Experimental Thermal and Fluid Science 77 (2016) 257–264

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Determination of convective and radiative heat transfer coefficients using 34-zones thermal manikin: Uncertainty and reproducibility evaluation

Miloš Fojtlín *, Jan Fišer, Miroslav Jícha

Department of Thermodynamics and Environmental Engineering, Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, 616 69 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 13 April 2016
Accepted 17 April 2016
Available online 19 April 2016

Keywords:
Thermal manikin
Heat transfer coefficient
Experimental work
Thermal comfort
Uncertainty evaluation

ABSTRACT

A lot of research has been done in order to investigate heat transfer coefficients of a human body in various postures, wind speeds and wind directions. However, there has not been any reference to measurement reproducibility and measurement confidence intervals. The purpose of this study is to determine heat transfer coefficients of a thermal manikin experimentally, while focusing on the repeated determination of the coefficients and statistical data evaluation. The manikin imitates human metabolic heat production; it measures combined dry heat flux from its surface and also its surface temperature.

The major part of the radiative heat flux was eliminated by a low-emissivity coating applied to the surface of the nude manikin. The tests were performed across 34 zones that correspond to parts of a human body. Both standing and seated postures were investigated. The tests were conducted at constant air temperature (24 °C) and constant wind speed (0.05 m s^{-1}). Based on three repetitions of each case, the mean values of heat transfer coefficients, with their uncertainty intervals, were calculated. Next, the results of this paper were compared to the results of similar experimental work of de Dear et al. (1997) and Quintela et al. (2004). A mismatch of the values is up to 1 W m^{-2} K^{-1}, while an extreme was found on the manikin's seat with a difference of over 1 W m^{-2} K^{-1}. The outcomes of this study provide essential information in form of separated values of the convective and radiative heat transfer coefficients that enable us to create detailed computational models of a thermal comfort.

1. Introduction

The analysis of heat exchange from a human body has been drawing a lot of interest for decades. Through the years, plentiful approaches have been developed to determine the heat transfer (eg., [1–15]). Clearly, motivation for this is simple. Urbanization made people to spend less of their time outdoors where the ambient conditions are given by the actual weather. Today, statistics show that average European citizens spend 80–90% of their workday time indoors, in buildings or vehicles [16]. Owing to this, a building design in terms of thermal comfort, air quality, and low energy demands is important. In addition, many independent studies provide evidence of improper thermal environment and its negative influence on the human body (e.g., [17,18]). However, such situations can be tackled, in the future, using modern computational methods. To do so, there is a need for anatomically detailed heat transfer coefficients.

The heat transfer coefficients represent an amount of heat transferred between the body and the ambient environment. The majority of the heat is exchanged via convection and radiation. In case the convection and radiation are not sufficient to cool down a human body, excretion of sweat and its evaporation takes place. Evaporation is based on mass transfer during which the latent heat is consumed. Since, there is a focus on the cases close to a thermal comfort state, only dry heat loss will be further examined—the cases disregarding sweating. The third mode of heat transfer, conduction, can be neglected, when there is a minor contact with solid objects. It is also the case of this study.

The very first studies, to determine the heat transfer coefficients, involved experimental subjects exposed to various thermal conditions [3–5]. Later on, simple heat emitting devices were used to simulate heat transfer, such as Stolwijk's 25-node model [19]. Nowadays, there is a greater demand for anatomically detailed and accurate heat transfer coefficients, resulting in the use of

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* Corresponding author.
E-mail address: fojtlin@eu.fme.vutbr.cz (M. Fojtlín).

http://dx.doi.org/10.1016/j.expthermflusci.2016.04.015
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modern technologies, typically thermal manikins of different kinds. Current manikin constructions resulted in the segmentation of their bodies into zones (segments) representing major human body parts (upper lower limbs, chest, back, etc.). Consequently, manikins have been examined in various body postures, with moving limbs, and under various air flow regimes. A full scale of possible manikins' applications is addressed, for instance, in Wyon's work [20]. On the other hand, the thermal manikin is not designed to measure the radiative or convective heat transfer coefficients directly. It determines heat flux from its surface in a combined form via radiation, convection, and conduction. Neglecting the conduction, the combined heat flux from the manikin is represented by the convection and radiation only. Because of a small temperature difference of the system, the manikin and the air, a linear description of the heat transfer in the following form is used.

$$Q_0 = Q_c + Q_r = h_c.(T_{sk} - T_a) + h_r.(T_{sk} - T_r) \tag{1}$$

Q_0 combined heat flux density (W m^{-2}),
Q_c convective heat flux density (W m^{-2}),
Q_r radiative heat flux density (W m^{-2}),
h_c convective heat transfer coefficient (W m^{-2} K^{-1}),
h_r radiative heat transfer coefficient (W m^{-2} K^{-1}),
T_{sk} manikin surface temperature (°C),
T_a ambient air temperature (°C),
T_r mean radiant temperature (°C).

