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Correction of the heat loss method for calculating clothing real evaporative resistance

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ABSTRACT

In the so-called isothermal condition (i.e., T_{air} [air temperature]$=T_{manikin}$ [manikin temperature]$=T_r$ [radiant temperature]), the actual energy used for moisture evaporation detected by most sweating manikins was underestimated due to the uncontrolled fabric 'skin' temperature $T_{sk,f}$ (i.e., $T_{sk,f}<T_{manikin}$). Thus, it must be corrected before being used to compute the clothing real evaporative resistance. In this study, correction of the real evaporative heat loss from the wet fabric 'skin'–clothing system was proposed and experimentally validated on a 'Newton' sweating manikin. The real evaporative resistance of five clothing ensembles and the nude fabric 'skin' calculated by the corrected heat loss method was also reported and compared with that by the mass loss method. Results revealed that, depending on the types of tested clothing, different amounts of heat were drawn from the ambient environment. In general, a greater amount of heat was drawn from the ambient environment by the wet fabric 'skin'-clothing system in lower thermal insulation clothing than that in higher insulation clothing. There were no significant differences between clothing real evaporative resistances calculated by the corrected heat loss method and those by the mass loss method. It was therefore concluded that the correction method proposed in this study has been successfully validated.

1. Introduction

Clothing evaporative resistance is the most important physical parameter to characterise the role of clothing as a moisture barrier. The determination of clothing evaporative resistance may be performed on human subjects and such test equipment as a sweating thermal manikin (Holmér and Elnäs 1981; Wang et al., 2010). Although human subject tests provide realistic data, such tests are often time consuming, costly and also, ethical issues may be involved. A full body sweating thermal manikin is one of the best tools to determine clothing evaporative resistance. Compared with human trial tests, sweating manikin tests are accurate, fast and provide repeatable results (Holmér, 2004).

Over the past decade, the determination of clothing evaporative resistance by means of a sweating manikin has received minimal attention. Due to the difficulty and complexity of clothing evaporative resistance measurements, researchers often use an indirect method to estimate clothing evaporative resistance through the link of permeability index and the Lewis Relation (Woodcock, 1962). One of the most comprehensive studies made on directly determination of clothing evaporative resistance using sweating manikins was reported in 2001. McCullough (2001) organized an interlaboratory sweating manikin study. Great variations in the reported evaporative resistance were observed among different types of sweating thermal manikins. The standard deviation of the inter-lab measurement reproducibility was greater than 50%. Such great variations were probably induced by many factors including different simulation approaches of sweating, different manikin configurations, different calculation methods, and poorly controlled testing condition and highly tolerable test protocol (Wang et al., 2012a). Wang et al. (2010, 2012b) examined the wet fabric 'skin' temperature on a thermal manikin and developed an equation to predict its surface temperature. Results demonstrated that the fabric 'skin' surface temperature was always lower than the manikin surface temperature due to moisture evaporation. Wang et al. (2011) performed a sweating manikin study to investigate the effect of two calculation methods (i.e., heat loss method and mass loss method) on clothing real evaporative resistance in a so-called isothermal condition ($T_{air}=T_{manikin}=T_r$). It was found that the clothing real evaporative resistances calculated by these two methods are not equal. Clothing real evaporative resistance calculated by the heat loss method was always higher than that by the mass loss method. This was mainly because some heat used for water evaporation on

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the wet fabric 'skin' and wet clothing spots (if any) came from the ambient environment (i.e., in the so-called isothermal conditions, $T_{sk,f} < T_{air}$, see Wang et al., 2012b).

As modern technology advances, the number of sweating thermal manikins has been steadily increasing and many modern thermal manikins are constructed with a sweating function (Holmér, 2004; Wang, 2011; Mayor et al., 2012). Some typical examples are the 'Newton' sweating manikin manufactured by the Measurement Technology Northwest (MTNW, Seattle, WA) and the 'Walter' sweating fabric manikin developed in the Hong Kong Polytechnic University (Fan et al., 2001). Interestingly, different types of sweating manikin use different methods to compute the clothing evaporative resistance. For instance, the heat loss method has been widely used on the 'Newton' sweating thermal manikin, whereas the mass loss method has often been chosen by the 'Walter' manikins. For the 'Newton' manikins, the fabric 'skin' is only put onto the manikin when performing wet tests and there is no feedback system between the fabric 'skin' and the manikin controlling system (Wang, 2011). Hence, the uncontrolled fabric 'skin' temperature is not equal to the regulated manikin surface temperature. Strictly speaking, there is no real isothermal testing condition on most modern sweating manikins. It is thus more accurate to name the testing condition $T_{air}=T_{manikin}=T_r$ as the so-called isothermal condition (Wang et al., 2011). In the so-called isothermal condition, the heat loss method overestimated the clothing real evaporative resistance and it should be corrected before use (Wang et al., 2011). However, no correction method has been proposed in the above study.

