Interlaboratory proficiency tests in measuring thermal insulation and evaporative resistance of clothing using the Newton-type thermal manikin

Magdalena Młynarczyk[1], George Havenith[2], Jean Léonard[3], Rui Martins[4] and Simon Hodder[2]

[1] Laboratory of Thermal Load, Department of Ergonomics, Central Institute for Labour Protection – National Research Institute, Warsaw, Poland

[2] Loughborough University, United Kingdom

[3] Centexbel, Grâce-Hollogne, Belgium

[4] Citeve, Vila Nova de Famalicão, Portugal

Corresponding author:

Magdalena Młynarczyk, Laboratory of Thermal Load, Department of Ergonomics, Central Institute for Labour Protection – National Research Institute, Czerniakowska 16, 00-701 Warsaw, PL

E-mail: mazwo@ciop.pl

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Abstract

Clothing acts as an important barrier for heat and vapour transfer between a human body and the environment. Parameters that could describe that transfer include, i.a. the thermal insulation (the so-called dry heat exchange) and the evaporative resistance (the so-called wet heat exchange). Once the above mentioned parameters are determined, it is possible to consciously adapt clothing ensembles to the existing thermal environment in the workplace.

In order to validate the mentioned method of thermal insulation and evaporative resistance measurements, the proficiency tests (PT) were organised. The main goal of the PT was to compare thermal insulation and evaporative resistance for one set of clothing using the Newton-type thermal manikin. In total, 4 laboratories participated in the PT study. The reference value of the thermal insulation (I_t) and evaporative resistance (R_{et}) were calculated as the mean of all the results. The assessment criteria included: a permissible error for thermal insulation and evaporative resistance measurements was 4% and 10%, respectively.

Calculations included, i.a., z-scores and indicators, such as the interlaboratory coefficient of variation or the reproducibility limit.

The results contribute to the worldwide discussion on standardised studies of evaporative resistance of clothing.

Key words

thermal manikin Newton, thermal insulation, evaporative resistance

Introduction

Clothing acts as a very important barrier for the heat and vapour transfer between a human body and the environment[1,2]. It protects a human body against e.g. excessive cooling or heating in a cold or hot environment, respectively. Two parameters, amongst others, are used to describe clothing, i.e. thermal insulation (the so-called dry heat exchange) and evaporative resistance (the so-called wet heat exchange)[1,2]. Determination of the above mentioned parameters makes it possible to consciously adapt clothing ensembles to the existing thermal environment in the workplace.

Clothing thermal properties are examined mostly with thermal manikins. This kind of equipment has been known since the early 40s of the 20th century, i.e. the time when the one segment copper manikin commissioned by the then US army was made[3]. The current development in the area of thermal manikins made it possible to construct a multi-segment device, which not only helps to simulate and to measure the dry heat exchange, but it also enables examining the wet heat exchange using a sweating system.

The solution allows determining important clothing properties, such as the thermal insulation and the evaporative resistance.

In general, the above mentioned properties are performed by a single laboratory[4] . However, interlaboratory comparative tests are conducted in order to improve testing methods performed with the use of thermal manikins.

In 2003 an international project ”Thermal insulation measurement of cold protective clothing using thermal manikins” (SUBZERO) was completed[5]. The study was performed by 8 laboratories and the results formed the basis for amending the EN 342 standard[6].

Interlaboratory tests including examination of evaporative resistance were also conducted. In 2001 the Kansas State University (KSU) coordinated an interlaboratory study of different thermal manikins equipped with a sweating system[7]. The study involved 6 laboratories. It aimed to determine thermal insulation as well as evaporative resistance of 5 clothing ensembles[7]. The results of the mentioned study confirmed that the procedure for investigating the dry heat exchange is very well developed and described. Therefore, the standards EN ISO 15831[8] and EN 342[6] enable carrying out thermal insulation testing in a correct manner. What remained problematic, however, was the study of the evaporative resistance. The manikins differed mainly in terms of implemented sweating systems and the number of sweating segments. It was assumed that those were the reasons for a wide range of the reproducibility limits.

