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Analysis of natural and forced convection heat losses from a thermal manikin: Comparative assessment of the static and dynamic postures

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ABSTRACT

The present experimental work is dedicated to the analysis of the effect of walking movements and air velocity on the convective heat transfer coefficients (h_{conv}) of the human body. A wind tunnel and an articulated thermal manikin of the Pernille type with sixteen body segments were used. Beyond the standing posture (static condition), a step rate of 45 steps/min was selected, corresponding to a walking speed of 0.51 m/s (dynamic condition). The free stream air velocity was varied from 0 to about 10 m/s. The experimental conditions were thus varied from natural to forced convection. The convection coefficients for the different body segments and the whole body were determined for each air velocity giving details about the differences between them.

In the case of the whole body, for the standing static reference posture and free convection, the mean value of h_{conv} was equal to 3.5 W m^{-2} °C^{-1}. In the dynamic condition the corresponding h_{conv} value was 4.5 W m^{-2} °C^{-1}. In forced convection, the highest values correspond to the highest wind speed and were equal to 22.4 W m^{-2} °C^{-1} for the static condition and 23.0 W m^{-2} °C^{-1} for the dynamic posture.

1. Introduction

The Kyoto Protocol and all the foregoing initiatives have been underlining the need for the reduction of energy consumption related with global climate changes. Such goal has several effects on industry, transportation and built environment, among others. In a certain sense, the EU Directive 2010/31/EU on the energy performance of buildings is a recognition that further efforts are needed in order to balance between building quality, energy efficiency and comfort requirements. With this in mind, and whenever we deal with human occupancy, it seems acceptable that improved analysis of heat transfer phenomena around human body may be of interest for such matters. The present contribution is directed to this particular goal. According to the latest experimental and numerical developments characterized by an increasing need for detail, this study is focused on the experimental evaluation of convective heat transfer coefficients for the whole human body and the body parts. Discussion about the convective trends in natural, mixed and forced regimes is also foreseen.

When heat transfer coefficients are considered, it must be recognized that most data available in the literature refer to the whole body and some of the first studies took place in the thirties by Büttner (1934) and Gagge (1937). Later on, the whole body natural convection heat transfer coefficients were characterized as equal to 5.1 W m^{-2} °C^{-1} by Colin and Houdas (1967), 4.0 W m^{-2} °C^{-1} by Seppänen et al. (1972) and 3.1 W m^{-2} °C^{-1} by Mitchell (1974). Afterwards, de Dear et al. (1997) obtained values of 3.4 and 3.3 W m^{-2} °C^{-1} for a standing and sitting thermal manikin, respectively, and Omori et al. (2004) proposed a value of 3.3 W m^{-2} °C^{-1} for the standing posture. With the development of thermal manikins, the heat losses from each part of the body have also been addressed and a set of data is now available.

Oguro et al. (2002a) and Quintela et al. (2004) proposed expressions to calculate h_{conv} in natural convection as a function of the difference between the skin and the air temperatures ($\overline{T}_{sk}-T_a$). While Oguro et al. (2002a) considered a manikin dressed and nude for both standing and sitting postures, in the work of Quintela et al. (2004) the experimental determination of convective and radiative heat transfer coefficients in standing, sitting and lying postures were considered.

Nilsson (2004) assessed the repeatability of heat transfer coefficients by considering five independent calibrations performed from

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1995 to 1998 and the results showed that the mean standard deviation was 8% for all zones. Kurazumi et al. (2008) have also investigated the convective and radiative heat transfer coefficients, focusing their research on the convective heat transfer area of the human body. Under natural convection conditions, the mannequin was placed in seven postures and the radiative heat transfer coefficient was determined for each posture and empirical formulas were proposed for the convective heat transfer coefficient of the entire human body, driven by the difference between the air and mean skin temperatures.

The effect of body motion was first considered in the work of Chang and Gonzalez (1989) using the sublimation technique with circular naphthalene disks affixed to five different segments of one articulated manikin. The static posture and four walking gaits (20, 40, 68 and 80 steps/min) were studied. The results for the heat transfer coefficient by convection have an intrinsic local nature and should not be compared with more recent thermal manikins where such coefficients are averaged through the surface of different parts.

More recently, the effect of walking on the convective heat transfer coefficients was considered by Oliveira et al. (2012). Beyond the standing static posture, three step rates were considered (20, 30 and 45 steps/min) and the convective heat transfer coefficients for the whole body and for the different body segments were determined for each step rate. In the case of the whole body, for the standing static reference posture, a correlation for natural convection was also presented.

