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CLOTHING REAL EVAPORATIVE RESISTANCE DETERMINED BY MEANS OF A SWEATING THERMAL MANIKIN: A NEW ROUND-ROBIN STUDY

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Abstract

The previous round-robin (RR) study on clothing evaporative resistance (R_{et}) has shown that the repeatability and reproducibility of clothing R_{et} measurements on sweating manikins were rather low. To further examine and enhance the measurement accuracy, a new strict but feasible test protocol was proposed and thoroughly examined in a new round-robin test. Eight laboratories participated in this study and three types of sweating manikins were used. Six clothing ensembles including body mapping cycling wear, light summer workwear, typical spring and autumn clothing for people living in subtropical regions, cold protective clothing and functional Gore-Tex coverall were selected. The measurement repeatability and reproducibility are analysed. The ultimate goal of the RR study is to provide solid support for amending ASTM F2370 standard and/or drafting a new ISO/EN standard.

Keywords: *evaporative resistance, clothing ensembles, repeatability, reproducibility, isothermal, sweating manikin*

1 Introduction

Clothing sits as a thermal and moisture barrier between the human body and its surrounding environment. To quantify the heat transfer property of this barrier, thermal resistance and evaporative resistance are often used. Clothing thermal resistance and evaporative resistance can be determined on human subjects and test equipment such as a sweating thermal manikin. Although human subject tests provide realistic data, such tests are often time consuming and costly. Human shaped full-size thermal manikins are a good alternative to determine clothing thermal and evaporative resistance. Such tests are accurate, fast and provide repeatable results.

The first research work made on sweating manikins to determine clothing evaporative resistance was appeared in 2001. McCullough [1] organised an interlaboratory study of different sweating thermal manikins. Six laboratories participated in this study and five sets of protective clothing ensembles were tested. Great variations in the reported evaporative resistance were observed among different types of sweating manikins. For example, differences between the clothing evaporative resistance reported by DERA and NCTRF for chemical protective clothing and cold weather protective clothing reached 337% and 342%, respectively. It is believed that different sweating simulation approaches, different manikin configurations, different calculation methods, and poor controlled testing conditions and test protocol are the main causes of great variations [2]. Later in 2005, based on McCullough's round-robin test, the ASTM F23 committee on personal protective clothing and equipment developed the current only standard on measurement of clothing evaporative resistance using a sweating manikin[3]. In 2010, the ASTM F 2370 standard has been updated to a new version, however, no important improvement has been made to the test protocol[4]. It seems that the test protocol specified in the current standard is not strict enough and great measurement variations still exist if technicians follow this standard.

With the goal of developing a strict but easy-to-follow test protocol on determination of clothing evaporative resistance in order to enhance measurement accuracy, Wang *et al.* [5-10] examined many factors including manikin construction parameters, calculation methods and testing conditions that affecting the measurement accuracy of clothing evaporative resistance. Based on recent findings, a small-scale interlaboratory study on measurement of clothing evaporative resistance was organised by Mayor in 2012[11]. The findings demonstrated that the measurement repeatability and reproducibility were enhanced compared the previous round-robin study. Nevertheless, only three laboratories participated in this study.

Currently, it is estimated that there are more than 120 thermal manikins in the world [2]. As modern technology advances, the number of sweating thermal manikins is steadily increasing and many modern thermal manikins are constructed with a sweating function. There is a great need to draft a new international standard to supervise technicians to perform clothing evaporative resistance tests and also, the standard will be beneficial to engineers and designers to develop more reliable and durable sweating manikins.

The main aim of this study is to report a new round-robin study on the measurement of clothing evaporative resistance by means of a sweating manikin. In this round-robin study, a strict but feasible test protocol was developed. Precision statistics on reported clothing evaporative resistance data were performed. It is expected that this new round-robin study will provide a solid guideline to draft a new international standard with regard to measurement of clothing evaporative resistance by means of a sweating manikin.

