Numerical study on the influence of human walking on contaminant transport indoors by using momentum theory method

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Abstract. Particle dispersion induced by human activities is important to human health especially in operation room and nursery. The application of dynamic mesh method in objects moving simulation has aroused considerable interests in recent years, which was not CPU-friendly. In this paper, we proposed a new momentum theory method for reducing calculation time. In this method, user defined function (UDF) was used for simulating interaction force between human body and air. RNG k-ε model was applied in turbulence simulation. In present paper, dynamic mesh method and momentum theory method were utilized to investigate the airflow flow field during human walking. The simulated air velocity results by these two methods agreed well. The influence of body walking on decay of particle concentration was also investigated. The results showed that decay rate decreased in presence of objects moving. The concentration of particle decreased to 10% in fifteen minutes in body walking process.

1. Introduction
People spend almost 90% of their times in indoor or other enclosed environment [1]. It is proved that the incidence of allergic diseases is associated with exposure to indoor allergens, such as pollen, dust, viruses, bacteria, fungi and so on [2]. Several studies show that people’s activities indoors (such as walking, cleaning, and using new furniture) can increase the particle mass concentration [1, 3-6]. It is recognized that walking is a major contributor to high pollutant concentration in indoor environments with human activities [4, 7]. Airflow generated by human body moving may cause high risk of bacterial transport from non-clean zones to patient’s wound [6]. Particle, as the carrier of bacteria, viruses and others, has significant influence on human health especially in enclosed environment, such as operation room, clean room and other places which need high cleanliness [5, 8]. Contaminant dispersion highly depends on airflow patterns [4]. Compared with particulate matter, gaseous pollutants mostly follow with air. Particulate matter may deviate from air streamline because its weight is different from gaseous pollutants [9]. Different ventilation systems cause different air flow fields [10, 11].

Measured data from controlled laboratory experiments are usually used to test the performance of numerical models. Zhang et al. studied airflow and contaminants transport in a cabin mockup by experimental measurements and numerical simulations [12]. Tao et al. conducted unsteady simulations of wakeflow induced by a moving manikin in a room [13]. Dynamic mesh method was used to study the effects of moving objects such as human moving and doors opening on indoor environment. The results showed good agreements with experimental [7, 14, 15]. The flow field and the pollutant field could be obtained at each time directly by dynamic mesh method. The dynamic mesh method needs to
update the grid in every time step, which spends too much calculation time. The momentum theory methods could save time by no-updating mesh compared with dynamic mesh methods. Brohus et al. found it is possible to simulate the influence of objects movements on airflow pattern using a relatively simple CFD model [8] (such as momentum theory methods), however the steady flow field was considered, in this paper, unsteady airflow field effected by human moving would be studied. The present studied the reliability of momentum theory method in moving manikin simulation. To verify reliability of numerical simulation, a small-scale chamber was built to measure airflow field and contaminants distribution. The decay of particle concentration affected by moving body in chamber was also studied in this paper. Otherwise, the simulated results by momentum theory method and Dynamic mesh method and experimental data were compared.

2. Methods
Measurements were conducted by using a small-scale chamber. Details of the chamber are provided in Fig. 1 and Table 1. The whole chamber consisted of two parts: a test chamber and a steady flow chamber. The geometry of test chamber was 1 m × 1 m × 1 m (width × length × height), while the steady flow chamber was 0.3 m × 0.3 m × 0.3 m (width × length × height). The rotating motor could drive human body model to move back or forth. A simplified human body simulator was designed to obtain better understanding of flow and contaminant transmission phenomena affected by moving body. The air velocity meter (VELOCITYCALC TSI 9515) was used to measure air velocities. In this chamber model, particle number concentration was measured by the particle counter (P-TRAK ULTRAFINE model 8525). The measured particle size range was from 0.02 μm to 1 μm. Experiments were carried out by testing the three cases with different ventilation velocities (case 1: 0.3 m/s, case 2: 0.4 m/s, and case 3: 0.5 m/s). The moving speed of human body was set to 0 m/s, 0.1 m/s, and 0.2 m/s, and the moving route was A–B–A circularly, as described by figure 1.

Numerical simulation was performed for the test chamber. Re-Normalization Group (RNG) k-ε model was applied. Dynamic mesh method and momentum theory method adopted 1,370,522 and 1,535,450 cells in the computation domain, respectively (see in figure. 2). Based on earlier developments of immersed boundary method, the uniform inlet velocity boundary was used in the test chamber. The turbulent intensity and hydraulic diameter in inlet boundary were set to 10% and 0.32 m [7]. The outlet was considered as outflow boundary conditions [14].

Figure 1. The schematic of the test chamber and experimental instrument
The dynamic layering method was applied in dynamic mesh model. The interface was used to exchange data. User defined function (UDF) was utilized to control body moving in dynamic mesh method. In momentum theory method, moving momentum source was defined in UDF to simulate the interaction between human simulator and air. Particle trajectories were injected from inlet. The particle with diameter of 1μm source was injected with a speed of 100#/s, and after 400s the injected particles would maintain balance with escaping and adsorption of particles. The initial velocity of the particles was the same as the airflow speed.

