The Influence of Human Activities on Pollutants Distribution in Waiting Rooms of Outpatients in Health Care Buildings

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Abstract. Unsteady CFD simulation with SST k-\(\varepsilon\) model and dynamic mesh was used to investigate the characteristics of human walking and how the human activities influence the pollutants distribution in outpatient waiting rooms of health care buildings in this study. The results show that apart from the differences of gender and age, the movement speed of personnel is also greatly influenced by the subjective factors, and the step size is obviously less affected by the subjective factors and greatly affected by physical health and body shape. Numerical simulation results show that when the fine mannequin is used, the wake produced by the forward movement of the leg is obviously smaller than the wake area after the body and arm. The pollutants are enabled to diffuse faster but without increasing the concentration because of swinging the hands and feet of the moving human body, the thermal plume of the body, and the faster moving persons. When moving the same distance, the concentration of contaminant caused by the wake behind the body changes the same.

1. Introduction

In the past few years, great changes have taken place in hospital construction in China. Based on the statistical data, we can find that the number of hospitals increased from 20,000 to 35,800 from 2012 to 2018. At the same time, there was also an obvious increasing of outpatient amount, which increased from 2 billion to 3.58 billion. As the space for medical services, the indoor air environment of hospitals is very important. It is beneficial to the treatment and rehabilitation of patients, otherwise, it is also helpful for improving the work efficiency of doctors and nurses. However, poor indoor environment in hospitals is universal due to the unreasonable ventilation. Human activities are always ignored in the researches of indoor air quality of hospitals. In recent years, a few scholars payed attentions to the influences of human activities on indoor environment. Wang, J. and Chow, T. (2011) investigated the influence of moving subjects on the dispersion and deposition of expiratory droplets in airborne infection isolation room by numerical simulation. Hang, J. \textit{et al.} (2014) studied the influence of human walking on the flow and airborne transmission in a six-bed isolation room by tracer gas simulation. Chow, T. and Wang, J. (2012) investigated the impact of surgeon bending movement on bacteria-carrying particles distribution in operating theatre by dynamic simulation. Wu, Y. and Gao, N. (2014) investigated the dynamic of the body motion induced wake flow and its effects on the contaminant dispersion. Tao, Y. \textit{et al.} (2017) investigated human-induced wake flow characteristics and its interaction with thermal conditions by performing CFD simulation with dynamic-meshing of a moving manikin model. Chen, M. \textit{et al.} (2020) investigated the effect of different model on human walking. However, the previous researches of effect of human moving on indoor air quality in hospital almost focused on operating theaters and isolation rooms. Few studies...
payed attention to the normal area such as waiting rooms, where crowds always gathered. In addition, characteristics of human walking in the outpatient waiting rooms is also not clear especially for patients.

This study researches human activities characteristics and the influence of human activities on pollutant distribution and diffusion in waiting rooms of outpatient department in a general hospital. It will finally help us to improve the indoor air quality of high personal density areas.

2. Materials and Methods

2.1 Field Measurement
Measurement of the characteristics of human waking was performed in the waiting rooms of outpatient of a general hospital in Wuhan, Hubei Province. The observer recorded the time $t$ and steps $n$ of 100 persons who walking from the starting point to the end point, as shown in figure 1. Characteristics of human walking in the outpatient waiting rooms could be calculated by Eq. 1. where $\lambda$ is step size, $s$ represents the distance, $n$ is step number, $f$ is stride frequency, $t$ is the time of walking and $v$ is the walking speed.

$$\lambda = \frac{s}{n} \quad f = \frac{n}{t} \quad v = \frac{s}{t}$$

Testo 535 measuring instrument was used to test the concentration of Carbon dioxide (CO$_2$) which was considered as pollutant of the waiting rooms.

![Figure 1](image1.png)

**Figure 1.** Setup of the measurement of human walking characteristics

2.2 Numerical Model
In order to investigate the air flow disturbance and CO$_2$ distribution induced by human moving in the waiting rooms of outpatient in a general hospital in Wuhan, a numerical model was established. The size of the simulated waiting rooms is 8m long (x), 6m wide (y) and 3m tall (z). Four air diffusers were mounted in the ceiling with the size of 0.25m (long) × 0.25m (wide). The air supply velocity is 2m/s. The layout of seats is shown in Figure 2.
Sitting human model and walking human model was established respectively. For the walking model, one is a nearly realistic human body walking including the moving forward torso with periodically varying speed and periodic motion of swinging legs and arms, another is a simplified cylinder. The height of all the models are 1.68m. The length of arms is 0.65m and the length of legs is 0.90m.

The whole zone was divided into three parts. In the central region, dynamic grids were adopted to demonstrate the walking body. In the left and right region, the grid was static. The physical model was built by using GAMBIT program. The schematic layout of the model is shown in Figure 1. Numerical analysis was conducted by FLUENT software with the dynamic grid. The mesh structure is shown in Figure 2.