Certain steps must be taken to separate the combined heat flux into radiative and convective parts. Generally, one of the heat transfer modes must be eliminated or calculated first. Thus, it is possible to determine the remaining mode. Commonly used approaches are briefly described in the following paragraphs.

1.1. Radiative heat transfer coefficient (h_r)

Some authors (e.g., [6]) calculate values of the whole body h_r from ASHRAE Handbook of Fundamentals [7]. This approach is quite simple and efficient; however, it does not allow examining the individual body parts, which is nowadays essential. The second known approach [8] was used to determine radiative heat fluxes within 16 segments of a standing thermal manikin by eliminating convective heat fluxes. Convection was suppressed through setting $T_{sk} = T_a$ in formula (1). This was achieved inside a climate chamber with independently controlled temperatures of $T_a = 34$ °C and $T_r = 27$ °C. The third known approach, presented by Kurazumi et al. [9], uses a radiant flux meter to determine local radiative heat fluxes from a surface of a thermal manikin. The manikin is set to a constant surface temperature of 33 °C. The mean local h_r was calculated for 11 body parts with regards to various manikin body postures.

1.2. Convective heat transfer coefficient (h_c)

In this section three experimental approaches to determine h_c are presented. The first approach is based on the use of heat flux sensors placed on the surface of a thermal manikin or a real human subject [10]. In order to eliminate Q_r, the heat flux sensors were covered with low emissivity aluminum foil ($\varepsilon = 0.04$). The major advantage of this method is that the heat flux sensor can be placed on moving objects (e.g., parts of human body, manikin). On the other hand, heat flux is recorded only at one spot, and to achieve a better resolution, several sensors must be involved. Since the flux meters are not immersed into the surface of a certain object, they can interfere with the airflow around the body as well as with the temperature of the surface [10]. Secondly, Chang et al. [11] and Nishi and Gagge [12] use a naphthalene sublimation method as a representative of convection process. Likewise, this method, again, allows examining only the local convection on the parts of the body where the naphthalene disc is stuck. Another disadvantage is a need for the extra laboratory equipment. The third approach involves thermal manikins with controlled skin temperature. This method is nowadays preferred by the majority of researchers (e.g., [1,2,6,14,15]). The Q_0 measurements are performed across the whole surface of the manikin with precise body segmentation. Accuracy of such measurements is, thus, much higher compared to the spot measurements. Yet, as previously mentioned, the manikins are not able to measure the convective heat flux directly. Consequently, the radiative heat flux must be eliminated, or it must be calculated. ASHRAE formula [7] for the whole body h_r is quite well accepted, but not sufficient for detailed examination. For a comprehensive calculation of h_r, Francisco et al. [13] present their own computational method. The third known approach is to cover the whole manikin with a low emissivity coating [1,2] suppressing the radiative flux. Finally, another possible method to eliminate radiative heat flux is to set the radiant temperature of the environment equal to the manikin's surface temperature. At the same time, an ambient air temperature is controlled to be lower than the mean radiant temperature. However, examples of such have not been found.

The available studies present results from experiments without any specification of the number of measurement repetitions. Evaluation of the uncertainties is also unavailable. Although, all the experiments were carried out in laboratory conditions with very precise equipment, repeatability and uncertainty of the measurements are still questionable. The aim of this study is to involve a computer-controlled thermal manikin Newton to determine the convective and radiative heat transfer coefficients repeatedly. Thus, the repeatability of the measurements can be critically reviewed. The following cases are to be investigated: (a) standing, (b) sitting thermal manikin in natural convection environment with resolution of 34 segments. These cases were opted to enable comparing the results with the generally accepted values of h_r and h_c.

2. Methods

The presented study involves a state-of-the-art thermal manikin Newton that replaces a human in order to simulate a metabolic heat production. The manikin measures the combined dry heat flux from its surface together with its surface temperature. To separate the combined flux (Q_0) to its parts (Q_r, Q_c), the approach of eliminating the radiative heat flux by the low-emissivity coating was selected.

The low-emissivity coating was created using thin aluminum cooking foil applied to the surface of the manikin with the exception of its hands (zones 11 and 12) and nose. Segmentation and curvature of these parts did not allow us to achieve a desired coating quality. Consequently, hands were not examined and the nasal area is negligible compared to the total face area. To fix the coating, sodium alginate mixed with water was used (in total around 7 g). A very tight fit of the coating was ensured by the foil polish (Fig. 1). Regarding several independent sources [1,2,10], the aluminum foil emissivity (ε) fits the range from 0.025 to 0.1. Our estimate is $\varepsilon = 0.025$ (polished foil [2]).

After the coating was finished, the manikin was placed into a calibration box, which itself was built inside a climatic chamber. The main role of the assembly was to maintain desired radiant and ambient temperature equal. Because of the equal radiant and ambient temperatures, the manikin's heat loss can be split into the convective and the radiative heat portions respectively using the low-emissivity coating. Next, three ambient temperature