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Modelling airflow, heat transfer and moisture transport around a standing human body by computational fluid dynamics☆

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ABSTRACT

In this study a combined computational model of a room with virtual thermal manikin with real dimensions and physiological shape was used to determine heat and mass transfer between human body and environment. Three dimensional fluid flow, temperature and moisture distribution, heat transfer (sensible and latent) between human body and ambient, radiation and convection heat transfer rates on human body surfaces, local and average convection coefficients and skin temperatures were calculated. The radiative heat transfer coefficient predicted for the whole-body was 4.6 W m^{-2} K^{-1}, closely matching the generally accepted whole-body value of 4.7 W m^{-2} K^{-1}. Similarly, the whole-body natural convection coefficient for the manikin fell within the mid-range of previously published values at 3.8 W m^{-2} K^{-1}. Results of calculations were in agreement with available experimental and theoretical data in literature.

1. Introduction

With the improved computer technology and CFD techniques, analysis of complex HVAC systems based on numerical calculations with sufficient accuracy and acceptable results is now possible for HVAC researchers [1–4]. Previous researches for thermal sensation used to be carried out by means of experiments. However, researchers have also used combined numerical simulation of CFD and radiation with experimental studies for thermal sensation. Many difficulties are emerged with numerical simulation method for airflow, thermal radiation and moisture transport due to thermo-physiological properties, complex shape of human body and all parameters of heat and mass transfer. In previous studies researchers used to simplify these parameters. For instance, researchers regarded the human body as a heat source without complicated physical shape. But, it is known from the experimental and theoretical data in literature, the physical shape of human body has great influence on the indoor climate. Thermal sensation of humans is dependent on local heat transfer characteristics of the human body surfaces. For this reason, consideration of local heat transfer characteristics of human body surface is highly important for numerical calculations with sufficient accuracy and acceptable results [5].

In this study, we used a combined numerical simulation model for airflow, thermal radiation, heat and moisture transfer with thermo-physiological properties between human body and its surroundings. In calculations virtual thermal manikin with real dimensions and physiological shape compared to average real human body is used.

2. Methods

2.1. Geometry of the manikin and the room

The room and manikin are modelled with CAD software package for flow field analysis. The CAD model of room and position of manikin in the room are shown in Fig. 1. In this study, numerical calculations were used to achieve the stagnant flow field in the room space. The manikin had the standard height (1.70 m), and weight (70 kg) and the total surface area (1.81 m^2). The manikin surfaces used in the simulation has 17 segments. The segments of the manikin are shown in Table 1. In calculations we assume that the manikin standing in a stagnant environment has naked body. For the standing human body, the metabolic heat production M was suggested as 100 W/m^2 based on the ASHRAE handbook [6]. The target of the air-conditioning system used in the simulation room was removing the heat and moisture production from the manikin. For this reason, supply velocity was 0.14 m/s and supply temperature was 22 °C. The wall surfaces of the room were taken as adiabatic for heat and moisture transport.

2.2. Computational grid

Today there are many computer software packages for indoor comfort analysis. In this study Fluent software is used for flow field, heat transfer and moisture transport analysis. Flow, temperature and moisture fields were calculated with three dimensional CFD. Fluent