2.3 Governing Equation and Boundary Condition
ANSYS Fluent was utilized to simulate the indoor airflows in waiting rooms of a general hospitals with human walking. SST k-ε model was utilized in this simulation. In order to consider the influence of the buoyance effect, the Boussinesq model was adopted. The integral form of the conservation equation for a general scalar, on an arbitrary control volume V with moving boundary could be written as (Hang, J. et al. 2014).

$$\frac{d}{dt} \int_{V} \rho \Phi dxdydz + \int_{\partial V} \rho \Phi (\vec{u} - \vec{u}_{g}) \cdot d\vec{A} = \int_{\partial V} \Gamma \nabla \Phi \cdot d\vec{A} + \int_{V} S_{\Phi} dxdydz$$  \hspace{1cm} (2)

Where $\rho$ represents the fluid density, $\vec{u}$ is the fluid velocity vector, $\vec{u}_{g}$ represents the grid velocity of the moving mesh, $S_{\Phi}$ is the source term, $\Gamma$ refers to the diffusion coefficient, $\partial V$ is the boundary of the control volume and $\nabla \Phi$ is the divergence of $\Phi$.

Boundary conditions were defined as Table 1. SST k-ε model was used in this study. The second-order upwind scheme was used for discretizing the convection and diffusion-convection terms in the governing equation. If the residuals for contaminant concentration and velocity were $1 \times 10^{-6}$ and $1 \times 10^{-4}$, the results of the simulation were assumed to be convergent.
Table 1. Boundary condition

| Item                        | Value                                      |
|-----------------------------|--------------------------------------------|
| Temperature of waiting rooms| Supply air: 23°C                           |
|                             | Wall: 18°C                                 |
|                             | Height: 1.68m                              |
|                             | Arm Length: 0.65m                          |
|                             | Leg Length: 0.90m                          |
|                             | Breathing area: 580×10⁶ m²                |
|                             | Breathing speed: 0.15 m/s                  |
| Human body                  | Swinging arm amplitude: 0.43 m             |
|                             | Shell temperature: 24°C                   |
|                             | Exhale temperature: 31°C                  |
| CO₂ concentration           | Supply air concentration: 450 ppm          |
|                             | Initial concentration: 450 ppm             |
|                             | Human exhaled concentration: 3000 ppm      |

2.4 Numerical Simulation Conditions
The detailed numerical simulation cases are listed in Table 2. In order to examine the influence of different human moving model and human thermal plume in different ventilation modes and layout of waiting rooms, orthogonal cases were studied.

Table 2. The list of numerical simulation cases

| No. | Ventilation modes | Human model                                      |
|-----|-------------------|--------------------------------------------------|
| 1   | All-air CAC       | Simple model, no moving                          |
| 2   | All-air CAC       | Simple model, normal velocity                    |
| 3   | All-air CAC       | Simple model, normal velocity                    |
| 4   | FCU               | Simple model, normal velocity                    |
| 5   | VRV               | Simple model, normal velocity                    |
| 6   | All-air CAC       | Simple model, normal velocity, Face to face      |
| 7   | All-air CAC       | Detailed model, normal velocity                  |
| 8   | All-air CAC       | Detailed model, high velocity                    |
| 9   | All-air CAC       | Simple model, fluctuation velocity               |
| 10  | All-air CAC       | Simple model, human surface heat flux            |

2.5 Model Validation
The validation case was simulated base exclusively on the measurements. CO₂ concentration variation with the height of waiting rooms in the general hospital by on-site measurement and numerical simulation are shown in Figure 3. As shown in Figure 3a), the values are different, the variation tendency agrees well, but there is a gap, because there was only one person exhales CO₂ in the simulation case but more persons in the field measurement. As shown in Figure 3b), the simulation results agree well with the measured results when we adjusted the persons number.
3. Results and Discussion

3.1 Characteristics of Human Walking in Outpatient Waiting Rooms

Figure 4a) shows the number of people in different walking velocity. It indicates that 71.0% of the samples walked with a velocity of 1-1.2m/s. Figure 4b) shows the number of people in different step size. It indicates that 80.0% of the samples walked with a step size of 0.55-0.67m. Table 3 shows the characteristics of human walking in the outpatient waiting rooms based on the on-site measurement of 100 persons. It suggests that there are obvious differences of step number n, step size λ, stride frequency f and walking velocity v in males and females, as well as in different ages.

![Figure 4](image)

**Table 3.** Characteristics of human walking in the outpatient waiting rooms

| Items         | Age         | n  | t(s) | λ (m/step) | f (step/s) | v(m/s) |
|---------------|-------------|----|------|------------|------------|--------|
| Ave<sub>total</sub> | 36.7        | 10 | 5.20 | 0.61       | 1.94       | 1.19   |
| Ave<sub>male</sub>  | 38.2        | 9.6| 5.32 | 0.63       | 1.84       | 1.17   |
| Ave<sub>female</sub> | 35.5        | 10.2| 5.11 | 0.59       | 2.03       | 1.21   |
| Ave 10-20 years old | 10.0        | 11.5| 5.80 | 0.52       | 1.98       | 1.03   |
| Ave 21-30 years old | 28.0        | 9.6 | 4.81 | 0.63       | 2.02       | 1.29   |
| Ave 31-40 years old | 37.7        | 9.8 | 5.16 | 0.62       | 1.93       | 1.19   |
| Ave 41-50 years old | 45.5        | 10.4| 5.51 | 0.59       | 1.92       | 1.12   |
| Ave 51+ years old  | 57.5        | 11.3| 6.73 | 0.54       | 1.67       | 0.90   |