Mayor[9] conducted tests of evaporative resistance, on the basis of the protocol set out in the standard ASTM F2370[10]. Three independent laboratories tested seven clothing ensembles with three thermal manikins: the 26- and 34- zones Newton thermal manikin and the Tore manikin consisting of 17-thermal zones. The interlaboratory reproducibility had quite high *R* values. It was assumed that one of the sources of error was a type of manikins used, and more precisely their differentiation. They were not uniform in terms of their construction and the sweating system applied. Often in interlaboratory tests, the protocol of measurements did not contain full and precise description of, e.g. calculation method of each values[7].

In order to verify whether tests with one type of manikin and a defined measurement protocol will reduce a wide range of reproducibility limits (*R*), interlaboratory proficiency testing (PT) was conducted.

The PT aimed to measure the evaporative resistance and the thermal insulation of a reference set of clothing using one type of thermal manikin: the Newton-type. The findings contribute to the worldwide discussion on standardised studies of evaporative resistance of clothing.

Material and method

Four laboratories located in four different European countries took part in the PT study. Thermal insulation was measured by 4 laboratories, while the evaporative resistance was examined by 3 laboratories.

Tests were performed in climatic chambers with a set of reference clothing and a thermal manikin of the Newton type. Detailed information on the studies is presented below.

Thermal manikin

The study was carried out with thermal manikins of the Newton type manufactured by the Measurement Technology NW USA. They were constructed using a thermally conductive carbon-epoxy composite shell with embedded resistance wire heating and sensor wire elements. The manikins differed in terms of a number of thermal segments used (26-segments and 34-segmetns). Mostly, the manikins had an internal sweating system which allowed examination of the wet heat exchange. For laboratory A, the skin was pre-wetted externally using a spray system, for B and D laboratories, the skin was wetted by the internal water supply system. The parameters of the manikins participating in the study are specified in Table 1.

Table 1. Specification of participating manikins

Laboratory	A	B	C	D
Type of manikin	Newton	Newton	Newton	Newton
Number of	34	26	34	34

segments				
Sweating system	pre-wetted (spray system)	internal water supply ($500\ g \cdot m^{-2} \cdot hr^{-1}$)	-	internal water supply ($500\ g \cdot m^{-2} \cdot hr^{-1}$)
Height [cm]	174.0	176.8	178.5	178.5
Chest circuit [cm]	93	91	91	91
Total surface [m^2]	1.878	1.814	1.874	1.867

Testing material

Clothing for tests - type R reference clothing - was selected in accordance with the assumptions of the EN 342[6] standard. In some cases, the need for the required thermal insulation of clothing ensembles necessitated a double layer (together: size S and size M). A set of reference clothing consisted of 3 layers of clothing. Fabrics (which were use in the tested clothing) were not a specific chemical special finish on these garments only standard processes in the textile production. These fabrics did not have any water repellent finish on. The detailed data on the materials used are presented in Table 2.

Table 2. The set of clothing ensemble

no.	Product	material	quantity of layers	no. of layer
1	shirt with long sleeves	55% polyester 45% cotton	2 (size S and size M)	1st layer
2	underpants long	55% polyester 45% cotton	2 (size S and size M)	1st layer
3	high socks	75% cotton, 22% polyamide, 2% elastane	1	1st layer

4	jacket	material FAS®, Fristads Kansas best twill, 100 % cotton; Weight 375 g/m²	1	3rd layer
5	shirt	woven checked flannel, 100 % cotton; weight 140 g/m²	1	2nd layer
6	pants	100 % cotton; weight 375 g/m^2	1	2nd layer
7	gloves		1	3rd layer
8	balaclava	100% acrylic	2 (size S and size M)	1st layer
9	boots		1	3rd layer

The manikin was clothed in a shirt with long sleeves (no. 1) put inside the underpants (no. 2) and the underpants (no. 2) were tucked into the socks (no. 3). The balaclava (no. 8) was put on the shirt with long sleeves (no. 1) (Figure 1). The second layer consisted of the shirt (no. 5) tucked into the pants (no. 6) (Figure 1). The last layer – the jacket sleeves (no. 4) were tucked into the gloves (no. 7) and the pants (no. 6) were put into the boots (no. 9) (Figure1). The way the manikin was dressed remained unchanged for all tests.

