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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 wasnot CPU-friendly. In this paper, we proposed a new momentum theory methodfor reducing calculation time. In this method, user defined function (UDF) was usedfor simulatinginteraction force between human body and air. RNG k-ε model was applied in turbulencesimulation. In present paper, dynamic mesh method and momentum theorymethod were utilizedto 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 alsoinvestigated. The results showed that decay rate decreasedin presence ofobjects 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 indoorenvironments with humanactivities[4, 7]. Airflow generated by human bodymoving maycause high risk of bacterial transport from non-clean zone to patient's wound[6]. Particle, as the carrier of bacteria, viruses and others,hassignificant influence on human healthy especially in enclosed environment, such as operation room, clean room and other places which needhigh cleanliness [5, 8].Contaminant dispersion highly depends on airflow patterns [4]. Compared with particulate matter,gaseous pollutantsmostly followwith air. Particulate matter may deviate from air streamline because its weight isdifferent from gaseous pollutants [9].Different ventilation systemscause 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.conductedunsteady simulations of wakeflow induced by a moving manikin in a room[13].Dynamic mesh method was used to studythe 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 byDynamic mesh method. The dynamic mesh method needs to

update the grid in everytime step, which spends too much calculation time. The momentum theory methods could save time by no-updating mesh compared withdynamic mesh methods.Brohus et al. found it is possibleto simulate the influence of objects movements on air flow 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 reliabilityof momentum theory method in moving manikinsimulation. To verify reliability of numerical simulation, asmall-scale chamber was built to measure air flow 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 conductedby 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 1m×1m×1m (width × length × height), whilethe steady flow chamber was 0.3m×0.3m×0.3 m (width × length × height).The rotating motor coulddrive human body model to move back or forth.Asimplified human body simulator was designed to obtaina 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. Inthis 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: 0.3m/s, case 2: 0.4m/s, and case 3: 0.5m/s).The moving speedofhuman body was set to 0m/s, 0.1m/s, and 0.2m/s, andthe 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 (seen 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 0.32m [7]. The outlet was considered as outflow boundary conditions[14].

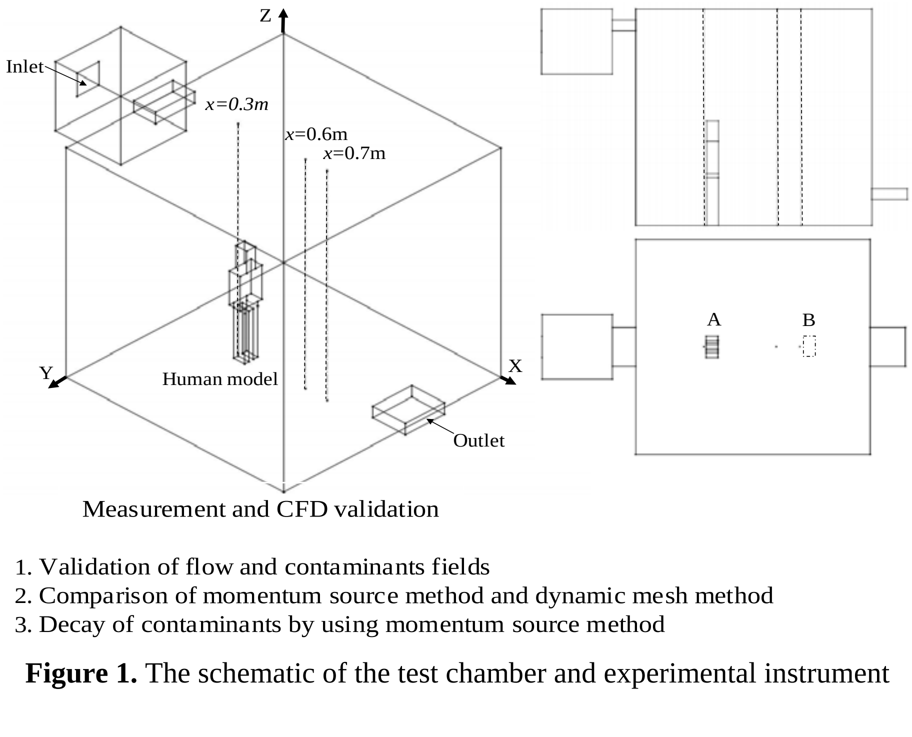

Figure 1. The schematic of the test chamber and experimental instrument

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Table 1. the details of thechamber

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

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 400*s* 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 is$\rho_d=1/2\times\rho\times v^2$, where ρ is airdensity and v is the average velocity located close to the body. The corresponding force is $F=1/2\times\rho\times v^2\times A$, 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.