Apart from the differences of gender and age, the movement speed of personnel is also greatly influenced by the subjective factors, and the step size is obviously less affected by the subjective factors and greatly affected by physical health and body shape.
3.2 Pollutants Distribution with Different Human Models

Figure 5 shows the CO$_2$ distribution in the outpatient waiting rooms with human moving. When the human moving into the contaminant zone, the front air pressure increases and enforces the air diffuse to the sides which will push the contaminant away. When the moving human walks far away the contaminant zone, wakes flow appears at the back of the body begin to entrain the contaminant.

Figure 6 shows CO$_2$ concentration distribution in the waiting rooms based on different human models when human is moving. Compared Figure 6 a) to 6 b), it can be found that without swinging arms and legs, pollutants are drawn into the wake flow and diffuse backward when human walking through the heavy pollution zone. At the same time, the new pollutant exhaled by another human in the left of the walking human diffuses to the front and the right with the wake flow. No increase when CO$_2$ concentration decreases. In the cases with swinging arms and legs, parts of pollutants diffuse to the right back at the beginning and the highest concentration appears at Z=1m. The pollutants change the direction to right front with the effect of wake flow from the beginning of the human moving. In this condition, another highest concentration appear at Z=2.5m.

![Figure 5. CO$_2$ concentration distribution with human walking](image)

![Figure 6. CO$_2$ concentration distribution in the waiting rooms with human moving](image)

3.3 Influences of Human Walking on Pollutants Distribution in Outpatient Waiting Rooms

CO$_2$ concentration distribution of the waiting rooms in the general hospital was affected by human moving velocity. Figure 7 shows the effect of different moving velocity ($\upsilon=0.1$–1m/s, $\upsilon=1.0$m/s, $\upsilon=1.5$m/s) on CO$_2$ concentration distribution. Results show that the faster the human walking, the faster the pollutant diffuse forward. However, no obvious difference in the peak of concentration and the diffusion range appears. The pollutants are enabled to diffuse faster but without increasing the concentration because of swinging the hands and feet of the moving human body and the faster moving persons. It also found that with the same distance moving, the concentration of contaminant caused by the wake behind the body changes the same.
Figure 7. CO$_2$ concentration distribution with different human moving velocities

3.4 Influences of Human Thermal Plume on Pollutants Distribution in Outpatient Waiting Rooms

As shown in Figure 8, because of the higher temperature, human exhaled air flow diffuses upward. Otherwise, the probability of the walk flow polluted by human exhaled is cut down. The phenomenon of pollutants diffusing forward with the walking is also not obvious. It indicates that the effects of human thermal plume on pollutants distribution should not be ignored especially in the high personal density areas.

![Figure 8](image)

a) model without human surface heat fluxes  
b) model with human surface heat fluxes

Figure 8. CO$_2$ concentration by human breathing with surface heat fluxes.

4. Conclusions

Based on the numerical simulation, conclusions can be drawn as the following.

1) Apart from the differences of gender and age, the movement speed of personnel is also greatly influenced by the subjective factors, and the step size is obviously less affected by the subjective factors and greatly affected by physical health and body shape.

2) When the fine mannequin is used, the wake produced by the forward movement of the leg is obviously smaller than the wake area after the body and arm.

3) The pollutants are enabled to diffuse faster but without increasing the concentration because of swinging the hands and feet of the moving human body, the thermal plume of the body, and the faster moving persons.

4) With the same distance moving, the concentration of contaminant caused by the wake behind the body changes the same.

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6. References

[1] Chen, M., Yin, Y.T., Zhang J.S., Zhou, C.H. (2020) The influence of human activities on air flow and pollutants distribution in the waiting area in a general hospital, Environmental Science and Engineering:491-505.
[2] Chow, T. and Wang, J. (2012) Dynamic simulation on impact of surgeon bending movement on bacteria-carrying particles distribution in operating theatre, Building and Environment, 57:68-80.

[3] Hang, J., Li, Y. and Liu, R. (2014) The influence of human walking on the flow and airborne transmission in a six-bed isolation room: Tracer gas simulation, Building and Environment, 77:119-134.

[4] Ronan, B., Branislav, U. and Daniel, T. (2004) Versatile walk engine, CH-1015 Lausanne Switzerland: Virtual Reality Laboratory, I&C, EPFL.

[5] Tao, Y., Inthavong, K. and J. Tu (2017). A numerical investigation of wind environment around a walking human body, Journal of Wind Engineering & Industrial Aerodynamics, 168:9-19.

[6] Wang, J. and Chow, T. (2011) Numerical investigation of influence of human walking on dispersion and deposition of expiratory droplets in airborne infection isolation room, Building and Environment 46, :1993-2002.

[7] Wu, Y. and Gao, N. (2014) The dynamics of the body motion induced wake flow and its effects on the contaminant dispersion, Building and Environment, 82:63-74.