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Numerical study of the effects of human body heat on particle transport and inhalation in indoor environment

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ABSTRACT

The inhalation of micron particles by a manikin standing in a ventilated indoor environment was numerically investigated using Computational Fluid Dynamics (CFD). Computations were conducted with various combinations of the free stream velocity (0.05–0.25 m/s representing typical indoor wind speeds.), occupant orientation relative to the free stream (back-to-the-wind or facing-the-wind) and heat transfer (isothermal or thermal flow). It was found that the body heat has a significant impact on the airflow field in the vicinity of the manikin by causing an upwards airflow on the downstream side of the manikin. It was also found that the effect of body heat on particle inhalation depends on the manikin orientation relative to the free stream. When the manikin is facing-the-wind, body heat has a little effect on particle inhalation and can be neglected. However for a back-to-the-wind orientation, the situation is much more complicated as the source height of inhaled particles depends on the speed of free stream. When the wind speed is low (0.05 m/s), the critical area is located near the floor level. The central height of the critical area then increases with increasing free stream speed until it reaches the nose height when the wind speed rises up to 0.25 m/s. This indicates that the body heat is an important consideration when investigating contaminant inhalation by human occupants in low-speed (typically less than 0.2 m/s) indoor environment.

1. Introduction

The transport characteristics of aerosol particles and their inhalation characteristics by human occupants in indoor environments have been attached a great importance as people spend approximately 90% of their time indoors and a number of health problems have been found to be associated with particle inhalation [1]. During the past decades, numerous experimental and numerical investigations [2–7] have been conducted under various conditions. It is generally accepted nowadays that the particle inhalability by a human occupant is subjected to many factors such as the particle size, ambient wind speed, occupant movement, airflow pattern, inhalation rate, inhalation pattern (mouth or nasal inhalation), and even the human facial features.

However, most of the previous investigations on particle inhalation failed to take into account the effects of the metabolic heat released from a human body. In fact, a human body is continually exchanging energy with its environment. The average thermal energy generated by a human body with an ordinary activity level and at a moderate room temperature was found to be up to 100 W [8]. Due to this heat, a temperature gradient is formed and drives a buoyant convection in the vicinity of the human body, which is known as the *human thermal plume*. Homma and Yakiyama [9] measured the human thermal plume around a person standing in quiescent air using smoke wire photography and hot-wire anemometry. It was found that the thermal boundary layer was approximately 50 mm thick at the face level and its velocity was upto 0.25 m/s. Using a laser Doppler anemometer, Johnson et al. [10] measured the airflow around a human body standing with its back towards the free stream (0.2 m/s). A significant upward airflow was observed in the downstream side of the human body and the upward velocity was found to be approximately 0.19 m/s at the nose level. A synthetic literature survey demonstrated that the human thermal plume can produce vertical air velocities of 0.1–0.25 m/s in the breathing zone [9–12]. This vertical velocity induced by body heat is roughly equal to the average wind speed in most indoor environments (0.05–0.25 m/s according to Baldwin et al. [13] and Schmees et al. [14]), it is therefore reasonable to expect that the buoyancy-driven convection may change

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significantly the airflow pattern and play an important role in transporting aerosol particles in the vicinity of a human body. This is especially true for fine and ultrafine particles as their movement is mostly controlled by the indoor flow field [15].

During the past years, the effects of human thermal plume on aerosol particle transport and inhalation in quiescent air have been investigated by few researchers. For example, using a sedentary thermal manikin, Rim and Novoselac [12] experimentally investigated the effects of human thermal plume on the inhalability of fine/ultrafine particles in stratified indoor air. It was found that when the particle source was at floor level and in near proximity to an occupant, the inhaled particle concentration by the manikin was upto 4 times higher than the ambient concentration. This proved that the thermal plume plays an important role in transporting pollutants and particles from the floor level to the breathing zone. However, the conclusions based on quiescent or quasi-quiescent indoor air conditions may not be quantificationally applicable to realistic situations where ventilation is operating and the orientation of an occupant relative to the free stream may be random. Therefore, for the purpose of accurate description of the effects of human metabolic heat on particle transport and inhalation, some important factors including the wind speed and the occupant orientation relative to the wind have to be taken into account.

Therefore in this study, in order that the role of human body heat in particle transport and inhalation could be better understood, a series of CFD computations were conducted using a standing thermal manikin. Various factors including the wind speed (0.05–0.25 m/s), manikin orientation relative to the free stream (back-to-the-wind or facing-the-wind) and their combinations were investigated. For the purpose of comparison, computations with isothermal conditions were also performed. The predicted airflow field was in good agreement with the experimental data available in the literature. The trajectories of inhaled particles under various conditions were also presented and discussed. The outcome yielded from this study can help to reduce contaminant exposure through appropriate orientation arrangement in indoor environments.

