Building and Environment 99 (2016) 210–220

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Fundamental study of ventilation in air layer in clothing considering real shape of the human body based on CFD analysis

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ARTICLE INFO

Article history:
Received 27 November 2015
Received in revised form
28 January 2016
Accepted 29 January 2016
Available online 3 February 2016

Keywords:
Clothing
Air layer
Ventilation
Computational fluid dynamics
Three-dimensional laser scanner
Thermal comfort

ABSTRACT

To properly predict thermal comfort using a thermal model of the human body, heat and moisture transfer in and around clothing as well as the thermophysiological response of the human body must be evaluated. Among the phases for modeling heat and moisture transfer in and around clothing, ventilation in the air layer in clothing is one of the most difficult elements to quantify. The low air velocity in clothing and the complex shape of the air layer complicates measurement. In this study, computational fluid dynamics (CFD) analysis around the human body considering the air layer in clothing was conducted instead of measurement. By importing three-dimensional (3D) shape data obtained by a laser scanner, the air distribution in and around clothing was observed by CFD analysis, for an adult human wearing single-layered clothing in typical indoor environmental conditions. The typical characteristics of the air flow around a clothed human body were clarified, and the influence of the ventilation of clothing air layers on the heat flux at the skin surface under the clothing was determined to be minimal. In addition, the results of the CFD analysis were consistent with those of a thermal manikin experiment, validating the CFD analysis.

1. Introduction

Several multi-node human thermal models have recently been proposed to create high-resolution temperature distributions of the human body [1–3]. In these models, the shape of the human body is precisely expressed. Thus, to adequately employ these human thermal models, the clothing model should also precisely express the local characteristics of the heat and moisture transfer at each part of the body. One treatment is to estimate the thermal resistance of clothing for each segment [4–7]. However, convective heat transfer and ventilation in clothing have not been quantitatively characterized, and the rational treatment of these factors is incomplete due to the difficulty of measuring air movement in the air layer formed by clothing. The air velocity to be measured is generally low and is distributed to all openings of the clothing (e.g., collar, cuff, and hem) and the surface of the clothing (pores in the cloth). Although several trials of local measurement of ventilation characteristics have been conducted [8–11], the complex shape of clothing hinders a comprehensive understanding of convective heat transfer and ventilation. Consequently, in the simulation models proposed thus far, ventilation is often neglected or treated as a decrease in the thermal resistance of clothing [12,13].

Computational fluid dynamics (CFD) is a powerful tool to address this problem by obtaining the air flow distribution without measurement. However, to characterize the real air distribution in the air layer of clothing, the calculation load becomes huge because the complex shape and small size of the air layer between the clothing and skin requires a large number of mesh divisions (control volumes) to numerically solve the basic equations of fluid dynamics. Thus, CFD analysis of the human body considering the air layer in clothing has not been fully attempted. Several studies have conducted CFD analysis around the human body [14–19], and some have considered the real shape of the human body [20–24]. However, clothing has not been considered precisely. Several studies have considered air movement in clothing using a simplified shape of the human body and the air layer in clothing [25–27]. Wang et al. [28] considered the permeation of clothing by air in CFD analysis, but the shape of the human body and the air layer in clothing were simplified.

In this paper, a whole-body 3D laser scanner was employed to capture the real shape of the human body and the air layer, and CFD analysis was conducted to simulate the air distribution in a whole

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http://dx.doi.org/10.1016/j.buildenv.2016.01.028
0360-1323/

Table 1
Dimensions of manikin and T-shirt.

Manikin		T-shirt		Area of air layer aperture	
Height	1.71 m	Garment length	0.68 m	Lower hem	272.9×10^{-6} m^2
Bust	0.89 m	Circumference at chest	0.98 m	Sleeves (sum of both sides)	8.8×10^{-6} m^2
Waist	0.80 m	Sleeve length	0.20 m	Neck	2.0×10^{-6} m^2
Hips	0.95 m	Thickness	0.0005 m	Volume of air layer	
Body surface area	1.64 m^2	Surface area	0.73 m^2		7.8×10^{-3} m^3

room by inputting the shape data, with a focus on the clothing air layer of a human standing at the center of the room. The characteristics of the air distribution and the ventilation in the air layer of the clothing were analyzed for the case of an adult male manikin wearing only a T-shirt under several typical environmental conditions both with and without forced convection. In addition, the simulation was validated by comparison with the data from a thermal manikin experiment.

