Zhao¹ and Naiping Gao^{1*}

¹School of Mechanical Engineering, Tongji University, Shanghai 201804, China

Abstract. Many factors such as human movement can weaken indoor temperature stratification and lead to the advantages of the displacement ventilation (DV) disappearing. Yet the investigation for the stratified destructive time during the human movement and the recovery time after human movement stops are still meagre so far. The concepts of dynamic steady-state and static steady-state are proposed to compute the stratified destructive time (T_b). The isothermal surface of 295K is engaged to explain the variation of T_b . At last, the stratified restoring time (T_c) after human movement stops are inquiries in our paper. The conclusion is as follows: Firstly, the value of T_b reaches a maximum value at the moving velocity of 1m/s, since the isothermal surface of 295K starts to be broken when the moving human velocity reaches 1.0m/s. However, the values of T_b remains about 50s for the human moving velocities between 2.4m/s to 4.0m/s. The reason is that the temperature stratification are disappear completely when the human moving velocity exceeds 2.4m/s. Finally, The T_c keeps in the 250s when the human moving velocity is between 1.2m/s to 2.0m/s. The current study provides new insights into the design of the DV system.

1 Introduction

Displacement ventilation (DV) is more effective than mixing ventilation owing to the temperature stratification. Designing indoor ventilation strategies in the planning phase would be more efficient than retrofitting existing systems based on user feedback. Whereas, the existed DV system is designed on the premise of stable temperature stratification[1-3]. However, many perturbed factors which contain human movement can weaken the temperature profile and lower indoor ventilated efficiency in the DV system, even destroying the desired effect of the designer[4]. While human movements have not yet been incorporated into indoor ventilation designing strategies, they have long been recognized for their substantial impact on temperature stratification. Moving humans weaken the temperature stratification and increase the temperature in the lower part of the room[5, 6]. The indoor air velocity raises and the temperature becomes more uniform when the heating power of the moving human increasd[7, 8]. The heating human lowers and oscillates the interface between lighter and heavier fluid[4]. The prolonged movement without intervals causes a more significant effect than that with intervals[9]. The displacement ventilation system needs more time to recover to the initial state after human movement than mixing and stratum ventilation systems[10]. Our previous paper investigates the importance of different factors of human movement on the influence of temperature stratification by orthogonal design experiments [11]. Although the temperature variation in the displacement ventilation system during

human movement was studied in the literature, the recovery process of temperature stratification and the relationship between temperature stratification and prolonged movement still need more inquiry.

The prolonged human movement is inevitable in the application of the DV system. According to our preliminary experiment, mean temperature fluctuations caused by long-term movement can reach 3K[11]. Such fluctuations deserve attention given that the general temperature difference between head and foot height in the DV system is 1.5-3.5K, and the recommended temperature difference is below 3K[3]. The prolonged movement can neutralize the advantages of the DV which made it forfeit the designed original intention. Likewise, the investigation of the temperature stratified recovery process after human movement is urgent.

The prolonged human movement and temperature stratified recovery process are surveyed in our paper by the CFD method. Firstly, the concepts of dynamic steady-state and static steady-state are proposed to calculate the stratified destructive time (T_b). On top of that, the isothermal surface is adopted to explain the variation of T_b . At last, the stratified restoring time (T_c) are surveyed. The discoveries quantify the repercussion of prolonged movement in the DV and clarify the relationship between the recovery time and human movement.

2 Methodology

Corresponding author: gaonaiping@tongji.edu.cn

2.1 Boundary conditions

The size of the DV room is 4m (W) × 4m (D) × 2.7m (H). The layout of the room is shown in Fig.1. There are five heating sources in the room. They are two computers (80W each), two sitting humans (77.6W each) and a moving human (100W). The heating sources distribute in the room symmetrically. The computers with the size of 0.4m (W) × 0.35m (H) × 0.4m (L) are placed on two desks. The desks are not heated. Two sitting humans with a dimension of 0.35m (W) × 1.2m (H) × 0.35m (L) face the computers. The track of the moving human with a length of 3.4m is located in the middle line of the room. The moving human is located on a side of the moving track.

The inlet and the outlet are on the same wall of the DV. The inlet's velocity and temperature are 0.2m/s and 291K. The dimension of the inlet and outlet is 0.5m (W) × 0.6m (H) and 0.3m (W) × 0.1m (H), respectively. There are eight measuring lines distributed in the DV. Each measuring line has 13 measuring points with a 0.2 m interval. The distance between the adjacent lines is 1m. The measuring lines locate far away from the heating sources because the heating source can disturb the measuring data of temperature stratification. The numerical models are the same as those applied in Wu's paper[12].