2. Numerical methods

2.1. Geometric model and boundary conditions

The computational domain of this study was a rectangular wind tunnel containing a 1.6 m tall standing human manikin facing the $+X$ direction and with its nose tip in the plane of $X = 0$ m, as illustrated in Fig. 1. The dimensions of the computational wind tunnel (4 m-width × 7 m-depth × 3 m-height) were created large enough so that the flow field near the manikin was free from the effects of the no-slip condition of the stationary surrounding walls. In order that the detailed airflow pattern and particle transport characteristics in the breathing zone could be captured, the manikin head was carefully built to represent 50 percentage of a human male aged between 20 and 65 years [16]. For the purpose of saving computational cost, the manikin body was simplified. Unstructured tetrahedral and prism meshes were adopted to discretize the computational domain, with fine meshes around the manikin to capture the geometric features of the manikin and the effects of human thermal plume, as illustrated in Fig. 2. The grid sensitivity test proved that the mesh independence was achieved at 4.0 million cells, with the skewness of the cells and $y+$ value on the walls dropped below 0.8 and 0.78 respectively.

In total 21 cases were computed with various combinations of free stream speed, manikin orientation relative to the free stream and the status of heat transfer, as summarized in Table 1. For each computational case, evenly distributed airflow velocity profile was applied at the tunnel inlet and a zero pressure boundary condition was applied at the tunnel outlet. For the facing-the-wind cases, the inlet was on the $+X$ side and the outlet was on the $-X$ side of the tunnel, which makes the free stream flows in the $-X$ direction (Fig. 1). On the contrary, the inlet was on the $-X$ side and the outlet was on the $+X$ side of the tunnel for the back-to-the-wind cases, which makes the free stream flows in the $+X$ direction (Fig. 1). The free stream velocity was chosen to be in the range of 0.05–0.25 m/s, which represents the typical wind speeds in most indoor occupational environments [14]. The periodic respiration activities of the human body were neglected and the inhalation was assumed to be steady according to Horschler et al. [17]. A constant inhalation rate of 15 litres per minute (LPM) representing a human light breath at light activity conditions [7,18] was applied equally at the manikin nostrils, namely 7.5 LPM for each nostril.

For heat transfer modelling, the heat transfer between the air phase and the particle phase is neglected due to the dilute particle concentration. A constant free stream temperature of 26 °C, which is a typical air-conditioning ventilation temperature in summer seasons, was applied at the inlet and a constant temperature of 31 °C was applied at the manikin surface, as recommended by Gao and Niu [19]. The tunnel walls were assumed to be adiabatic.

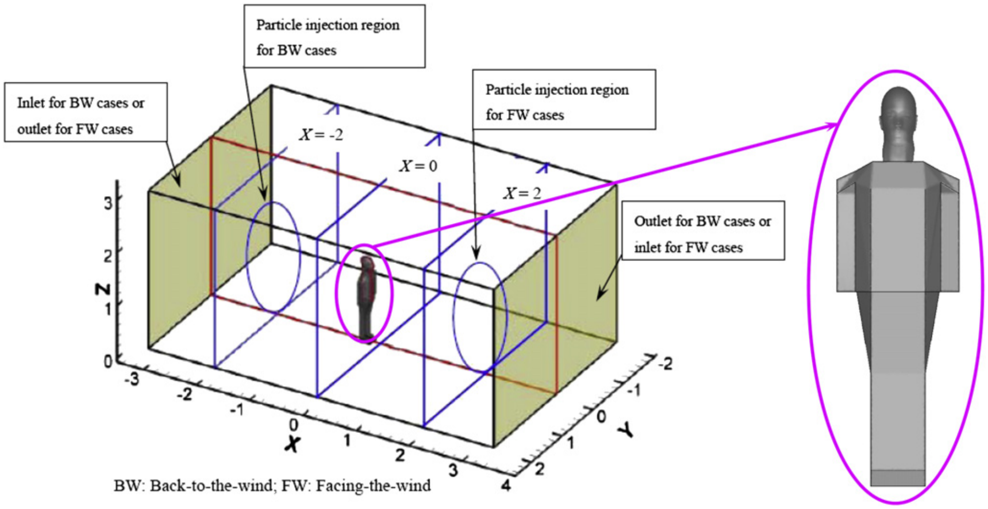

Fig. 1. The computational domain and human manikin.