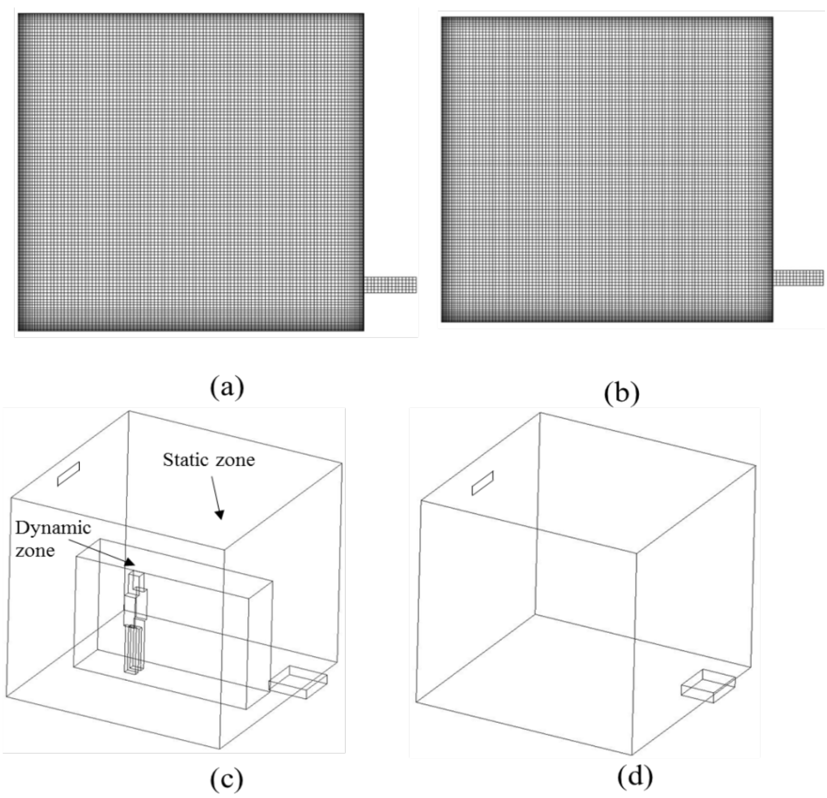

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Figure 2. The grid of the test chamber by dynamic mesh method (a: dynamic mesh method grid, c: CFD physical model) and momentum theory methods (b: momentum theory method grid, d: CFD physical model).

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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.

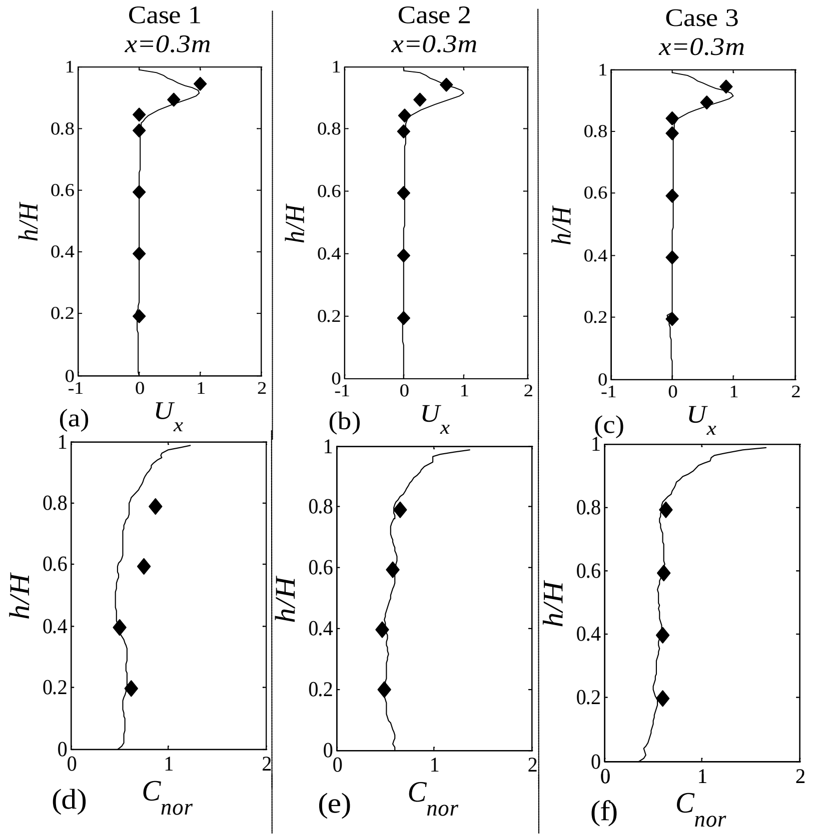

Figure 3. Air flow velocity and particle concentration distribution in x-direction at x=0.3m in the mid-section of the chamber at three air supply velocities (U_x=v/v_s, v is the local airflow x-direction velocity, v_s is the maximum airflow x-direction velocity along this line,C_{nor}=C/C_{in}, C is 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 methodat 3 lines in themid-section of the test chamber were compared with the dynamic mesh methodresults (see Fig. 4). These linepositionswere*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 valueswere much larger in the upper part because it was near the air supply inlet.

