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Radiative and convective heat transfer coefficients of the human body in natural convection

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Abstract

The purpose of this study was to investigate the convective and radiative heat transfer coefficients of the human body, while focusing on the convective heat transfer area of the human body. Thermal sensors directly measuring the total heat flux and radiative heat flux were employed. The mannequin was placed in seven postures as follows: standing (exposed to the atmosphere, floor contact); chair sitting (exposed to the atmosphere, contact with seat, chair back, and floor); cross-legged sitting (floor contact); legs-out sitting (floor contact); and supine (floor contact). 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 under natural convection, driven by the difference between the air temperature and mean skin temperature corrected using the convective heat transfer area.

Keywords: Natural convection; Convective heat transfer coefficient; Radiative heat transfer coefficient; Heat transfer area; Posture; Human body

1. Introduction

The convective heat transfer coefficient and convective heat transfer area of the human body must be determined in order to calculate the convective heat exchange between the body and the environment. The studies on measurement of convective heat transfer between the body and contacting surfaces have not been reported.

The arms may be in contact with the sides and the thighs may be in contact with each other in standard postures. The standing posture leaves the body open to rather vigorous convective processes in the surrounding air. Even sitting positions can expose the body to convective flows, if the contacting areas are assumed to be very small, as most ordinary postures expose more body surface area to air currents than they shield, as demonstrated by the relatively area of contact between the feet and the floor in sitting and standing postures (non-convective heat transfer area). The calculation formulas taken into account these non-convective heat transfer areas have not been established, however. It is simple to assume that the standing and chair sitting positions expose "all" the body surface area, and this is probably why research has concentrated on these postures.

Most studies on convective heat exchange from the human body have focused on the convective heat transfer coefficient. Previous studies [1–40] have determined this

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coefficient by measuring local coefficients and then calculating the ratio of that area to the entire body surface area. If one considers the results given above, however, such calculations include non-convective heat transfer area, and are thus of questionable accuracy. According to the principles of heat transfer, it is necessary to use the convective heat transfer area to more accurately calculate the convective heat transfer coefficient. In fact, only a handful of studies have taken into account the local heat transfer area of the human body.

Previous research reports have also estimated total heat transfer from the body using physiological measurements and heat flow sensors, as well as standard formulas, and then used the radiated heat to calculate the convective heat transfer coefficient of the body. However, the angle factors (configuration factors) for the local body are necessary to calculate radiative heat transfer. These have not been found, and the suggested estimates for their values are very questionable.

Some researchers have focused on experimental rather than theoretical formulas. Some have used simple heat emitting devices or assemblies to model the convective heat transfer coefficient of the human body [1–5,41,42], some have used real subjects to investigate the heat balance of the human body [6–22,43], others have used thermal mannequins [10,23–37], and some have used the mass and heat transport properties of naphthalene [38–40].

The figures and formulas for convective heat transfer coefficient established in the above reports differ with experimental procedures and theoretical calculations. The body has a complex shape, and it stands to reason that measured values would vary in validity and accuracy when calculating the heat transfer coefficient, both for body parts and for the entire body. Furthermore, most of the above studies used standing or sitting postures to measure the convective heat transfer coefficient. As mentioned previously, researchers tend to select simpler postures for which the entire body surface area contributes to the convective processes.

These experiments have sometimes used different wind speeds to create conditions of forced convection, or used temperature differences between the air, skin, and floor to create conditions of natural convection. The experimental formula is based on the driving force behind the convection expressed as a function. Such figures and calculations have differed depending on the experimental methods and computational logic used. This is because the shape of the human body is complex, and there may be some variation in the validity and effective accuracy of the selected measurements used to calculate the heat transfer coefficient.

Much research has been carried out since Winslow et al. [6] published their partitional calorimetry method, and since Hardy and DuBios [8] published their direct calorimetry method for measuring the heat exchange between the human body and its surrounding environment through convection. However, these experiments assumed that convective heat exchange took place at a uniform rate across the whole body surface.

Starting with Nielsen and Pedersen [10] later experiments used models of the human body, and measured forced convection wind speeds in small discrete areas. These measurements were considered representative of natural convection, and convective heat transfer coefficients were thus calculated. All of these experimental methods worked on the assumption that convective heat exchange was diffused equally across the surface of the human body.

On the other hand, Lee et al. [24] applied Colin and Houdas' conception [11] of the influence of natural convection across the whole body to limited areas of the human body surface, and proposed a convective heat transfer coefficient based on a mixed air flow model incorporating rising airflow due to natural convection together with the forced convection currents. Experiments designed to estimate the heat transfer coefficient at the location of such mixed air flows have also assumed that convective heat exchange takes place uniformly across the locations into which the surface of the object has been divided, with the exception of surfaces that are in contact with the floor and physically unable to permit the passage of air.

In addition, Tanabe and Hasebe [25] and Kuwabara et al. [33] considered that in forced convection experiments using moderate wind speeds, airflow direction had a great impact on convective heat exchange on limited areas of the human body's surface. In the areas with the exception of surfaces in contact with the floor and physically unable to permit the passage of air, there are heat exchanges, irrespective of whether or not they were facing the direction of the air current. However, even these experiments which aimed to find the heat transfer coefficient of limited areas of the human body's surface due to forced convection, they are assumed that all the parts of the surface hold uniform convective heat exchange.

It is, therefore, apparent that to determine the convective heat transfer coefficient for a particular direction of air flow or at a particular point is difficult, and that even those studies purporting to measure the coefficient at one particular point assume a uniform rate of heat exchange across the whole surface of the object under investigation. In other words, prior studies have been founded on the assumption that even under airflows with varying properties, convective heat exchange occurs evenly across the whole surface of the human body.

Most researchers have used a convective heat transfer area ratio of 1.0 for the convective heat transfer area for calculations of convective heat transfer area in the standing and chair sitting postures. According to Refs. [44,45], however, Kurazumi et al. took measurements and found that 10–20% of the body surface area did *not* contribute to the convective heat transfer surface.

It is commonly thought that the body's radiative heat transfer coefficient is calculated in the same way as the convective heat transfer coefficient and heat balance, but