2 Methods

2.1 Sweating thermal manikins

Eight laboratories participated in this study. All eight thermal manikins can be divided into three types based on their structure: 'Tore', 'Newton', and 'KEM'. The 'Newton' manikin can also be categorised into two groups based on the sweating methods: the new version Newton manikin and the old version Newton manikin. The 'Tore' manikin and the old version 'Newton' manikins use a piece of pre-wetted fabric to simulate moisture-saturated skin. The 'Tore' thermal manikin at Lund University, the 'Newton' manikin at Loughborough University and the 'KEM' manikin were not made to sweat at head/face, hands and feet. The new version 'Newton' thermal manikin can sweat at each individual segment and its segmental sweating rate can also be controlled individually according to the test requirement.

Table 1 Participating organisations and types of sweating manikins

Organisation	Code	Type of manikin	Number of segments
Lund University (SE)	LUND	Tore	17
Loughborough University (UK)	LOUGHBOROUGH	Newton	34
Centexbel (BE)	CENTEXBEL	Newton	26
CeNTI (PT)	CENTI	Newton	34
CIOP (PL)	CIOP	Newton	34
Soochow University (CN)	SOOCHOW	Newton	34
SGS Hong Kong Ltd. (CN)	SGS	Newton	34
Kyoto Electronics Manufacturing Co. Ltd. (JP)	KEM	KEM	17

2.2 Clothing ensembles

Six sets of clothing ensembles including body mapping sportswear, traditional four-season clothing and protective clothing were selected and tested. The characteristics of these six clothing ensembles are presented in Table 2.

Table 2 Characteristics of six tested clothing ensembles

Ensemble code	Clothing component	No. of layer	I_{tot}* (clo)
EN 1	Briefs 1(65% polyamide, 27% polyester, 8% elastane), Body mapping cycling wear (2 pieces, colour: B/W), Taiga socks (76% wool, 23% polyamide, 1% Lycra®)	1	0.84
EN 2	Briefs 1(65% polyamide, 27% polyester, 8% elastane),Taiga summer work wear: short sleeve t-shirt (colour: red), short pants(colour: beige), Taiga socks (76% wool, 23% polyamide, 1% Lycra®)	1	0.84
	Briefs 1(65% polyamide, 27% polyester, 8% elastane),Taiga short sleeve t-shirt (colour:	2	

EN 3	red), one-layer Jacket(100% polyester, colour: orange), trousers (96% polyamide, 4% Lycra, colour: black), Taiga socks (76% wool, 23% polyamide, 1% Lycra®)		1.43
EN 4	Briefs 2(91% polyamide, 9% elastane), Eider™ underwear (97% Outlast®, 3% Spandex), Atunas™ Polartec fleece jacket (grey/black), Atunas™ fleece trousers (100% polyester), sports socks (72% cotton, 26% polyamide, 2% Lycra®)	2	1.97
EN 5	Briefs 2(91% polyamide, 9% elastane), Taiga Cold weather clothing: Red Tevon jacket (combined with Dever foder), Black Barton trousers (combined with Prescot byxfoder), Black Polartec power trousers, Red Polartec Dayton sweater, sports socks (72% cotton, 26% polyamide, 2% Lycra®)	3	3.24
EN 6	Briefs 2(91% polyamide, 9% elastane), white Atmos underwear (100% polyester, Swiss Eschler), Black Gore-Tex coverall, sports socks (72% cotton, 26% polyamide, 2% Lycra®)	2	1.65

*I_{tot}, the total thermal insulation measured on a 'Newton' type manikin. The clothing total thermal insulation was calculated from manikin's segments with the exception of head (face), hands and feet.

2.3 Test protocol

Prior to performing the round-robin test, both the thermal manikin and the climatic chamber were calibrated. A pre-examination on the tightness of the fabric skin was made to ensure that the fabric skin is tightly fitted to the manikin body. Any notable air gaps between the fabric skin and the manikin body should be removed. If the 'skin' is too loose, a new tight fitting one should be used. For the new version 'Newton' manikin, appropriate sweating rates should be adjusted to ensure that the fabric skin at any involved segment is fully wet. In addition, wetting the fabric skin before dressing up the manikin was proposed. In this study, the constant manikin/fabric skin surface temperature mode was used.

