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Experimental study of the effects of human movement on the convective heat transfer coefficient

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ABSTRACT

This present study is dedicated to the analysis of the effects of moving speed, moving direction angle and temperature difference between human body and environment on the convective heat transfer coefficients of the human body. The experiments were carried out in a full-scale cabin with a thermal manikin. Five moving speeds of the manikin (0.2, 0.5, 0.8, 1.1 and 1.3 m/s) were carried out with a motor on a 10 m-length-rail, and four temperature differences were selected (4, 8, 12 and 16 °C) by changing the heating power of the manikin. Eight moving direction angles between the moving direction and the manikin face were set. In each experimental case, the temperatures of the environment and the wall in different heights were measured by the thermocouples to calculate the convective heat transfer coefficients. Through comparison with experimental data of the human body in wind tunnel, it can be demonstrated that the effect of the moving speed on the convective heat transfer coefficients is weaker than that of wind speed for the trunk parts of the manikin, while stronger for the upper limbs. The convective heat transfer coefficients are obviously affected by the moving direction angles under the moving condition for different body parts: in general the body parts having higher convective heat losses when they move against the wind. The experimental results also show that the convective heat transfer coefficients increase as the moving speeds and the temperature differences, i.e., the higher values correspond to the higher speeds and the higher temperature differences.

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1. Introduction

Nowadays people are on a growing demand for the heat resistance to living environment and thermal comfort [1]. In order to balance the energy efficiency and the comfort requirement, further efforts to study the heat exchange between the human body and the environment are needed [2]. During the last decade, researchers have already conducted several experiments to discuss the detailed knowledge of the heat exchanges between the human body and the environment [3–9], among which it can be speculated that the environment and the posture of the human body affect more for the convective heat transfer coefficient than the radiative heat transfer coefficient. Hence, the researches of the convective heat transfer coefficients under different conditions are important and necessary.

For experimental studies, the whole body convection heat transfer coefficient was characterized as equal to 5.1 W/(m^2 K) by Colin and Houdas [10], 4.0 W/(m^2 K) by Seppänen et al. [11] and 3.1 W/(m^2 K) by Mitchll [12]. Omori et al. [13] presented a value of 3.3 W/(m^2 K) for the standing posture. Ono et al. [2] measured the convective heat transfer coefficient of the human body in outdoor environment with a thermal manikin placed in a wind tunnel complemented with a CFD analysis. Oguro et al. [14–16] measured the convective heat transfer coefficient for each part of the human body under both the airflow and the calm conditions. During the last two decades, experimental researches have been focused on the effects of wind speed, wind direction angle, temperature difference, body posture and walking on the convective heat transfer coefficient. Using a thermal manikin in an immobile state, de Dear et al. [17] measured the convective heat transfer coefficients of the human body under different wind speeds and wind direction angles in the wind tunnel. The convective heat transfer coefficients were found to change as a power exponent function of the wind speed, and affected by wind direction angles mainly in the part of limbs. For the temperature difference cases, extensive researches were realized by Oliveira et al. [18] using a thermal in swinging the limbs, which suggested that the convective heat transfer coefficient was generally positive correlated with the temperature difference between the human body and the environment. For the posture cases, Quintela et al. [19] conducted the experiments considering three postures (standing, sitting and

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lying). The results indicated that the lying posture appeared to be more efficient than the standing and sitting postures for the heat exchange by the convection.

In the above experiments, the thermal manikin was generally put in a climate chamber and different environmental settings by the adjustment of wind tunnel and other instruments were implemented. Due to the manikins being in an immobile state or swinging the limbs in the experiment, there comes the question that both the limbs pendulum and the wind tunnel conditions cannot fully display the status of human movements in reality. In this work, experimental investigation was conducted in a full-scale cabin with a long track, to achieve the real movements of the manikin and assess the convective heat transfer coefficients for the different 20 body parts, under the conditions of different moving speeds, moving direction angles and temperature differences between human body and environment.

2. Methods

2.1. Experimental setup

The experiment was conducted in a full-scale cabin (24 m × 2.3 m × 2.6 m) with a thermal manikin. The thermal manikin (named as "Newton", MTNW) was mainly composed of epoxy metal materials. The heating devices were built under the innermost layer of the skin and the temperature sensors were embedded in the surface of the skin. This manikin was articulated and divided into 20 parts independently controlled by the computer. In this study, the realization of the manikin's constant moving speed relied on a 10 m-long-rail (10 m × 0.56 m × 0.09 m) located in the middle of the cabin, and a trolley (0.6 m × 0.6 m × 0.165 m) with a regulated speed motor was on the rail. The frequency of the motor could be manually adjusted and different frequencies corresponded to different speeds of the trolley. It took about 0.5 s for the trolley to achieve the set speed through repeated test, and the uniform motion time of the manikin was about 20 s at the speed of 0.5 m/s, which meant that the acceleration time was much less than the uniform motion time. Hence it was feasible to assume that the manikin was in a state of constant moving speed. Fig. 1 is a schematic diagram of the experimental setup. It should to be noted that the cabin was long enough to reduce the limitation effects of the wall at the two ends of the flow field [20].