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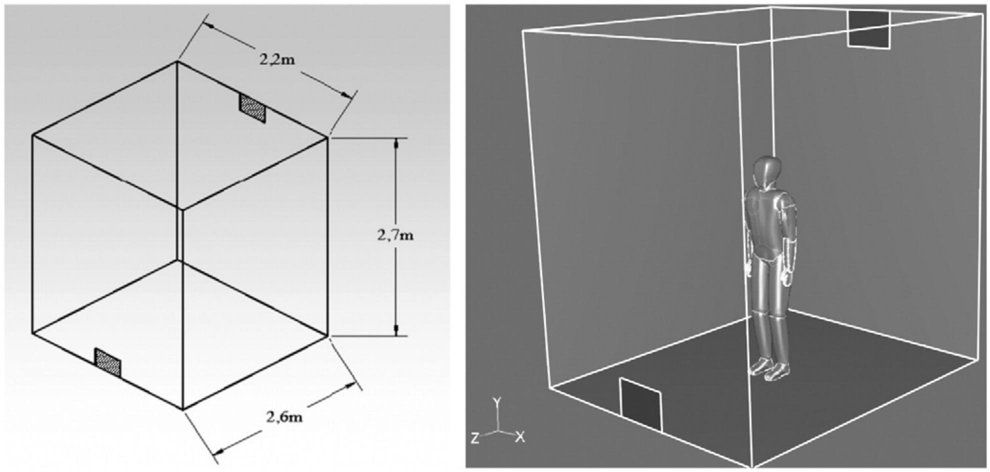


Fig. 1. Dimensions of CAD model of the room and position of the manikin.

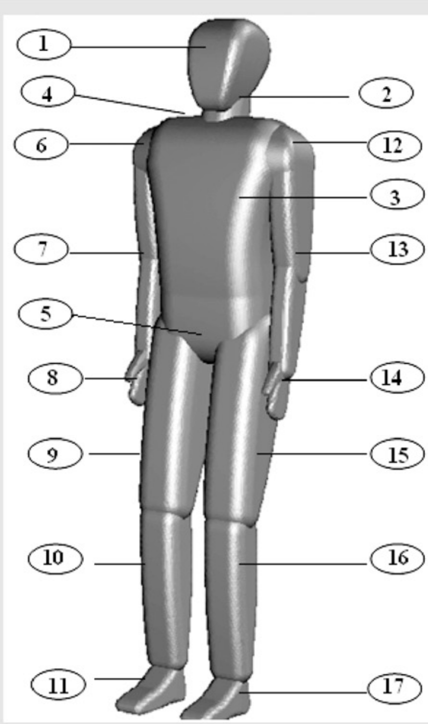
software solves continuum, energy and transport equations numerically with natural convection effects [7]. In numerical solution, second order discretization method was used for convection terms and Simple algorithm was chosen for pressure velocity coupling. We use (RNG) k–ε model for turbulence modelling. This turbulence model is generally used for such calculations due to stability and precision of numerical results in literature [8]. In this study, the radiation heat transfer is computed by the use of surface-to-surface radiation modelled by a discrete beam approach.

In the solution process, meshing is very important for the verification, stability and precision of the results. Unstructured grids are useful for complex geometries thus, tetrahedral elements were chosen for grid generation. Mesh structure of the surfaces of the manikin and the room are shown in Fig. 2. For grid generation, Gambit package software program is used. Computational domain consists of 1,500,000 tetrahedral elements. Meshes should be well designed to resolve important flow features which are dependent upon flow condition parameters. For this reason, the main volume of the room is subdivided into two parts. Second part of the main volume is the volume1 subtracted from volume2 to get the precise and stable results of the numerical solution in the environment of the manikin surfaces. The convergence is assumed when the normalized residuals of flow equations are less than 10^{-4} and the energy, concentration and radiation equations are less than 10^{-6}.

2.3. Boundary conditions

Table 2 shows the boundary conditions in detail for the surfaces of the thermal manikin and the wall as well as for the supply and exhaust openings.

Table 1
Segments of manikin and total area of surfaces of the manikin



Surface number	Surface name	Area (m^2)
1	Head	0.130
2	Neck	0.019
3	Chest	0.280
4	Back	0.140
5	Pelvis	0.018
6	Right shoulder	0.023
7	Right arm	0.139
8	Right hand	0.025
9	Right thigh	0.234
10	Right leg	0.147
11	Right foot	0.046
12	Left shoulder	0.023
13	Left arm	0.139
14	Left hand	0.025
15	Left thigh	0.234
16	Left leg	0.147
17	Left foot	0.046
Total surface area		1.81
Height		1.70 m