Nude wet tests were performed before clothing tests to acquire an averaged boundary air layer's evaporative resistance (i.e., R_{ea}). Clothing R_{et} experiments were performed in the sequence of EN1-EN6-EN2-EN5-EN3-EN4. Each clothing ensemble should be fully dry before testing. When dressing up the manikin, the t-shirt should be worn over the underwear briefs and under the trousers. The outer long-sleeve shirt should be worn with the shirttail hanging out over the trousers. The top button at the neck should be unfastened. For each tested clothing ensemble, three independent replications should be carried out. If the intra-lab repeatability is higher than 10%, additional tests should be done to ensure the intra-lab repeatability below 10%.

2.4 Test conditions

All tests were performed in an isothermal condition. The air temperature inside the climate chamber was controlled at 34.0±0.5 °C, and the manikin's surface temperature was set to 34.0 °C. The relative humidity in the chamber was maintained at 40±5%. For all participating laboratories except the Loughborough University, the air velocity was set to 0.4±0.1 m/s. The air velocity inside the climatic chamber at Loughborough University was 0.15±0.05 m/s.

2.5 Calculations

Clothing evaporative resistance values were calculated by the parallel heat loss method (Eq.1). Each laboratory is responsible to process their testing data and the calculated clothing evaporative resistances are provided. Processed data and raw data from each participating laboratory were gathered and further examined by the project coordinator to ensure the correctness of all calculations.

The parallel heat loss method is defined in Eq(1)

$$Ret_{heat,p} = \frac{p_{sk} - p_{air}}{\sum_{i=1}^{n} \left(\frac{A_i \times He_i}{A}\right)} \qquad \text{Eq(1)}$$

where, $Ret_{heat,p}$ *is* the clothing total evaporative resistance calculated by the parallel heat loss method, Pa·m^2/W; A and A_i are the total sweating surface area and segmental sweating surface area, respectively, m^2; i is the number of segment of the sweating thermal manikin (i=1,2,…, n); p_{sk} and p_{air} are the water vapour pressure on the saturated fabric skin surface and in the ambient air, respectively, kPa; He_i is the segmental evaporative heat loss, W/m^2, in isothermal conditions, the evaporative heat loss equals the heating power of the manikin(i.e., there is no dry heat loss).

The water vapour pressures at the wet fabric skin surface and the partial water vapour pressure in the chamber can be computed by Eq(2) and Eq(3), respectively.

$$p_{sk} = \exp(18.956 - \frac{4030.18}{34 + 235}) \times RH_{sk} \qquad \text{Eq(2)}$$

$$p_a = \exp(18.956 - \frac{4030.18}{t_{air} + 235}) \times RH_{air} \qquad \text{Eq(3)}$$

where, t_{air} is the ambient air temperature, ^{o}C; RH_{sk} and RH_{air} are the relative humidity at the wet fabric skin surface and in the ambient air, respectively, %. In this study, it is assumed that the RH_{sk} on the saturated wet fabric skin surface was 100 %.

2.6 Data analysis

Mean data were reported. All calculations were made by using Microsoft Excel for Mac 2011 Version 14.1.0(Microsoft Corporation, Albuquerque, NM, USA). Precision statistics were performed according to ASTM E691[12]. The within-laboratory (or intra-laboratory) repeatability standard deviation and the inter-laboratory reproducibility standard deviation were calculated and reported.

The repeatability standard deviation SD_r and the reproducibility standard deviation SD_R are expressed as

$$SD_r = \sqrt{\sum_1^p \frac{SD^2}{p}} \qquad \text{Eq(4)}$$

where, SD is the standard deviation of the mean clothing evaporative resistance determined in one laboratory and p is the number of laboratories.

$$SD_R = \sqrt{(SD_x)^2 + (SD_r)^2 \times (n - 1)/n} \qquad \text{Eq(5)}$$

where, SD_x is the standard deviation of the mean value of clothing evaporative resistance determined in all participating laboratories; n is the number of test results.