2.2. Physical parameters

The physical parameters of the experiment were measured, including the skin temperature and heating power of different parts of the manikin, the temperature of the ambient air and the wall, and the air velocity of the environment (Fig. 1). For measuring the air velocity before the manikin movement, eighteen one-dimensional hot-wire anemometers with three locations in *Y* direction were used (Kanomax, system 6242 with model 1550, 1504 and velocity probe 0963-00 A200, Japan). Every six anemometers were placed as two groups with two locations (0.6 m, 1.2 m) in *Z* direction on one pole (Fig. 1(b)). The poles were placed for every 3 m along the rail, and the first one was placed 2 m away from the beginning of the rail, as shown in Fig. 1(c). Three measurements were operated in which the anemometers were settled to face the *X*, *Y*, *Z* direction, respectively. The anemometer measurement velocity ranged from 0.1 to 4.99 m/s with the resolution of 0.01 m/s and the sampling frequency of 10 Hz. de Dear et al. [17] stated that if the wind speed was less than 0.1 m/s, the experiment was conducted under the still air condition. In this work, all data of air velocity before the manikin movement was less than 0.1 m/s. The thermocouples for wall temperature were placed on the wall, and 4.5 m away from the beginning of the rail (OMEGA, type K CHROMEGA®-ALOMEGA, model CO1-K, America). The thermocouples for air temperature were placed near the wall, and 5.5 m away from the beginning of the rail (OMEGA, model 5TC-TT-K-36-36, America). The location of the thermocouples for wall temperature is shown in Fig. 1(c). The thermocouples for air temperature were at different heights corresponding to the 20 parts of the manikin body, and the location in *Z* direction is given in Table 1. In addition, the temperature and heating power of the skin were measured directly through the computer connected to the manikin.

2.3. Experimental cases

The experimental cases include moving speed, moving direction angle and the temperature difference between the human body and environment. Five set speeds were selected by changing the frequency of the motor: 0.2, 0.5, 0.8, 1.1 and 1.3 m/s. Eight moving direction angles between the moving direction and the manikin face were fixed for the manikin. Four temperature differences between the human body and environment were set: 4, 8, 12 and 16 °C. Since the environment temperature was uncontrollable in this work, the different temperature differences between the manikin and the environment were achieved by regulating the manikin temperature according to the environment temperature. With the above three settings of the experimental conditions, 160 kinds of experimental cases were designed in this study, shown in Table 2. In addition, in order to ensure the accuracy of the data and avoid the operation error, each experimental case was repeated three times.

2.4. Calculation of h_c

The heat exchange between the human body and the environment (Q) in this experiment can occur by convection (C), radiation (R) and conduction (K). As the conduction is limited to the body parts in contact with solid surfaces, the heat transfer by the conduction is much less than that by the convection and the radiation when the manikin is exposed to the air thus can be neglected [18]. As the superficial area of the manikin is considered to be much smaller than that of the wall in the presented study, the heat transfer by convection and radiation can be generally simplified as below [21]:

$$C = h_c \times (T_{sk} - T_a) \times A_{sk} \tag{1}$$

$$R = \varepsilon_{sk} A_{sk} (\sigma T_{sk}^4 - \sigma T_w^4) = h_r \times (T_{sk} - T_w) \times A_{sk} \tag{2}$$

where h_c and h_r are the convective and the radiative heat transfer coefficient (W/(m^2 K)), T_{sk}, T_w and T_a represent the temperatures of the body surface, the wall and the environment (K), respectively. σ is the Stephan–Boltzman constant (5.67 × 10–8 W/(m^2 K)). ε_{sk} is the blackness of the manikin which can be assumed as 0.82 (from the NEWTON Instruction) in this experiment.

Thus, Eqs. (1 and 2)can be expressed in terms of h_c and h_r by:

$$h_r = \frac{\varepsilon_{sk}(\sigma T_{sk}^4 - \sigma T_w^4)}{T_{sk} - T_w} \tag{3}$$

$$h_c = \frac{q}{T_{sk} - T_a} - h_r = \frac{q}{T_{sk} - T_a} - \frac{\varepsilon_{sk}(\sigma T_{sk}^4 - \sigma T_w^4)}{T_{sk} - T_w} \tag{4}$$

where q is the total heat transfer density between the skin surface and the environment.

In this study, the control mode of the thermal manikin is the constant power control in consideration of decreasing the apparatus system error. Due to the finite length of the track, the surface temperature of the manikin was decreasing during the process of

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