In the case of forced convection, a relevant study was developed by de Dear et al. (1997) through a wide range of wind speeds, varying from still air to 5.0 m/s. Both standing and sitting postures were investigated, as there were eight different azimuth angles. Another interesting work was carried out by Silva and Coelho (2002), considering three flow incidences (front, back and side) and two postures (seated and standing), and Oguro et al. (2002b) considered the same postures with the manikin nude and clothed facing upwind and downstream flows. Ono et al. (2008) measured the convective heat transfer coefficient for the human body in an outdoor environment by means of a thermal manikin placed in a wind tunnel complemented with a computational fluid dynamics (CFD) analysis. Different wind velocities were considered and the mean convective heat transfer coefficients for the whole body were 6.6, 10.0 and 16.3 W m^{-2} °C^{-1}, for 0.5, 1.0 and 2.0 m/s, respectively. In a different perspective, Defraeye et al. (2011) investigated the convective heat transfer for cyclists. The convective heat transfer coefficients of the whole body and of the 19 body parts of a cyclist were determined. Wind speed correlations based on power-law equations were proposed and the results have shown that the power-law exponent does not differ significantly for the individual body segments for all positions tested. More recently, Luo et al. (2014) considered five moving speeds of a manikin (0.2, 0.5, 0.8, 1.1 and 1.3 m/s) carried out with a motor on a 10 m-length-rail, and four temperature differences (4, 8, 12 and 16 °C) by changing the heating power of the manikin. They concluded that to explain the details of the differences between the moving condition and the wind tunnel condition, which may be caused by the flow field, further analysis of the flow field should be foreseen.

In a complementary perspective, extensive research has been done in the assessment of the thermal insulation of clothing, a field directly related to heat transfer by convection and radiation. When the analysis of human typical postures is considered and restricting the focus to experimental conditions close to the ones of the present study, i.e., considering the walking effect and high air velocity, the studies of Anttonen (2000); Nilsson et al. (2000); Havenith and Nilsson (2004); Anttonen et al. (2004) and Oliveira et al. (2008, 2011) are relevant contributions.

In the present work the convective heat transfer coefficients are addressed in a complementary perspective with novel approaches. Body motion is taken into account – a rather seldom feature considered in previous studies besides the work of Chang and Gonzalez (1989) – in both natural and forced convection, but the actual methodology as well as the thermal manikin differs significantly from the available in the eighties and followed by Chang and Gonzalez (1989). In addition, a wider range of air velocity is considered, up to 10 m/s. Such air velocity values are also not easy to find in other studies, and this distinct characteristic is presented in this paper. Several combinations of tests were performed and comparisons between static (i.e. standing still) and dynamic (i.e. walking at 45 steps/min) conditions are made. The main purpose is to measure convective heat transfer coefficients for all the conditions tested with the manikin operating under the thermal comfort regulation mode, a condition that represents another different approach and also not often addressed, besides the work of Oguro et al. (2002a) and Oliveira et al. (2012).

2. Methods

2.1. Heat transfer coefficients

The exchange of heat between a solid and the environment can occur by convection (C), radiation (R) and conduction (K). In the case of the human body, the heat transfer by conduction is limited to the body parts in contact with solid surfaces, which are generally restricted to a few, namely to the feet, and thus usually neglected. Therefore, the heat is transferred mainly by convection and radiation.

The study of convective heat transfer between the human body and the environment represents a great challenge. In fact, the heat transfer by convection depends on various factors and exact analytical solutions are actually not available. Hence, the heat transfer by convection is generally calculated making use of Newton's law of cooling (Fanger, 1972)

$$C = h_{conv} \times (T_s - T_a) \quad (1)$$

where h_{conv} is the convective heat transfer coefficient [W m^{-2} °C^{-1}] and T_s and T_a represent the mean temperatures of the body surface and the environment [°C].

For the dressed human body, the heat transfer by convection is calculated in an analogous way from (Fanger, 1972; Parsons, 2003)

$$C = f_{cl} \times h_{conv} \times (\overline{T}_{cl} - T_a) \quad (2)$$

where f_{cl} is the clothing area factor and $\overline{T}_{cl}$ is the mean clothing surface temperature [°C].

In the case of radiation, the heat transfer for the dressed human body is calculated by an expression similar to Newton's law (Fanger, 1972; Parsons, 2003)

$$R = f_{cl} \times h_{rad} \times (\overline{T}_{cl} - \overline{T}_r) \quad (3)$$

where h_{rad} is the radiative heat transfer coefficient [W m^{-2} °C^{-1}] and $\overline{T}_r$ is the mean radiant temperature [°C].

Therefore, in studies concerning the human body heat exchanges with the environment, the overall sensible heat released by convection and radiation, $\overline{Q}_s$ [W m^{-2}], can be calculated from the following equation:

$$\overline{Q}_s = f_{cl} \times h_{conv} \times (\overline{T}_{cl} - T_a) + f_{cl} \times h_{rad} \times (\overline{T}_{cl} - \overline{T}_r) \quad (4)$$

for the case of a clothed body (Fanger, 1972; Parsons, 2003), or from

$$\overline{Q}_s = h_{conv} \times (\overline{T}_{sk} - T_a) + h_{rad} \times (\overline{T}_{sk} - \overline{T}_r) \quad (5)$$

for the naked human body (Fanger, 1972; Parsons, 2003), where $\overline{T}_{sk}$ is the mean skin temperature [°C].