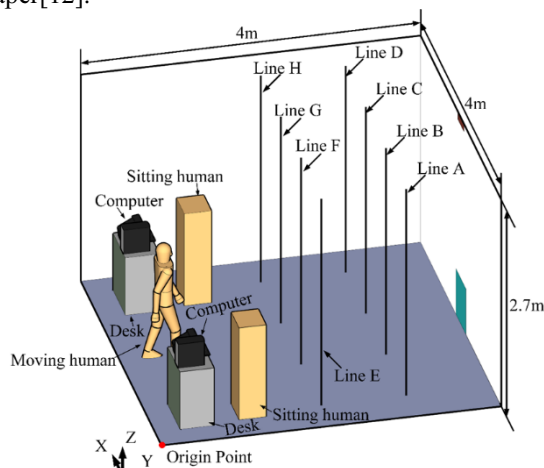


Fig. 1. The lay chamber.

2.2 Meshing

The dynamic mesh is employed in our study. The computational domain is divided into three parts which consist of one dynamic mesh zone in the middle and two static mesh zone on two sides[13]. The method of sliding mesh is engaged to transfer the energy and momentum in the interface between the dynamic and static mesh zone. Yet the coarse meshes with 0.4 million are used in our paper since the case with coarse meshes can save time spent compared with the medium meshes. The cases with coarse meshes need 10 days to compute. However, the cases with medium mesh need 100 days for the workstation with 64 Intel Xeon 2.9 GHz processors.

2.3 Experiment condition

Ten kinds of velocities with a 0.2m/s interval are conducted in our paper. The other boundary conditions of these experiments are all same. The single journey for the human movement on the track can be divided into three stages. Firstly, the human accelerates on the first 0.4m of the track. Subsequently, the human pass by the journey with a length of 2.6m in the middle of the track at a uniform speed. At last, the human decelerates in the latter 0.4m of the track. Then the moving human varies the moving direction and repeats the previous trips. Based on the preliminary experiment, the temperature stratification reaches a new steady-state during human movement when the human continues moving for 400s. In order to distinguish the stable state without human movement, the stable state during human movement is referred to as the dynamic steady-state. The temperature stratification is constant in the dynamic steady-state. The stable state without human movement is called the static steady-state. On top of that, the temperature stratification can be recovered to the initial state after the human movement stops for 300s. The moving human moves on the track for 500s and then rest for 400s in our study.

2.4 Evaluation indexes

Defining T_b as the stratified destructive time. It means the time that from the time of human movement starts to the time of temperature stratification reaches the dynamic steady-state. The equation of T_b is as follows:

$$T_b = T_1 - T_2 \quad (1)$$

Where T_1 is the time that human movement starts, s; T_2 represents the time that the temperature stratification reaches the dynamic steady-state, K.

Defining T_c as the stratified restoring time. It means the time that from the human movement stops to the temperature stratified recovery to the static steady-state. We obtain:

$$T_c = T_4 - T_3 \quad (1)$$

Where T_3 is the time that human movement stops, s; T_4 is the time that the temperature stratification recovery to the static steady-state, K.

3 Results

3.1 The stratified destructive time

Fig. 2 displays the stratified destructive time under different moving velocities. The stratified destructive time (T_b) means the time that from the time of human movement starts to the time of temperature stratification reaches the dynamic steady-state. The T_b is zero for the human moving velocities lower than 0.4m/s. It implies that the temperature stratification is not weakened in this range. Then, the T_b increases dramatically for the moving velocities between 0.6m/s to 1m/s. The value of T_b reaches a maximum value at the moving velocity of 1m/s. Soon, the T_b decreases significantly for the moving velocities from 1m/s to 2m/s. Later, the values of T_b remain the same level for the human moving

velocities in the range of 2.4-4.0m/s. The T_b is about 50s when the velocity exceeds 2.4m/s.