3 Results

The clothing evaporative resistance values calculated based on the parallel heat loss method of six clothing ensembles are presented in Table 3. As the manikins 'Tore', 'KEM' and the old version 'Newton' were not made to sweat at head, hands and feet, clothing evaporative resistance calculated from other segments with the exception of head, hands and feet was also calculated. The mean value of each test scenario, repeatability standard deviation (SR_r) and reproducibility standard deviation (SD_R) are also listed.

Table 3 The clothing evaporative resistance calculated by the parallel heat loss method

Test scenario	Organisation	Ret_{all}	Ret_{part}
Nude	CENTI	15.5	16.6
	CENTEXBEL	13.8	14.3
	CIOP	14.2	14.4
	KEM	-	13.9
	LOUGHBOROUGH	-	-
	LUND	-	15.3
	SGS	13.0	13.7
	SOOCHOW	14.4	14.7
	Mean	**14.2**	**14.7**
	***SD*$_r$**	**0.28**	**0.32**
	***SD*$_R$**	**0.93**	**1.04**
	CENTI	18.0	19.4
	CENTEXBEL	15.8	17.0

EN 1	CIOP	17.7	17.9
	KEM	-	16.6
	LOUGHBOROUGH	-	20.5
	LUND	-	16.2
	SGS	16.5	17.3
	SOOCHOW	16.4	16.8
	Mean	**17.1**	**17.7**
	SD_r	**0.28**	**0.46**
	SD_R	**0.93**	**1.56**
EN 2	CENTI	21.1	24.0
	CENTEXBEL	18.9	21.1
	CIOP	20.0	20.9
	KEM	-	20.8
	LOUGHBOROUGH	-	21.0
	LUND	-	21.6
	SGS	19.7	21.6
	SOOCHOW	19.4	20.9
	Mean	**19.8**	**21.5**
	SD_r	**0.54**	**0.62**
	SD_R	**0.94**	**1.24**
EN 3	CENTI	32.2	44.4
	CENTEXBEL	28.8	37.7
	CIOP	32.5	39.4
	KEM	-	32.4
	LOUGHBOROUGH	-	43.0
	LUND	-	32.8
	SGS	30.8	39.9
	SOOCHOW	29.3	36.2
	Mean	**30.7**	**38.2**
	SD_r	**0.68**	**0.93**
	SD_R	**1.81**	**4.49**
EN 4	CENTI	31.3	43.2
	CENTEXBEL	27.2	37.3
	CIOP	32.7	42.0
	KEM	-	33.8
	LOUGHBOROUGH	-	43.0
	LUND	-	32.4
	SGS	30.7	39.9
	SOOCHOW	30.8	39.7
	Mean	**30.5**	**38.9**
	SD_r	**0.55**	**0.72**
	SD_R	**2.06**	**4.16**
EN 5	CENTI	67.1	161.1
	CENTEXBEL	47.9	119.9
	CIOP	61.7	124.3
	KEM	-	103.8
	LOUGHBOROUGH	-	126.5
	LUND	-	102.4
	SGS	70.3	127.6
	SOOCHOW	68.8	127.4
	Mean	**63.2**	**124.1**
	SD_r	**1.97**	**2.67**
	SD_R	**9.27**	**18.27**
	CENTI	38.5	64.4
	CENTEXBEL	33.1	52.0
	CIOP	40.0	55.2
	KEM	-	47.6

EN 6	LOUGHBOROUGH	-	56.2
	LUND	-	44.8
	SGS	36.7	55.2
	SOOCHOW	38.0	55.0
	Mean	**37.3**	**53.8**
	SD_r	**1.14**	**1.66**
	SD_R	**2.79**	**6.10**

-, Data not able to measure; Ret_{all}, clothing evaporative resistance based on data from all segments; Ret_{part}, clothing evaporative resistance calculated from all segments excluding the head, hands and feet.

