A Study on Evaporative Resistances of Two Skins Designed for Thermal Manikin Tore under Different Environmental Conditions

Fa-Ming Wang*, Chuan-Si Gao, Kalev Kuklane, Ingvar Holmér*

Thermal Environmental Laboratory, Division of Ergonomics and Aerosol Technology, Department of Design Sciences, LTH, Lund University, Lund SE-221 00, Sweden

Abstract: A cotton skin and a waterproof but permeable Gore-Tex skin were designed for the thermal manikin "Tore" to simulate different sweating styles (the wet cotton skin inside and Gore-Tex skin outside to simulate the sweating style of thermal manikin "Walter", and Gore-Tex skin inside with wet cotton skin outside to simulate the sweating style of thermal manikins "Newton"). The evaporative resistances of two skin combinations with clothing ensembles were compared at different environmental conditions. In addition, the total evaporative resistance of clothing ensemble was calculated by both the heat loss method (option 1) and the mass loss method (option 2) according to ASTM F 2370. We found that the effect of different sweating mechanisms on the clothing evaporative resistance should be considered. The results showed that the total evaporative resistances calculated by option 2 were more accurate than values in option 1 under the isothermal condition. It was also found that differences of the total evaporative resistance between two skin combinations with clothing ensembles decreased with the increasing clothing ensemble layer. In a non-isothermal condition, the total evaporative resistance calculated by option 1 was more accurate than the value obtained in option 2, which was due to the lower ambient temperature and condensations between each adjacent layer.

Keywords: evaporative resistance, heat loss, fabric skin, sweating simulation, thermal manikin, isothermal

1. Introduction

The total thermal resistance and evaporative resistance are the two most important parameters for clothing comfort [1]. It is well documented that an accurate clothing thermal resistance can be easily acquired by using the heated thermal manikins [2-4]. However, it is difficult to get accurate value of evaporative resistance by using different thermal manikins at different laboratories worldwide and former studies [5-7] have shown a large variation at different laboratories. There are three types of sweating styles being used to measure evaporative heat loss of clothing ensembles at present: pre-wet cotton underwear covered on a dry manikin, manikin with pump to regulate water supply through sweat glands for a knit cotton skin, and sweating fabric manikin based on a water filled body covered with waterproof but permeable fabric or laminated fabric [8, 9]. Different sweating mechanisms may cause effects on the value variation among laboratories, however, large variations could be avoided if the main reasons were found and improved.

In this paper, two skin combinations (wet cotton skin inside with Gore-Tex skin outside, and Gore-Tex skin inside with wet cotton skin outside) were used to investigate the effect of different sweating mechanisms on total evaporative resistance. The final results calculated by the two options according to ASTM F 2371 were also compared and analyzed.

2. Methodology

2.1 Clothing Ensembles Tested

A cotton skin and a waterproof but permeable Gore-Tex skin designed for thermal manikin Tore were used in this study. Two skins were tested in combination with a pair of long sleeve cotton underwear and a permeable coverall. The details of these garments are listed in Table 1.

* Corresponding author's email: faming.wang@design.lth.se; ingvar.holmer@design.lth.se

2.2 Thermal Manikin

A Swedish 17-section walking thermal manikin Tore was used in the tests, shown in Figure 1. Tore is made of plastic with a metal frame inside to support body parts and for joints [10]. It has the size of an average Swedish male of 1980s. Its height is 170cm, chest and waist circumferences are 94 cm and 88 cm respectively, with total heated body area of 1.774 m^2. Tore weighs 33 kg and that makes it easy to handle. The walking movements are created by pneumatic cylinders fixed to wrists and ankles.

Table 1 Clothing ensembles

Clothing ensemble		Descriptions
Knit cotton skin (code: C)		Color: midnight blue Dry weight: 326 g
Gore-Tex skin (code: G)		Color: white Dry weight: 342 g
Knit underwear (code: U)		Color: darkolivegreen Dry weight: 624 g
Permeable coverall (code: P)		Color: dimgray Dry weight: 584 g

Figure 1 The thermal manikin Tore.

2.3 Test Conditions

The water vapour pressure (2.1 kPa) was controlled to ensure the same moisture vapor pressure gradient. Hence, the evaporative vapor loss should be the same for all temperatures. For the ambient temperature, two levels were chosen: 34 °C (isothermal condition where skin temperature equals ambient temperature and thus no dry heat loss) and 22 °C (non-isothermal condition). The chosen 2.1 kPa vapor pressure, when combined with these temperatures, resulted in relative humidities of 40 %, and 80.5 % at 34 and 22 °C, respectively.

The cotton knit skin was rinsed in an Electrolux W3015H washing machine for 4 minutes and then centrifuged 4 seconds to ensure no water was dripped. All garments were put in the climatic chamber at least 24 hours before tests. In addition, three platinum air temperature sensors set at the height of 0.1, 1.1 and 1.7 m were used to record the ambient temperature. The whole manikin system was on a balance with one-decimal accuracy (± 2 g), where the weight of clothing ensemble was recorded continuously during the measurement.

2.4 Calculation Options

ASTM F 2370 is the only standard that addresses the measurement of evaporative resistance of clothing [11]. The standard specifies two options to calculate clothing evaporative resistance. Option 1 (the heat loss calculation) can be expressed as:

$$R_{et} = \frac{(p_s - p_a)A}{H_e - \frac{(T_s - T_a)A}{R_t}} \quad (1)$$

where, R_{et} is the total evaporative resistance of clothing ensemble and surface air layer (kPa m^2/W); p_s is water vapor pressure at the manikin's sweating surface (kPa); p_a is water vapor pressure in the air flowing over the clothing (kPa); A is area of the manikin's surface that is sweating (m^2); H_e is power required for sweating areas (W); T_s and T_a are temperatures at the manikin surface and in the air flow over the clothing respectively (°C); R_t is the total thermal resistance of the clothing ensemble and surface air layer (°C m^2/W).

JFBI Vol.1 No. 4 2009 doi:10.3993/jfbi03200908