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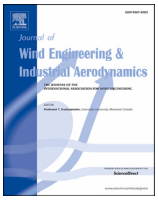

A numerical investigation of wind environment around a walking human body

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ABSTRACT

Human-induced wake flow characteristics and its interaction with thermal conditions was investigated by performing CFD simulations with dynamic-meshing of a moving manikin model. The manikin motion with and without swinging limbs was achieved by the re-meshing method to update the grid with each time step. The results focused on determining what discrepancies are produced in the flow field by a simplified geometry in the form of a cylinder, swinging limbs and thermal conditions; and whether such assumptions can be made for larger multi-body analysis. Using a cylinder showed differences in the velocity field behind the head and leg gap. The flow field between the rigid motion and swinging limb motion, showed significant discrepancies which corresponded to the gait phase. There were increased airflow disturbances at the hands and ankles (furthest body parts from the pivot point). The influence of thermal plume on the wake flow was minor during walking motion because of the walking speed of 1.2 m/s which dominated the buoyant thermal plume velocity. However, after the manikin stopped moving the thermal plume velocity became comparable to the residual wake.

1. Introduction

Wind flowing over a human body influences thermal comfort (Sasaki et al., 2000) and pollutant exposure in outdoor conditions. Its fluid dynamics have primarily been investigated by considering a stationary human body exposed to an oncoming wind (Inthavong et al., 2013; Se et al., 2010; Irwin, 2008; Murakami and Deguchi, 1981; Inthavong et al., 2012; Li et al., 2014). The induced wake exhibits similarities to boundary layer separation of flows over bluff bodies, where a mixing zone of vortices entraining air into a reverse flow region is formed (Flynn and Ljungqvist, 1995; Mahjoub Said et al., 2008; Zhang et al., 2016). Therefore, simplified geometries such as vertical finite cylinders and cuboids were used as substitutes for human bodies (Poussou et al., 2010; Thatcher et al., 2004). This leads to discrepancies in flow features due to the simplified geometry. For example when legs are considered as two cylinders instead of single cylindrical block, there is increased mixing in the wake, influenced by the gap width (Edge et al., 2005; Flynn and Ljungqvist, 1995). Another issue that arises with flow over a stationary manikin is the flow separation at the feet which neglects flow disturbances caused by the manikin motion; thus the near wake characteristics during walking are only partially represented.

A second factor to consider is the effects of heat transfer leading to thermal plumes from the human body. Murakami et al. (1999) investigated the thermal and dynamic effects of 0.25 m/s and 2.5 m/s wind on stationary bodies. Velocity and temperature fields around the body revealed a thin layer of warm rising air around the body under a stagnant or weak wind environment; but this disappeared when the wind velocity increased. Combining a wind tunnel experiment and CFD, Li and Ito (2014) and Ono et al. (2008) showed thermal plumes emitting from around a human body in an outdoor environment. Therefore, the effect of heat transfer is an important component for wind flow over a human body.

Flow measurements of moving bodies presents significant challenges due to set up, large scales, and its dynamic nature. There are a few studies that have investigated the fluid dynamics from a moving manikin including: Inthavong et al. (2016) who investigated an isothermal 1/5th scaled rigid moving manikin model; Luo et al. (2015) and Oliveira et al. (2014) who investigated natural and forced convection heat transfer from a moving thermal manikin in rigid motion. In the thermal model studies, the heat transfer coefficient increased as a power exponent function with increase of the moving speed.

Recently a growing number of computational studies have laid emphases on the effects of human activity on the wake dynamics. CFD with dynamic mesh advances the modelling capability to capture transient effects of manikin motion. This was used to qualitatively capture the wake flow from moving blocks (Brohus et al., 2006; Poussou et al., 2010).

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Realistic anthropomorphic manikins have also been used as they provided more realistic results in the near-body regions (Choi and Edwards, 2012; Gao and Niu, 2005; Hang et al., 2014; Mazumdar et al., 2010; Oberoi et al., 2010; Wu and Gao, 2014; Tao et al., 2016). While these studies are gradually developing its complexity by being integrated with particle modelling for air quality assessments, some characteristics of the dynamic wake induced by the walking motion that is modelled, remains unclear. For example, there are differences in flow field due to a moving rigid body motion, and that of a swinging human gait cycle, and in combination with a thermal plume. These processes are important for understanding exposure to airborne contaminants which can be prevalent in the urban environments (e.g. pollutants, and exhaust fumes in pedestrian/urban streets).

This study's aim is to understand the fundamental wake flow dynamics, in particular of flow separation over moving bluff bodies. The fundamental dynamics are prevalent in many motion-induced wake flows such as wind turbines (Abdelsalam et al., 2014; Lam and Peng, 2016) and pollutant transport induced by vehicle movement in tunnels (Chung and Chung, 2007; López González et al., 2014) and urban street canyons (Solazzo et al., 2008). The wake flow generated by human activity has significant interests the assessment of air quality as the human activity constitute an important factor in influencing exposure to air pollutants in both indoor and outdoor workplaces.

