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Theoretical analysis of the effects of human movement on the combined free-forced convection

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ABSTRACT

The airflow pattern close to a moving human is proved to be a combined free-forced convection due to the temperature difference between the moving human and the environment. In this paper, theoretical analysis was conducted to study the effects of human movement on the mixed convective heat transfer, expressed by Nusselt, Reynolds and Grashof numbers. The correlations of these non-dimensional numbers for each segment of the human have been established. It can be demonstrated that the increasing values of the Reynolds (forced convection) and Grashof (natural convection) numbers take a positive effect on the total rate of convective heat transfer, and the proportions of the forced and natural convection are on the same level. The heat transfer of the mixed convection is affected by the specific geometry characteristic of the different body segments. For the windward and leeward body segments, the heat transfer of mixed convection is more obvious during the human movement than other segments, while the heat transfer of mixed convection for the upper limbs by the body sides are much less obvious. In addition, a detailed information of the flow field around the moving body can be speculated from the correlation equations of the mixed convection for 18 body segments.

1. Introduction

An important goal in thermal comfort research is an enhanced understanding of the relationship between the human body and the surrounding environment [1]. Since the advent of thermal manikin in 1940s, researchers have already conducted several experiments to investigate the detailed knowledge of the heat exchanges between the human body and the environment [2–8], among which it can be speculated that the environment and the posture of the human body affect more for the convective heat transfer than the radiative heat transfer. During the last decade, experimental researches have been focused on the effects of wind speed, wind direction angle, temperature difference, body posture and limbs swing on the convective heat transfer coefficient [9–14]. One of the most noted study was by de Dear et al. [15], who measured the convective heat transfer coefficients of the human body under different wind speeds and wind direction angles in the wind tunnel, and correlated the convective heat transfer coefficients as a power exponent function of the wind speed. Among the researches, it is worth mentioning that Oliveira et al. [16] analyzed the correlation between the Nusselt and Grashof numbers, which suggested the flow regime and heat transfer results of the natural convection.

A review of the literature has shown that when dealing with the forced convection in the manikin experiment, the effects of free convection were usually ignored, as $(Gr/Re_L^2) \ll 1$. However, when there is an unstable temperature gradient, situation may arise for which free and forced convection effects are comparable, in which case it is inappropriate to neglect either process. In a combined natural and forced convection, both natural and forced convection participate in the heat transfer process. The forced flow can be in the same direction as the flow created by natural convection (called assisting flow), opposite direction (called opposing flow), and perpendicular direction (called transverse flow) [17]. During the past decades, several experiments have been conducted to study mixed convection heat transfer under different indoor environments, accordingly, heat transfer correlations in terms of a combination of the dimensionless numbers were also proposed [18–21]. However, very few works have dealt with mixed convection created by human movement, which is a kind of transverse flow. Therefore it is of great challenge and importance to understand the heat transfer characteristics of mixed convection caused by human movement.

In this work, using experimental data of the convective heat transfer coefficients of a moving manikin [22], Nusselt, Reynolds

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and Grashof numbers for the 18 different body parts, under the conditions of different moving speeds and temperature differences between human body and environment are investigated. The purpose of this paper is to correlate mixed convection heat transfer results for human movement by an expression of Nusselt, Reynolds and Grashof numbers, then investigate the effect of specific geometry characteristics of body segments on mixed convection, and speculate the effect of human movement on the airflow motion and heat transfer.

2. Methods

2.1. Experimental detail

The experiment was conducted in a full-scale cabin (24 × 2.3 × 2.6 m) with a thermal manikin (named as "Newton", MTNW). The realization of the manikin's constant moving speed relied on a 10 m-long-rail (10 × 0.56 × 0.09 m) located in the middle of the cabin, and a trolley (0.6 × 0.6 × 0.165 m) with a regulated speed motor was on the rail, which can realize a range of speed from 0 to 1.3 m/s. 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. A more detailed description of this experiment was shown in Ref. [22], and Fig. 1 is a schematic diagram of the experimental setup. The convective heat transfer coefficients of different body parts were obtained from the heat balance between the human body and the environment [22].

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. Here two moving direction angles were fixed between the moving direction and the manikin face. Four temperature differences between the human body and environment were set: 4, 8, 12 and 16 °C.