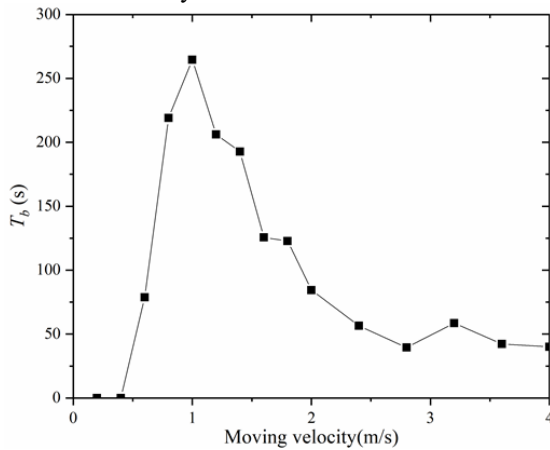


Fig. 2. The stratified destructive time (T_b) under different moving velocities

Indoor air temperature is close to 295K when the temperature stratification reaches the dynamic steady-state. The isothermal surface of 295K is chosen in our paper to study the influence of the moving human on temperature stratification. Fig. 3 reveals the isothermal surface of 295K when the temperature stratification reaches the dynamic steady-state under different moving velocities. Take Fig. 3 as an example to explain the phenomenon in Fig. 2. The human movement affects the local area of the stratified interface for the human moving velocities lower than 0.4m/s, the local area is mainly around the moving human. Temperature stratification is not weakened in this stage. Human movement can hardly affect indoor temperature stratification. Whereas, human movement with velocities between 0.6m/s to 1m/s can influence all the areas of the stratified interface. The stratified interface oscillates enormously with the velocity increase. The value of T_b increases in this stage. The stratified interface starts to be broken when the moving human velocity reaches 1.0m/s. Owing to the influence of the wake of the moving human, the stratified interface of 295K moves downward and mixes with ambient air when the human moving velocity is in the range of 1.2-2m/s. The air mixed hugely when the human moving velocity increases. The T_b decreases during this velocity period. The temperature stratification are disappear completely when the human moving velocity exceeds 2.4m/s. The fragmentized stratified interface is located in the lower part of the room. The protective effect of the inlet to the temperature stratification in the lower part of the room is disappeared. Fig. 4 verifies our opinions. The T_b maintain the same level in this stage. The effect of the DV is the same as the mixed ventilation system at this moment.

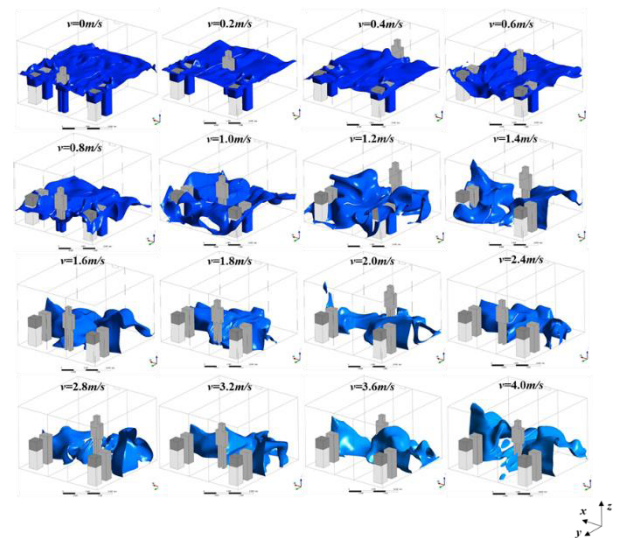


Fig. 3. The isothermal surface of 295K when the temperature stratification reaches the dynamic steady-state under different moving velocities.

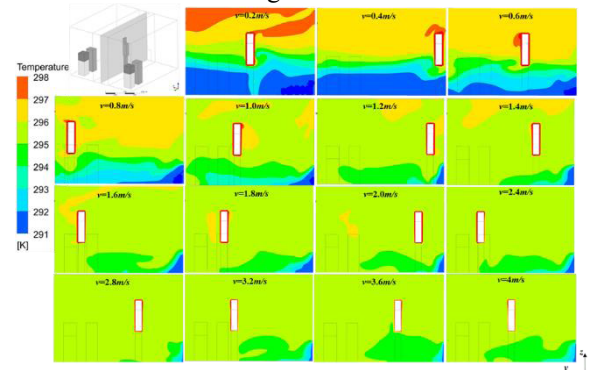


Fig. 4. The temperature stratification under different moving velocities

3.2 The recovery of temperature stratification

Fig. 5 (b) exhibits the stratified restoring time (T_c) under different moving velocities. It can be seen that the T_c is zero when the human moving velocity is lower than 0.4m/s. The T_c goes up in the range of 0.6-1.0m/s. The T_c of the cases when the human moving velocity between 1.2m/s to 2.0m/s keeps at the same level of 250s. The T_c slowly climbs when the human moving velocity exceeds 2.4m/s.