In this study, the numerical setup was first validated with experimental data of a simplified cylindrical body, before being applied to a manikin under rigid and swinging motion. Thermal and isothermal conditions were also evaluated to examine the interaction between the thermal plume and the effects of motion. The results focused on the spatial and temporal characteristics of the flow field and vortex structures. The range and strength of the flow field around the manikin was explored to show the extent of the disturbed airflow area, and the observable parameters that influence the contaminant transport could be deduced. Thermal analysis was investigated to determine under which circumstances the thermal plume was significant or negligible by comparing the relative magnitude between the thermal plume and the motion-induced airflow.

2. Methodology

2.1. Cylinder geometry for model validation

To validate the numerical model setup, a transient simulation of near wake flow around a vertical cylinder was performed. The solution was time-averaged and its velocity field was compared with PIV measurements by Rostamy et al. (2012). A circular cylinder with a diameter of 31.5 mm and an aspect ratio (height/diameter, H/D) of 3 is similar to the manikin model. The cylinder was placed inside a computational domain with dimensions of 1.96m × 0.91m × 1.13m. The free stream velocity was $U = 20$ m/s giving a Reynolds number of 42000 based on the cylinder diameter, and a turbulence intensity of 0.6% based on Rostamy et al. (2012).

To solve the boundary layer separation in the viscous sub-layer on the cylinder surface, 10 prism cell layers were extruded with a first cell grid spacing of 1×10^{-4} m. This produced a dimensionless wall distance (y^{+}) of less than 5 within the viscous sub-layer, and ensured enough grid points within the buffer region where turbulent production rapidly increases. A structured hexahedral mesh with 3.1 million cells was generated and a time step of $t = 1 \times 10^{-3}$ s was used.

2.2. Manikin model and boundary conditions

A manikin with dimensions of 1.7m-height, 0.58m-width, and aspect ratio $H/D = 2.93$ was placed in a computational domain of 2.6 m (x-coordinate) × 6.0m (y-coordinate) × 2.7 m (z-coordinate). The coordinate system located the manikin at an initial standing position at $x = 0$ m, $y = 0$ m, facing the $+y$ direction 1m from the back wall (Fig. 1a). Unstructured tetrahedral cells and prism layers were generated for the domain (Fig. 1b). To capture the boundary layer separation around the manikin, 10 prism layers were generated on the manikin surface to keep the dimensionless wall distance $y^{+} < 5$. For the dynamic meshing, the domain was re-meshed at each time step to update the moving manikin.

The number of steps per second (called cadence) and the walking speed of a person are subject to various human factors. We assumed a cadence of 2 steps per second with a mean walking speed of 1.2 m/s based on gait parameters presented in Al-Obaidi et al. (2003). To reduce the computational demand of dynamic meshing, walking gestures were simplified as swinging pendulums with the base taken at the shoulder and hips, and therefore no bending of knees and elbows. The total flexion angle for the arms and legs were 60°and 40° based on Han et al. (2013) and the rotating limb angular velocities were calculated from the length of limbs, the swinging period, and walking speed. The gait cycle was achieved by defining the angular limb velocities through a User-Defined-Function (UDF) in the commercial CFD software ANSYS Fluent v16 (Fig. 2). Under a walking speed of 1.2 m/s, the manikin walked for a distance of 3.6 m thus travelled for 3 s and then stopped for 3 s to determine the evolution of the wake during motion and after the manikin has come to rest.

In numerical studies, the body temperature is usually set in the range of 30.3 °C–33.7 °C (Murakami et al., 1999; Salmanzadeh et al., 2012; Li et al., 2013). In this study, the manikin used a fixed surface temperature of 32 °C, with an air temperature of 22 °C. Since our objective was to compare the thermal plume around the manikin during walking, the convective heat transfer from the body surface was the main contributor, and radiation, evaporation, and respiration were not considered. Likewise, clothing was not considered. A grid independence study was conducted by consecutively reducing individual cell spacing by a factor of

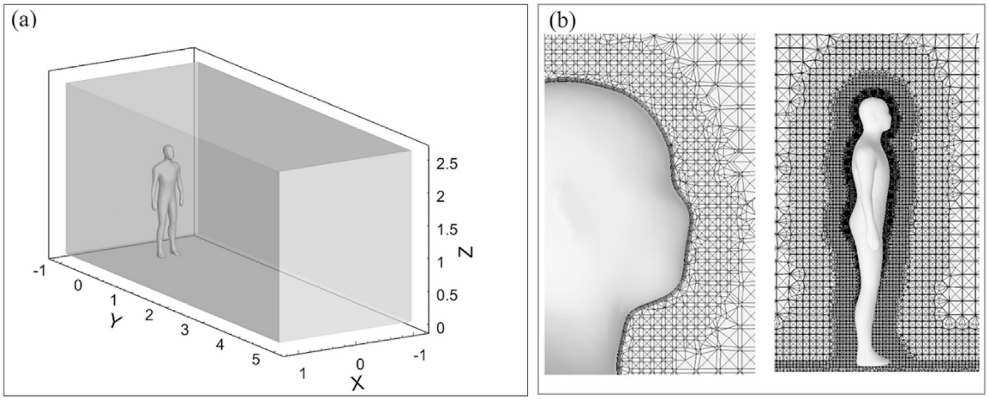

Fig. 1. (a) Computational domain of the room, x- y- z- coordinates are in meters; (b) Prism layers and tetrahedral mesh generation around the manikin body.