Figure 1. Items of the tested clothing ensemble (from the left): first layer, second layer, third layer

Methodology

Thermal insulation. Methodology for the dry heat exchange, i.e. testing of thermal insulation of the reference clothing ensemble was developed in accordance with EN ISO 15831[8] and EN 342[6].

A methodology for an examination of the dry heat exchange was based on the following assumptions: the manikin surface temperature set at 34.0°C; the air temperature in the climate chamber controlled at ±0.1°C; relative humidity inside the chamber at the level of 40±5%; the air velocity at 0.4±0.1m/s; air flow directed towards the front side of the thermal manikin.

The calculation was made according to EN ISO 15831 standards[8]. The serial (1) and parallel (2) method were calculated.

$$I_t = \sum_i f_i \left[\frac{(t_{sk,i} - t_a) \cdot a_i}{H_{ci}} \right] \quad (1) \qquad I_t = \frac{\left[\left(\sum_i f_i \cdot t_{sk,i} \right) - t_a \right] \cdot A}{\sum_i H_{ci}} \quad (2)$$

$$f_i = \frac{a_i}{A} \quad (3)$$

where:

I_t – the total thermal insulation of clothing m^{2o}C/W;

$t_{sk,i}$ – local surface temperature of i-segment of the manikin [°C]

t_a – air temperature in environmental chamber [°C]

A – the total body surface area of the manikin, m^2;

i – the number of segment of the manikin (i=1,2,…, n);

H_{ci} – heating power fed to the i-segment of the manikin, W;

a_i – surface area of i-segment of the manikin, m^2;

f_i – area factor of i-segment of the manikin.

Evaporative resistance. Evaporative resistance of a clothing ensemble was tested with a thermal manikin wearing a special fabric skin. The skin was made from 80% polyamide and 20% elastane (lycra®), which is semi-permeable. The elastic skin covered the manikin tightly, thus preventing formation of air gaps. The test conditions were set in such a way so as to comply with the ASTM F2370-10 standard[10].

The proposed methodology for testing of the wet heat exchange under the so-called 'isothermal conditions' was based on the same assumptions as the one for the dry heat exchange, i.e. the same values were applied with regard to the manikin surface temperature, the relative humidity and the air velocity inside the chamber. Additionally, the air temperature in the climate chamber remained within 34.0±0.5°C.

Within the framework of the PT study, the sweat rate was set at 500 $ml/hr \cdot m^2$ for laboratories B and D, and fabric skin was pre-wetted for laboratory A. The heat loss calculation option was used. All calculations were based on the parallel method, which is defined as[10]:

$$R_{et\_heat,p} = \frac{p_{sk} - p_a}{\sum_{i=1}^{n}\left(\frac{A_i \times H_{ei}}{A}\right)} \quad (4)$$

where:

$R_{et\_heat,p}$ – the total clothing evaporative resistance calculated by the parallel heat loss method kPa·m^2/W;

A , A_i – the total sweating surface area and segmental sweating surface area, respectively, m^2;

i – the number of segment of the sweating thermal manikin (i=1,2,…, n);

p_{sk}, p_a – the water vapour pressure on the whole fabric skin surface and in the ambient air, respectively, kPa;

H_{ei} – the segmental evaporative heat loss, W/m^2.

The water vapour pressures at the fabric skin surface and in the air temperature were calculated by the Antoine's equation[16,17]:

$$p_{sk} = \exp\left(18.956 - \frac{4030.18}{t_{sk} + 235}\right) \times RH_{sk}[mb] \quad (5)$$

$$p_a = \exp\left(18.956 - \frac{4030.18}{t_a + 235}\right) \times RH_a[mb] \quad (6)$$

where:

t_{sk} , t_a – temperatures at the wet fabric skin surface and in the ambient air, respectively, ^{o}C;

RH_{sk} , RH_a – the relative humidity at the wet fabric skin surface and in the ambient air, respectively, % (assumed that RH_{sk} on the saturated wet fabric skin surface was 100%).

Criteria for assessing the participants' results

The results of the evaluation are based on the assumptions set out in the standards: EN 342[6], EN ISO 15831[8] and ASTM F2370-10[10]. The reference value was determined by calculating the mean for all the measurements.

