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Simulation of a mannequin's thermal plume in a small room

Xinli Jia [a], John B. McLaughlin [a,*], Jos Derksen [a,b], Goodarz Ahmadi [a]

[a] Clarkson University, Potsdam, NY 13699, USA

[b] University of Alberta, Edmonton, Alberta TG6 2V4, Canada

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ABSTRACT

Simulation results are presented for the buoyancy-driven flow in a small room containing a seated mannequin that is maintained at a constant temperature. The study was motivated, in part, by a published experimental study of the thermal plume around a human subject. The results presented are a step toward the goal of using DNS to develop a more detailed understanding of the nature of the flow in the thermal plume created by humans modeled here as heated mannequins. The results were obtained without using sub-grid scale modeling and are helpful in establishing the resolution requirements for accurate simulations. It is seen that the results for the highest resolution grid are in reasonable quantitative agreement with a published experimental study of a human subject's thermal plume. The results for the velocity field are used to compute the trajectories of small particles in the room. Results are presented for the trajectories of five-micrometer solid particles that are initially dispersed near the floor in front of the mannequin. The simulation results show that the buoyancy-driven flow around the mannequin is effective at dispersing the particles over a large portion of the room.

1. Introduction

This paper presents simulation results for the velocity and temperature fields in a small room containing a heated mannequin. The study was motivated in part by the work of Craven and Settles [1]. Cravens and Settles performed an experimental study of the thermal plume around a standing human subject. The ceiling of the room in which the person was standing was 3.25 m above the floor, and the subject was 1.73 m tall. The subject stood in a rectangular box that measured $1.00 \times 0.81 \times 0.51$ m. The temperature on the surface of the subject's clothing was measured at 40 locations, and the average value was found to be 26.6 °C; the average skin temperature based on the same 40 locations was 31.8 °C. The air in the room was thermally stratified, and varied from 20 °C at the floor to 22.5 °C at the ceiling. Theater fog, consisting of 5 μm particles, was used to visualize the flow around and above the subject. PIV measurements using turbulent eddies as "particles" were used to measure the air velocity at various locations. Cravens and Settles obtained results for the magnitudes of the time-averaged velocities at various points around the mannequin; they did not report values of the turbulent intensities. The largest velocity was 0.24 m/s, and it occurred at a distance equal to 0.43 m above the subject's head (2.16 m above the floor).

Cravens and Settles also reported the results of Reynolds-averaged Navier–Stokes (RANS) simulations of the flow around a simplified model of the human subject in their experiments. Thermal stratification could be incorporated into their simulations. For the stratification in their experiment, the average air temperature was 21.3 °C, and the mannequin's surface temperature was 26.6 °C. On the basis of previous experimental studies of the transition to turbulence on vertical heated surfaces (see, for example, Incropera and DeWitt [2]), they assumed that the transition occurred when the Rayleigh number

* Corresponding author. Tel.: +1 315 268 6663.
E-mail address: jmclau@clarkson.edu (J.B. McLaughlin).

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was 10^9, which corresponds to a height equal to 1.2 m above the floor. Their simulations predicted that the largest vertical velocity was 0.2 m/s, and it occurred at 2.12 m above the floor. Without stratification, the largest vertical velocity was found to be 0.3 m/s and it occurred at approximately 2.8 m above the floor.