To date, no solid work has been performed to examine the correction of the isothermal heat loss method. Thus the main aim of this study was to propose a valid correction method to correct the actual evaporative heat loss occurred in the wet fabric 'skin'-clothing system during a wet test on a 'Newton' sweating manikin. Both theoretical analysis and validation experiments were performed to explore the knowledge in this area.

2. Methodology

2.1. Theoretical analysis

Assume: the radiant temperature is equal to the ambient air temperature ($T_r=T_{air}=34.0$ °C). The knitted fabric 'skin' is tightly fitted to the manikin body and there is no air gap between the manikin body and the fabric 'skin'. It is assumed that there is no air penetration through the fabric 'skin' and the 'skin' is so thin that the effect of thickness on the heat transfer can be neglected. Also, the fabric skin is assumed to be completely saturated and the moisture content of the fabric 'skin' is constant due to a continuous water supply by the manikin system. The resistance of the completely saturated fabric 'skin' is assumed to be constant.

Previous studies (Wang et al., 2011, 2012b, 2014a) have demonstrated that the fabric 'skin' and wet clothing spots (if any) will draw heat from the ambient in a so-called isothermal environment due to the negative temperature gradient between the uncontrolled fabric 'skin' and the ambient (i.e., $T_{sk,f} < T_{air}=T_{manikin}$). Obviously, the heating power $Q_{manikin}$ (i.e., evaporative heat loss) that is supplied to the manikin is not equal to the actual energy Q_{skin} (or Q_{evap}) that is used for water evaporation occurring in the wet fabric 'skin'-clothing system. To date, controlling the wet fabric 'skin' surface temperature is still not available (personal communications, Wang and Burke, 2014) due to the immature sensor technology. Thus, unlike the mass loss method which calculates all energy used for moisture evaporation, the heat loss method should be corrected before calculating the clothing real evaporative resistance.

For the nude scenario in the so called isothermal condition (i.e., $T_{air}=T_{manikin}=T_r$), the amount of energy used for water evaporation on the wet fabric 'skin', Q_{skin} can be calculated by Eq. (1)

$$Q_{skin} = Q_{manikin} + Q_{env} \tag{1}$$

where $Q_{manikin}$ is the power supplied to the thermal manikin, W; Q_{env} is the heat taken from the ambient environment, W.

As the fabric 'skin' should be tightly fitted to the manikin body, there is no or minimal air gap between the fabric 'skin' and the manikin surface (see Fig. 1). The heat will be transferred from the manikin surface to the fabric 'skin' mainly through conduction, thus one has

$$Q_{manikin} = Q_{cond} \tag{2}$$

where Q_{cond} is the conductive heat transfer from the manikin surface to the fabric 'skin', W.

For the nude scenario, the fabric 'skin' is directly exposed to the ambient air. The heat will be transferred from the ambient

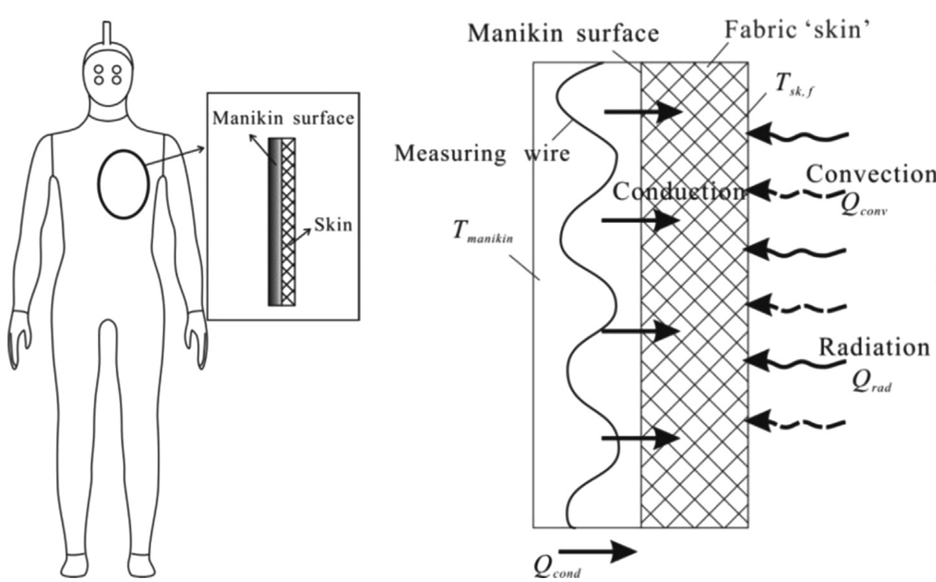

Fig. 1. The heat transfer mechanism among the manikin surface, the wet fabric 'skin' and the ambient air in a so-called isothermal condition (i.e., $T_{air}=T_{manikin}=T_r$) with a nude fabric 'skin'.