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Study on the impacts of human walking on indoor particles dispersion using momentum theory method

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ABSTRACT

Particle dispersion can be influenced by human activities' inducing effect, which may not be allowed in high-demanded cleanness environment, such as operation room. The application of dynamic mesh simulation method has been widely applied for objects moving, which is not CPU-friendly in calculation as well as complex meshing required. Thus, we proposed a new method of momentum theory to investigate human motion induced effects on indoor environments (i.e., momentum source implemented into Navier-Stokes equations to simulate human/objects moving). Experiments were conducted for validation. RNG k-ε model was adopted for turbulence modeling. Both methods of dynamic mesh and momentum theory were used to investigate the impacts of human induced motion on indoor environments of airflow distributions and particles dispersion. It was found that momentum theory method is sufficiently fine when compared to dynamic mesh (flow and particle deviation within 15% and 5% respectively). Momentum theory method was then employed to investigate the decay process of particle concentration influenced by human walking in a chamber, which could save 90% of the calculation time compared to dynamic mesh method. The results also indicated that particles decay would be delayed in the presence of object moving. Particle concentration in different zones of the chamber was also discussed. We found that particle decay effected by human motion (with speed of 0.2 m/s) was 19.6% faster than that without human motion in the region with larger background airflow velocities.

1. Introduction

People spend almost 90% of their time indoors or other enclosed environments [1]. It has been documented that incidence of allergic diseases is associated with exposure of the indoor allergens, such as pollen, dust, viruses, bacteria, fungi and so on [2]. Particle, as the carrier of bacteria, viruses and others, would have more important impacts on human health risk in high-demanded cleanness environments, such as operation room, clean room and other places which require higher cleanness degree [3,4], and may even correlate with human health hazards in public places [5]. Several studies have shown that human activities (such as breathing, walking, moving etc.) can increase local particle mass concentration [1,4,6–8]. It has been recognized that walking is a major contributor to high pollutant concentration in indoor environment with human activity [7,9,10]. For instance, airflow generated by human body may cause a high risk of bacterial transport from the non-clean zone to the patient's wound [8].

Contaminant dispersion highly depends on surrounding airflow patterns [9,11,12]. Different from gaseous pollutant, particulate matter has worse tracking behavior due to its size and weight [7,13]. Different ventilation systems cause different flow fields [14]. Licina et al., 2015 simulated particle transport phenomenon with particles released from feet and by human cough. The results suggested that accurate simulation of air patterns should be prioritized [15]. Factors that affect airflow field included room details, ventilation patterns [4], wind speed [16], and other factors such as air temperature and density [17]. Over the past few decades, mixing ventilation system was widely used in operating room as air in room mixed quickly and evenly, which leads to a rapid dilution of airborne particles [18]. There are also many other dynamic factors having significant impacts on airflow field, such as cleaning, human or animal's moving [19], human breathing [15,20] and door opening and closing [21]. In order to remove particles from operation room as soon as possible, laminar flow pattern has been utilized in operating rooms and many researchers [1,3,7,21–23] had approbated its performance. Decreasing the duration of door opening, raising air change rate and using a curtain at the doorway were recommended to reduce inter-cubicle exposure hazards [24]. The dynamic behavior of people or other objects could cause much higher air

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velocity magnitudes than the background level. Therefore, it is necessary to study the effects of people or other moving objects on airflow and contaminant transport [13,23].

Airflow and contaminants transport can be studied by either experimental measurements or numerical simulations [18,25]. Measured data from a properly controlled laboratory-scale experiment can be used to test the performance of different numerical models. RNG k-ε model is commonly selected for turbulence modeling applied for indoor airflow simulations [26]. For modeling of indoor particles dispersion, there are four main methods: Lagrangian-based model, drift flux model, Markov chain model and Eulerian-based model [27–30]. With these methods, simulated particle concentration by the Lagrangian model agreed well with experimental data when particle trajectory number was sufficient [29,30]. Both Eulerian and Markov chain models could not simulate particle motion accurately when in the presence of air jet at indoor environment. Therefore, the Lagrangian model will be applied in the current work. Dynamic mesh method was widely used to study the effects of indoor moving objects, such as human moving, doors opening, showing good performance after validating with experimental data [22,31,32]. The wake flow induced by a moving manikin in a room had a recirculation region after the head [33]. Highest air velocity existed at the upward flow region in front of the upper body and downward flow in the back of the body [16]. However, by using dynamic mesh method, the interfaces were applied to achieve data exchange (e.g., momentum transfer) between static and dynamic zone, resulting in considerate expenses in terms of CPU power. Hence, the grid should be re-meshed every time step. Moreover, complex mesh making is always required due to the complex geometry of moving objects. This would encourage us to use other relatively simple and efficient methods for the simulation of indoor moving objects (or human).