2.2. Combined free-forced convection

The airflow pattern close to the moving body might be a mixed convection flow due to the temperature differences between the manikin and the environment. The importance of buoyancy forces in a mixed convection flow can be measured by the ratio of the Grashof and Reynolds numbers:

$$\frac{Gr}{Re^2} = \frac{g\beta\Delta TL}{\upsilon^2} \tag{1}$$

where g (=9.8 m/s^2) is the gravitational acceleration, β is the thermal expansion coefficient, which can be assumed as the reciprocal of the temperature for the ideal gas, ΔT is the temperature

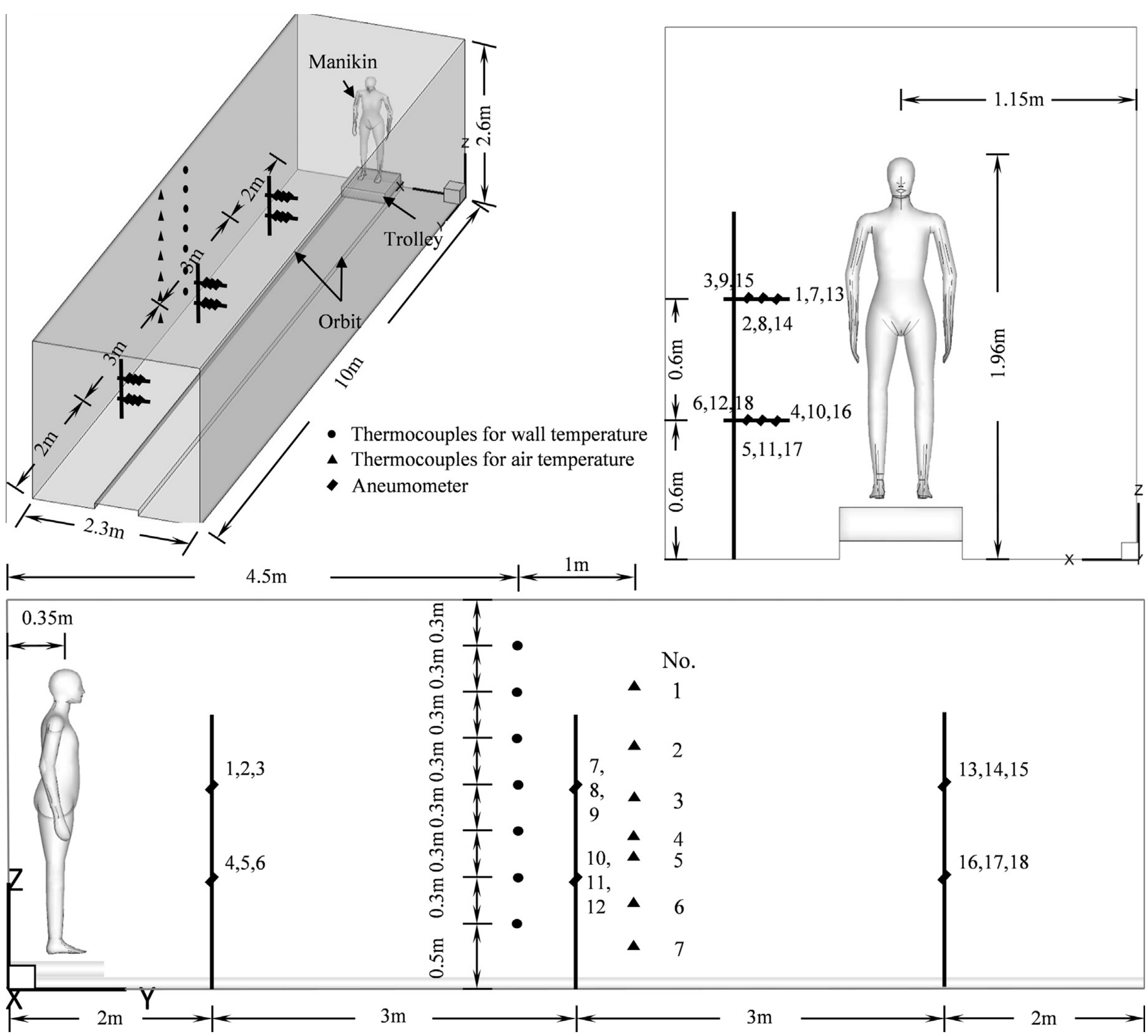

Fig. 1. Schematic diagram of the experimental setup.