2. Method

2.1. Scanning the shapes of the manikin and clothing

As a basic condition, a T-shirt with half sleeves was analyzed as the clothing condition in this paper. A manikin with the dimensions of an average Japanese male in his twenties (Nanasai MD-20A) in a standing posture was the measurement target. The dimensions of the manikin and T-shirt are listed in Table 1.

The position coordinate data of the body and clothing surfaces were measured with a 3D laser scanner (Hamamatsu Photonics C9036). This instrument irradiates an object with a laser and uses reflected light to measure its surface position coordinates. As shown in Fig. 1, two scans were conducted; the first scan was conducted for the standing naked manikin, and the second scan was conducted for the manikin with a T-shirt. To obtain the shape of the air layer between the skin and the clothing, the scanned image without clothing was subtracted from the scanned image with clothing. For this procedure, the manikin was carefully maintained in the same posture and position in both scans.

2.2. CFD analysis by importing the scanned shape data of the human body and the clothing

The object of the CFD analysis was a rectangular room in which the male manikin wearing a T-shirt stood at the center (Fig. 2). A coordinate system with its origin at the center of the floor was introduced to the region of the analysis, as shown in Fig. 2 (x was the direction of the width of the room, y was the direction of the depth of the room, and z was the direction of the height of the room). The position coordinates of the surfaces of a male manikin and the T-shirt measured by the scanner were imported to create the CFD analysis model. A homogeneous thickness of clothing was established based on the scanned surface (the outer surface of the clothing).

The air in the clothing and the room air were continuous through the openings of the clothing and the pores of the cloth surface. To consider the air permeation through clothing, the clothing was treated as “air with hypothetical heat and air transfer resistances of the clothing” in the CFD analysis. In the momentum conservation equation, the pressure loss due to the porous material of the clothing was represented by Darcy's law, as shown in equation (1):

$$\Delta P = R \cdot v, \qquad (1)$$

where P is pressure (Pa), R is air resistance (Pa·s/m), and v is air velocity (m/s). The resistance was assumed to be isotropic. In the heat balance equation, the thermal resistance due to the solid matrix of the cloth was added to the “clothing” region.

A commercial code, SCRYU/Tetra Ver. 11 [29], was employed for the calculations, and a low-Reynolds number-type k-ε turbulence model [30] was used. Additional details of the conditions are summarized in Table 2. An example of the mesh design around the human body of the CFD model is shown in Fig. 3. The space was divided into discrete small solid figures, primarily tetrahedrons and pyramids (the lengths of the sides ranged from 1 to 64 mm), and prisms for finer divisions at the surfaces of the skin, clothing, and walls of the room (five layers of prisms with a sides of ca. 0.4 mm for the skin and clothing surfaces and 7–10 mm for the wall surface). The convergence was considered completed when the average fluctuation was less than 10^{-4} for all variants (velocity, pressure, temperature, kinetic energy of turbulence, and dispersion of turbulence).

As the boundary conditions, the surface temperatures of the walls and the skin were maintained constant (Table 2). The skin temperature was set to a homogeneous temperature of 35 °C for clothed skin and an unclothed head, whereas the skin temperature for the unclothed segment, with the exception of the head, was set to 28 °C. Radiation analysis was omitted due to the limitations of the CFD analysis code employed in this analysis. To consider air permeation through the clothing, the clothing was treated as special “air” with air resistance equivalent to a hypothetical porous material; consequently, the clothing cannot be recognized as a radiative surface in the current CFD code. Both the surface temperatures of the skin and the wall of the room were fixed as boundary conditions, and therefore only the clothing temperature was influenced by radiation. Furthermore, the radiation heat fluxes both from skin to clothing and from clothing to the ambient wall were simultaneously neglected. Therefore the error induced by neglecting radiation did not significantly influence the air flow and temperature distribution results in this analysis.

2.3. Calculation cases

The calculations were conducted for eight cases, as shown in Table 3. All calculations were for the steady state. The conditions of the air flow in the room and the clothing air permeation were varied, as indicated in Table 3. For the conditions of the air flow in the room, the following patterns were targeted: (a) natural convection (driven only by the temperature differences, with no forced convection); (b) air conditioning (air is supplied from the upper wall with a velocity of 4 m/s and with an angle of 45° upper to the vertical wall behind the person, and the outlet is positioned at the bottom of the wall in front of the person, as shown in Fig. 2); (c) air flow from the entire wall facing the human with an air velocity of 1.5 m/s; and (d) air flow from the entire wall facing the human with