Simplified method of momentum theory have been applied to investigate the effect of moving objects on the surrounding airflows in other fields (such as marine science, wind energy etc.), i.e., incorporated Navier-Stokes equations with momentum source resulting from moving objects. For instance, Meyers and Meneveau studied the interactions between wind turbines and wakes to assess the wind turbine conversion efficiency [34]. Gao et al. used momentum theory of the propeller to calculate the propeller induced velocity [35]. It performed reliably when simulating the influence of movements using a relatively simple CFD model by applying momentum theory method [3]. However, the simplified method has not applied for objects moving in indoor environment. Thus, the main goal of this work is to testify the feasibility and applicability of momentum theory method to simulate human moving impacts on both airflow and indoor contaminant dispersion. Further, findings of this work would give some suggestions for high-demanded ventilation system design to reduce the negative impact of moving objects on human health.

2. Methods

This paper aims to investigate the feasibility of momentum theory method to simulate human moving as well as its impacts on indoor environment. Experimental method of small-scale chamber and CFD simulation were employed in the current work. We first carried out a series experiments to validate simulation. During simulations, both methods of dynamic mesh and momentum theory were applied for human motion effects on airflow. Next, momentum theory method was employed to study a case for particles decaying in a test chamber. Fig. 1 shows the general structure of this study.

2.1. Small-scale measurements in a chamber

Measurement was conducted in a small-scale chamber. The chamber was consisted of two main parts: test (main) chamber and steady flow (inflow) chamber. The dimensions of test chamber and steady flow chamber were 1 m × 1 m × 1 m (width × length × height) and 0.3 m × 0.3 m × 0.3 m (width × length × height), respectively. A simplified human body (box-shaped objects) was designed for gaining a better understanding of airflow phenomena affected by moving body. A rough assumption is made in the current work that the human model is testified for flat plate-like surfaces moving in the perpendicular direction in the flow. A more accurate human manikin has been presented by Melikov [36] and [37]. However, the box manikin model with shape edge was widely used in numerical simulation. The measured and simulated results agreed well (such as [38]). Tao et al., 2016 compared simplified cylinder and idealized manikin by CFD simulation [33]. Thus, the simplified box-shaped module should be sufficient aiming at studying the influence of object moving on indoor environment. Moreover, study [39] highlighted the importance of thermal plume generated by heated manikin on both indoor airflow and particle dispersion. Effect of thermal plume by human's movements is ignored in the current work for the sake of small temperature difference between human objects and airflow.

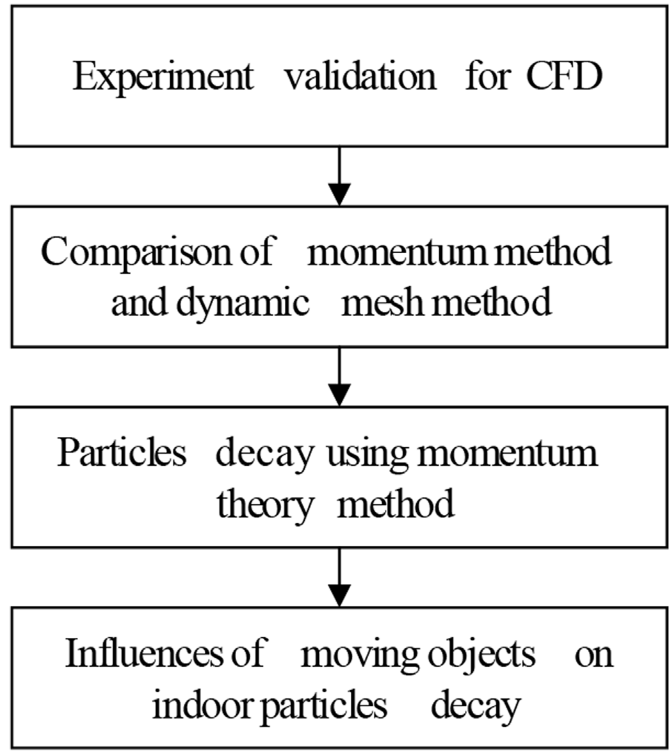

Fig. 1. The structure of this work.

The rotating motor was used to drive human body module to move back/forth wards. Details of the measurement scheme and chamber were presented in Fig. 2 and Table 1. In this chamber, the x-direction air velocity and the particle number concentration were measured by an air velocity meter (VELOCITYCALC TSI 9515) and a particle counter (P-TRAK ULTRAFINE model 8525). Measured concentration was in the range of 0-5E + 5 (#/cm^3) with particle size dimensions of 0.02–1 (μm).

The position of measuring points were along the lines (x = 0.3, 0.6, 0.7 (m)) shown in Fig. 2. Experiments were firstly carried out by measuring x-direction velocity of each point under different air supply conditions. Particulate matter source was released (emissions from burning mosquito coils) at the inlet close to inflow chamber. Once mechanical ventilation switched on, concentration of emitted particulates monitoring would be started. When the concentration of particulate matter at outlet remained constant, particle concentration (particle number concentration of monitoring points) field was considered to be in a steady state. And then the decay process of particles would be studied.