The dynamic pressure \( \rho_d = \frac{1}{2} \times \rho \times v^2 \), where \( \rho \) is air density and \( v \) is the average velocity located close to the body. The corresponding force is \( F = \frac{1}{2} \times \rho \times v^2 \times A \), where \( A \) is the front area of the moving person (Brohus et al. 2006). In this paper, the momentum source was set in the front/behind surface of the human model, and momentum source direction coincides with the direction of human walking.

| Name          | \( y \)-Direction width(m) | \( z \)-Direction width(m) | \( x \)-Direction width(m) |
|---------------|----------------------------|----------------------------|----------------------------|
| Steady flow chamber | 0.3                        | 0.3                        | 0.3                        |
| Test chamber  | 1.0                        | 1.0                        | 1.0                        |
| Moving body  |                            |                            |                            |
| Body         | 0.1                        | 0.15                       | 0.05                       |
| Head         | 0.04                       | 0.094                      | 0.05                       |
| Left hand    | 0.02                       | 0.15                       | 0.05                       |
| Right hand   | 0.02                       | 0.15                       | 0.05                       |
| Leg          | 0.02                       | 0.22                       | 0.05                       |

**Figure 2.** The grid of the test chamber by dynamic mesh method (a: dynamic mesh method grid, c: CFD physical model) and momentum theory methods (b: momentum theory method grid, d: CFD physical model).
3. Results

3.1. Validation of CFD Model

The simulated velocities and particle concentration in x-direction at x=0.3m in the mid-section of the test chamber were compared with experiment results, as described in Fig. 3. The velocity distributions and contaminants field were similar between numerical and experiment results. It showed that the CFD model is acceptable. In this figure, the x-velocity and concentration of particle in the upper part were higher than that in lower part because of the air supply from inlet.

![Figure 3](image-url)

Figure 3. Air flow velocity and particle concentration distribution in x-direction at x=0.3m in the mid-section of the chamber at three air supply velocities (U_x=v/v_s, v is the local airflow x-direction velocity, v_s is the maximum airflow x-direction velocity along this line, C_{nor}=C/C_{in}, C is the local particle concentration, C_{in} is the particle number at inlet, case 1, case 2, case 3 stands for air supply 0.3m/s, 0.4m/s, 0.5m/s, respectively).

The air velocities simulated by momentum theory method at 3 lines in the mid-section of the test chamber were compared with the dynamic mesh method results (see Fig. 4). These line positions were x=0.3 m, x=0.6 m and x=0.7 m. The comparison of x-directions velocity and velocity magnitude at t=2 s were given in the figure. The accuracy of the momentum theory method prediction was satisfied. The velocity values were much larger in the upper part because it was near the air supply inlet.
Comparison of air flow velocities in x-direction and air flow velocity magnitudes between momentum theory method and dynamic mesh method at t=2s, air supply: 0.5m/s, walking speed: 0.1m/s (U=v/vs, v is the local air flow velocity, vs is the maximum airflow velocity along this line).

3.2. Decay of Particle Concentration
The simulated particle concentration decay curves with different moving speeds of human (moving from A to B) simulator were presented (Fig. 5). The decay of contaminant concentration conformed to exponential decay law, and the concentration reduced to 10% in fifteen minutes. The concentrations of particle in different moving velocities were same at t=0.s. Higher human simulator moving velocity led to a lower decay rate of particle number concentration. The data from this figure suggests that when the concentration of particles decreased to 10%, it would take respectively about 12, 12.5 and 14 minutes if the walking velocity was 0 m/s, 0.1 m/s or 0.2 m/s.

![Decay of Particle Concentration](image)

Figure 5. Decay of particle number concentration (C is the total particle numbers in the chamber)
4. Discussion
The velocity distributions and contaminants fields obtained from CFD were verified experimentally. Simplified methods (such as momentum theory method) included the object movements indirectly (Brohus et al. 2006). Comparison of air flow fields between dynamic mesh method and momentum theory method showed that later method was acceptable. The particle concentration increased along Y coordinate in the test chamber. Inclusion of movements in dynamic mesh method consumed considerable computing time. The results of particle concentration decay rate showed that faster human movement resulted in slower contaminants concentration decay. Momentum theory method has several advantages over dynamic mesh method. Compared with traditional method, it can simplify the model and reduce calculation time. As a coin has two sides, the errors in flow field were induced by the simplified model. To improve the speed and accuracy of calculation, momentum theory method also need to be optimized. Further studies on preventing transmission of respiratory diseases are needed.

5. Conclusions
In present study, the dynamic of body motion induced wake flow was investigated by using dynamic mesh method and momentum theory method. Momentum theory method was used to study the air flow field and the decay of particle concentration. The results showed that the momentum theory method was reliable. The walking of human influenced the local air velocity field and the particle dispersion. The decay of particle concentration was affected by walking velocities. We can get that moving of objects hampered the decay of contaminants. The results showed that it is possible to simulate the influence of human walking on indoor environment using a relatively simple CFD model. The findings would provide a convenient method for assessing indoor environmental with moving objects.

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