The simulations to be reported were performed for a seated mannequin in a room that is much smaller than the room in which the above experiments were performed. Since one goal of the study was to evaluate the feasibility of using DNS to study the human thermal plume, the smaller size of the room is important. As in the work reported by Craven and Settles, no air enters or leaves the room. The choice of the room was motivated by experiments carried out with one or more medical mannequins in a small room that were reported by Marr [3,4] and Spitzer et al. [5]. In these studies, the mannequin(s) could be heated or unheated and breathing was also included in some experiments. A significant difference between these experiments and the results to be reported is that, in all of the experiments, air flowed into the room through a floor vent and exited through a ceiling vent. To include the forced convection in a simulation, a finer grid would be needed to account for the small scale fluctuations in the flow entering the room. Alternatively, one could follow the approach used by Abdilghanie et al. [6] who used large eddy simulation (LES) to compute the flow in the above room. Earlier LES studies of indoor airflows were reported by Davidson and Nielsen [7], Zhang and Chen [8,9], and Jiang and Chen [10]. In addition to conducting measurements of velocity and temperature, 5 μm particles were released near the floor and the effectiveness of a mannequin's thermal plume in dispersing the particles was investigated. In the present paper, results are also presented for the motion of 5 μm particles that are released in a volume near the floor and directly in front of the mannequin. The simulation results show that the thermal plume is effective in lifting the near floor particles and bringing them to the breathing zone as well as dispersing the particles over a large volume of the room.

The present study addresses a set of issues different than those considered in the study by Abdilghanie et al. [6]. The focus of the present study is on the flow driven by the thermal plume created by a single mannequin that is seated in the room. No air either enters or leaves the room. This reduces the computational requirements for an accurate simulation since it eliminates the need to simulate the small eddies that enter the room through the inlet flows. Despite this simplification, the thermal plume of a mannequin or person still presents significant computational challenges for accurate simulations. Features such as the largest instantaneous vertical velocities directly above the mannequin's head were sensitive to the spatial resolution used in the study.

Although the simulations to be discussed were performed for the same room as was considered by Marr et al. and Spitzer et al., there are several significant differences. First, a simple block model of a seated mannequin was used in the simulation instead of the anatomically realistic mannequin used in the above study. Second, furniture was not included in the simulation. Finally, the temperature of the mannequin was chosen to be 5 °C warmer than the initial air temperature (i.e., the mannequin's surface temperature was 25 °C instead of 31 °C and the initial air temperature was chosen to be 20 °C). This choice was motivated by the experiments reported by Craven and Settles [1].

2. Formulation of the problem

2.1. Geometry and boundary conditions

The room for which the simulations were performed is shown in Fig. 1, which also shows the Cartesian coordinate system that will be used in what follows. The dimensions of the room's interior are 2.4 m × 1.8 m × 2.45 m in the x, y, and z directions, respectively. A layer of insulating material of thickness 0.11 m was added above the ceiling so that the temperature of the ceiling could vary with time as the air above the mannequin became warmer. The room was equipped with a single inlet located on the floor in front of the mannequin and a single outlet located on the ceiling behind the mannequin. As a consequence of the insulation above the ceiling, a short rectangular duct preceded the outlet. In the present study, however, no air either entered or left the room. Fig. 1 also shows the simple block model of a mannequin that was used in the simulation. The mannequin is centered on the geometrical symmetry plane ($x = 0.9$ m) of the room. The widths of the mannequin's torso in the x and y directions were 0.44 m and 0.72 m, respectively, and the top of the mannequin's head was 1.24 m above the floor. The distance between the mannequin's head and the ceiling was 1.21 m, which was somewhat smaller than the distance between the top of the human subject's head and the ceiling in the experiments of Craven and Settles (1.52 m).

At the initial time, the temperatures of the air, floor, walls, and ceiling were set to 20 °C. The mannequin's temperature was 25 °C, and this temperature was imposed throughout the simulation. Isothermal boundary conditions were imposed on the floor and walls. Although one would expect some warming of these surfaces over time, the simulations to be discussed were performed for sufficiently short periods of time that it is unlikely that these boundary conditions would greatly affect the results to be reported. The temperature of the ceiling was not imposed after the initial instant in time so that its temperature could gradually rise due to the thermal plume above the mannequin. Thermal conduction was permitted through a layer of thermal insulation above the ceiling that was 0.11 m thick. The air was initially motionless throughout the room. Any motion of the air was, therefore, caused by thermal buoyancy.

2.2. Numerical methods

The simulations were performed with a lattice Boltzmann method (LBM) that was developed by Inamuro et al. [11,12]. The Boussinesq approximation was used to incorporate buoyancy into the Navier–Stokes equation. There are two classes