The averaged clothing evaporative resistance of the boundary air layer based on data from all manikin's segments is 14.2 Pam^2/W. If the manikin's head, hands and feet were excluded, the reported *Rea* value is slightly increased to 14.7 Pam^2/W. The repeatability SD for Ret_{all} and Ret_{part} and the reproducibility SD for Ret_{all} and Ret_{part} are 0.28, 0.32, 0.93 and 1.04 Pam^2/W, respectively. Similarly, the mean clothing total evaporative resistance Ret_{all} of clothing ensembles EN1, EN2, EN3, EN4, EN5 and EN6 are 17.1, 198.8, 30.7, 30.5, 63.2 and 37.3 Pam^2/W, respectively. With the exception of the head, hands and feet, the Ret_{part} of EN1, EN2, EN3, EN4, EN5 and EN6 are 17.7, 21.5, 38.2, 38.9, 124.1 and 53.8 Pam^2/W, respectively. The observed repeatability standard deviation values of each participating laboratory are ranged from 0.28 to 2.67 Pam^2/W. In contrast, the reproducibility standard deviation values have a greater variability, ranging from 0.93 to 18. 27 Pam^2/W.

4 Discussion

To the best our knowledge, this new round-robin study is the most comprehensive one in terms of the number of participating laboratories, the strictness of test protocol and types of clothing ensembles. Compared with the previous round-robin studies, our statistical results have demonstrated that both the test repeatability and reproducibility have been greatly enhanced. It is thus believed that the test protocol adapted in our study is reliable and easy to follow.

One of our important findings is that the clothing evaporative resistance values calculated from all body segments are always smaller than those calculated from segments with the exception of head, hands and feet. Therefore, we may only compare the values calculated from the same body segments. The results presented in Table 3 showed quite good agreement with our theoretical analysis: any exclusion of the manikin segment will cause a greater clothing evaporative resistance. If the clothing is evenly distributed over all body parts, the exclusion of body segments will not cause a significant change in the reported clothing evaporative resistance (e.g., the test scenarios nude and EN1). On the contrary, if clothing is unevenly distributed over the whole body, any exclusion of a segment with a low evaporative resistance will generate a much greater clothing total evaporative resistance. For example, if no clothing is covered on the manikin's hands, head and feet while thick layers are covered on the other body parts (e.g., EN5), the total evaporative resistance Ret_{part} of EN5 was increased approximately two fold compared with Ret_{all}. Therefore, the number of body segments used for calculating clothing total evaporative resistance must be indicated when reporting the value.

Further, protective clothing EN5 showed a greater variability than other types of clothing ensembles. The evaporative resistance value of EN5 determined by CENTI was much greater than those reported by other participating laboratories. A closer look at the experimental raw data, we found that the segmental heat losses at the chest, stomach, mid back, buttocks, and calf are lower than 20 W/m^2. Such low segmental heat losses were mainly because a much lower sweating set rate of 200 $ml/hr/m^2$ was used. In contrast, the sweating set rates adapted by other seven laboratories were much higher (over 500 $ml/hr/m^2$). As the tested clothing will absorb moisture from the skin surface, a rather small sweating rate may not be able to maintain a fully saturated fabric skin. It is thus obvious that the low segmental heat losses found on CENTI's manikin is because the fabric skin at these areas has been dried out. On the other hand, the ISO 15831 standard [13] recommends any segmental heat loss should be larger than 20 W/m^2 when testing clothing thermal resistance using a manikin. Similar to the above requirement, the observed segmental heat loss during a clothing evaporative resistance test should also be larger than 20 W/m^2.

5 Conclusions

Based on the findings obtained in this study, some useful suggestions are proposed to enhance the repeatability and reproducibility of clothing evaporative resistance measurements:

1) It is recommended that the measurement of clothing evaporative resistance should be carried out in an isothermal condition. The evaporative resistance determined under such a condition is called clothing real evaporative resistance.
2) With regard to the testing condition, the relative humidity inside the chamber must be recorded throughout the test and an average value should be used when calculating the partial water vapour pressure. If a great variability presents during the test, one has to immediately terminate the test and a further check of the chamber is need. The relative humidity should not either be set too high or low. Too high relative humidity will cause slower evaporation and thereby smaller segmental heat losses.
3) We can only compare the clothing evaporative resistances measured under the same test condition and calculated based on the same method. If the manikin does not sweat on the head, hands and feet, the measured clothing evaporative resistance will always be higher than those do sweat all over the body segments. For the same type manikin, any exclusion of a sweating segment from the calculation will also generate a higher clothing evaporative resistance value.

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