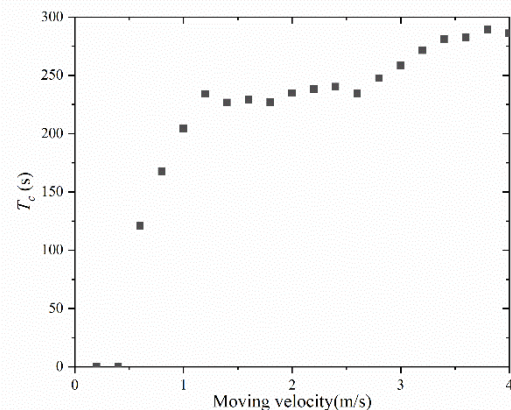


Fig. 5. The stratified restoring time under different moving velocities

4 Conclusions

Many factors can disturb the indoor temperature stratification which reduces the advantages of DV, such as human movement. So far, the investigation on the effects of human movement on temperature stratification is still deficient. Firstly, the concepts of dynamic steady-state and static steady-state are proposed to calculate the stratified destructive time (T_b). The dynamic steady-state and static steady-state means the stage that the temperature stratification keeps constant during and without human movement, respectively. In addition, the isothermal surface is adopted to explain the variation of T_b . Finally, The stratified restoring time (T_c) is investigated. The conclusions are as follows:

(1) The T_b value is zero for the human moving velocities lower than 0.4m/s. Then, it increases dramatically for the moving velocities between 0.6m/s to 1m/s. The value of T_b reaches a maximum value at the moving velocity of 1m/s. Soon, it sharply decreases when the moving velocities are from 1m/s to 2m/s. However, the values of T_b remains about 50s for the human moving velocities between 2.4m/s to 4.0m/s.

(2) The human movement affects the local area of the stratified interface when the human moving velocities are lower than 0.4m/s. Whereas, human movement with velocities between 0.6m/s to 1m/s can influence all the areas of the indoor stratified interface. The stratified interface starts to be broken when the moving human velocity reaches 1.0m/s. The temperature stratification are disappear completely when the human moving velocity exceeds 2.4m/s.

(3) The value of T_c is zero when the human moving velocity is lower than 0.4m/s, and then it rapidly goes up in the range of 0.6-1.0m/s. The T_c keeps in the 250s when the human moving velocity is between 1.2m/s to 2.0m/s. The T_c slowly climbs but is still lower than 300s when the human moving velocity exceeds 2.4m/s.

Conference on Healthy Buildings, Department of Building Technology and Structural Engineering, Aalborg University, Washington DC, USA, 1997, No. 70, Vol. R9728.

7. H. Matsumoto, Y. Ohba. J. Asian Arch. Build. Engineer. **3**, 1 (2004) 71-75.
8. Q. Zhang, H. Yuan, G. Zhang, T. Deng. J. Hunan Univ. **8** (2007) 002.
9. W. Wu, Z. Lin. Build. and Environ. **87** (2015) 142-153
10. W. Wu, Z. Lin. Build. and Environ. **85** (2015) 211-219.
11. L. Feng, F. Zeng, R. Li, R. Ju, N. Gao. Energy and Build. **234** (2021) 110700.
12. Y. Wu, N. Gao. Build. and Environ. **82** (2014) 63-74.
13. S.B. Poussou, S. Mazumdar, M.W. Plesniak, P.E. Sojka, Q. Chen. Atmospheric Environ. **44**, 24 (2010) 2830-2839.

References

1. E. Mundt. Build. Environ. **30**, 1 (1995) 129-133.
2. Y. Li, M. Sandberg, L. Fuchs. Indoor Air **2**, 4 (1992) 225-243.
3. X. Yuan, Q. Chen, L.R. Glicksman. ASHRAE Trans. **105** (1999) 353.
4. M. Sandberg, M. Mattsson. *The effect of moving heat sources upon the stratification in rooms ventilated by displacement ventilation*, in Proceedings of the 3rd International Conference on Air Distribution in Rooms, Aalborg, Denmark, 1992.
5. M. Mattsson, *On the efficiency of displacement ventilation, with particular reference to the influence of human physical activity*, Centre of Built Environment, Royal Institute of Technology, Gavle, Sweden, 1999, p. 62.
6. E. Bjørn, M. Mattsson, M. Sandberg, P.V. Nielsen. *Displacement ventilation: effects of movement and exhalation*, in Proceedings of the 5th International