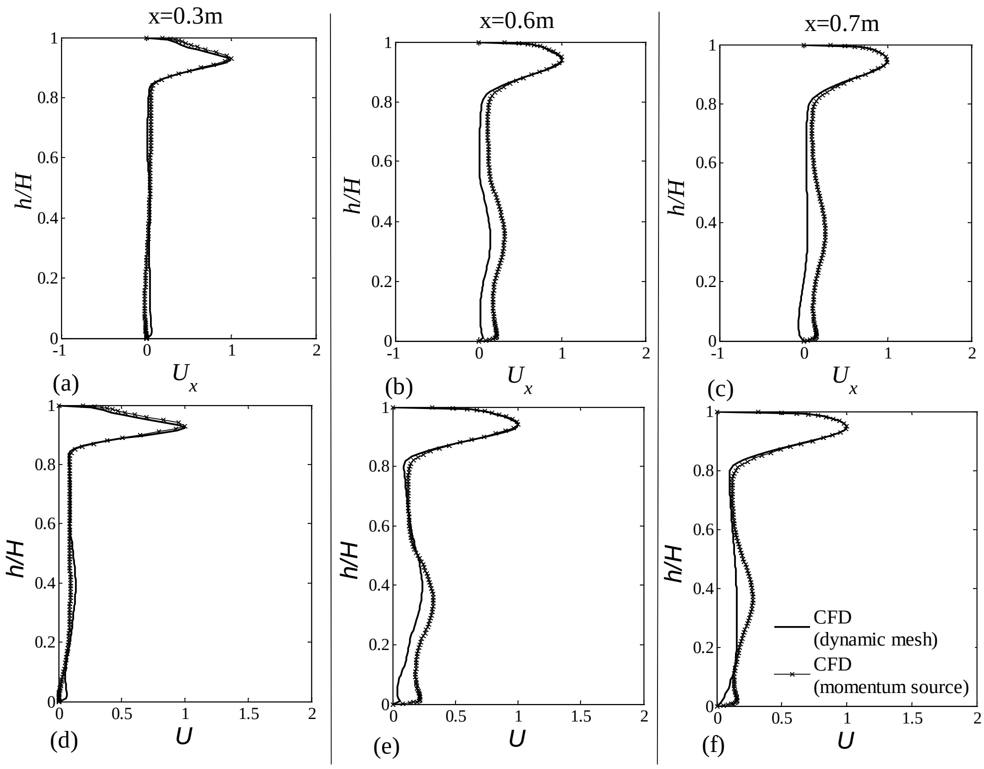

Figure 4. Comparison of air flow velocities in x-direction and air flow velocity magnitudesbetween momentum theorymethod and dynamic mesh method at t=2s, air supply: 0.5m/s, walking speed: 0.1m/s(U=v/v_s, v is the local air flow velocity, $v_s$is the maximum airflow velocity along this line).

3.2. Decay of Particle Concentration

The simulated particle concentration decay curveswith different moving speedsof human (moving from A to B)simulatorwere presented(Fig. 5). The decay of contaminant concentration conformedto exponential decay law, and the concentration reduced to10% in fifteen minutes. The concentrations of particle in different moving velocitieswere same at *t*=0s. Higher human simulator moving velocity leaded tolowerdecay rate of particle number concentration. The data from thisfigure suggests that when the concentration of particles decreasedto 10%, it would take respectively about 12, 12.5 and 14 minutes if the walking velocity was 0 m/s, 0.1m/s or 0.2 m/s.

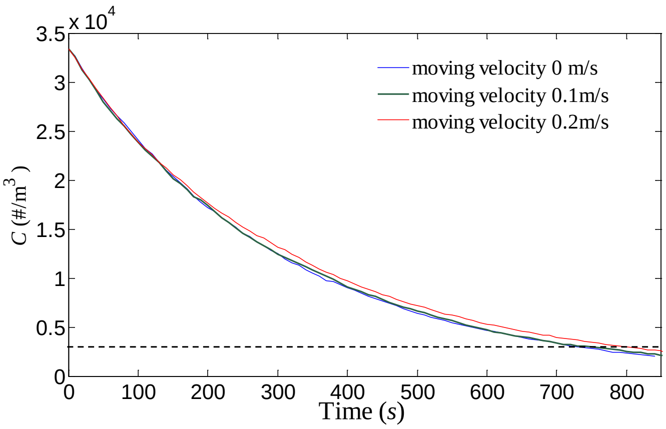

Figure 5. Decay of particle number concentration (C is the total particle numbers in the chamber)

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4. Discussion

The velocity distributions and contaminants fields obtained from CFD were verified experimentally. Simplified methods (such asmomentum 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 increasedalong Y coordinate in the test chamber. Inclusion of movements in dynamic mesh method consumed considerable computing time. The results of particle concentration decay rate showedthat faster human movement resultedinslower contaminants concentration decay.Momentum theory method has several advantages over dynamic mesh method. Compared with traditional method, it can simplify the modeland 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 influencedthe 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. Theresults showed that it is possible to simulate theinfluence of human walking on indoor environment using a relatively simple CFDmodel. The findings would provide a convenient method for assessing indoor environmental with moving objects.

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