In accordance with the above-mentioned standards, a permissible error for intra-laboratory measurements should stay below 4%[8] with regard to setting the thermal insulation of clothing, (for the same clothing ensemble). For the evaporative resistance, intra-laboratory permissible error should not exceed 10%[10]. According to the aforementioned standards, the reproducibility limit (*R*) for total insulation testing for the serial and parallel model is set at 6.8% and 5.3%[8], respectively. In case of the evaporative resistance, the reproducibility limit is 50%[10]. The presented tests were based on more liberal criteria, i.e. they used intra-laboratory permissible errors and not interlaboratory ones.

Assessment criteria assumed the 4% and 10% error threshold for thermal insulation and evaporative resistance, respectively.

Results

The results of the proficiency testing (PT) of the dry and wet heat exchange are presented below.

Dry heat exchange – thermal insulation

The PT study determined three different values of thermal insulation: the boundary air layer (I_a - from a nude manikin), the total thermal insulation (I_t) of the tested set of clothes and the effective thermal insulation (I_{cle}). The results of the mean value, standard deviations and the required range of each value with a permissible error of 4%, are summarised in Table 7 (appendix 1).

The results divided according to the calculation methods are shown in the graphs (Figures 2-5).

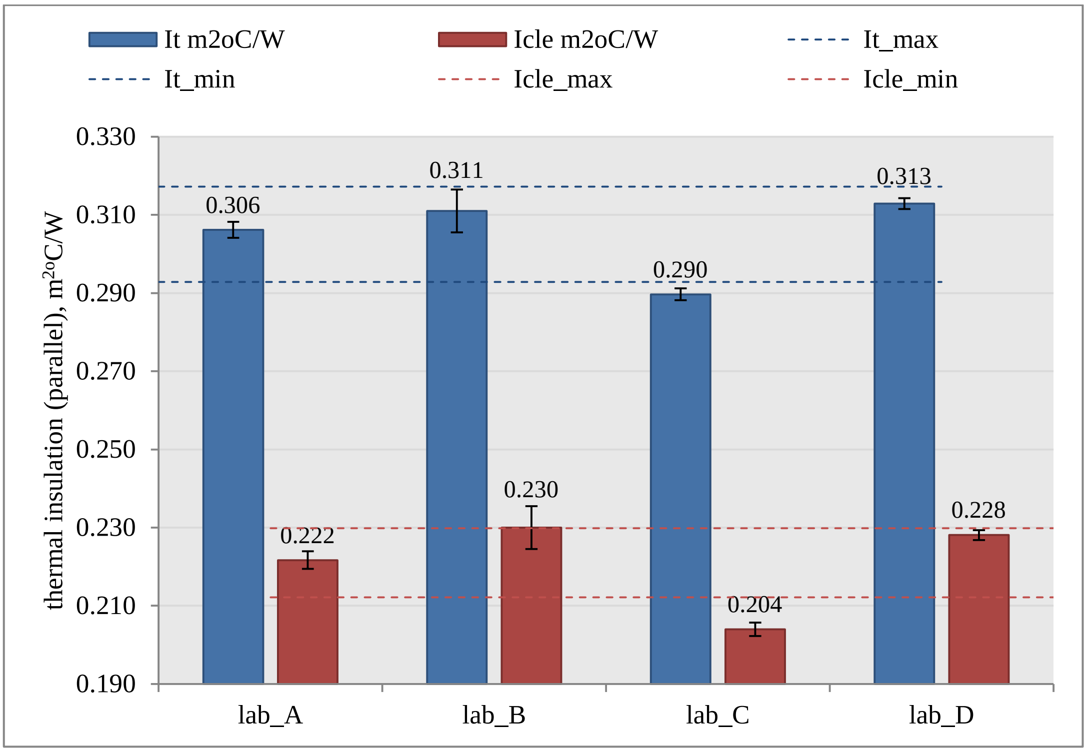

Figure 2. The total thermal insulation (I_t) and the effective thermal insulation of reference clothing (I_{cle}) obtained by individual laboratories and reference values with the permissible range 4% error calculated by the parallel method

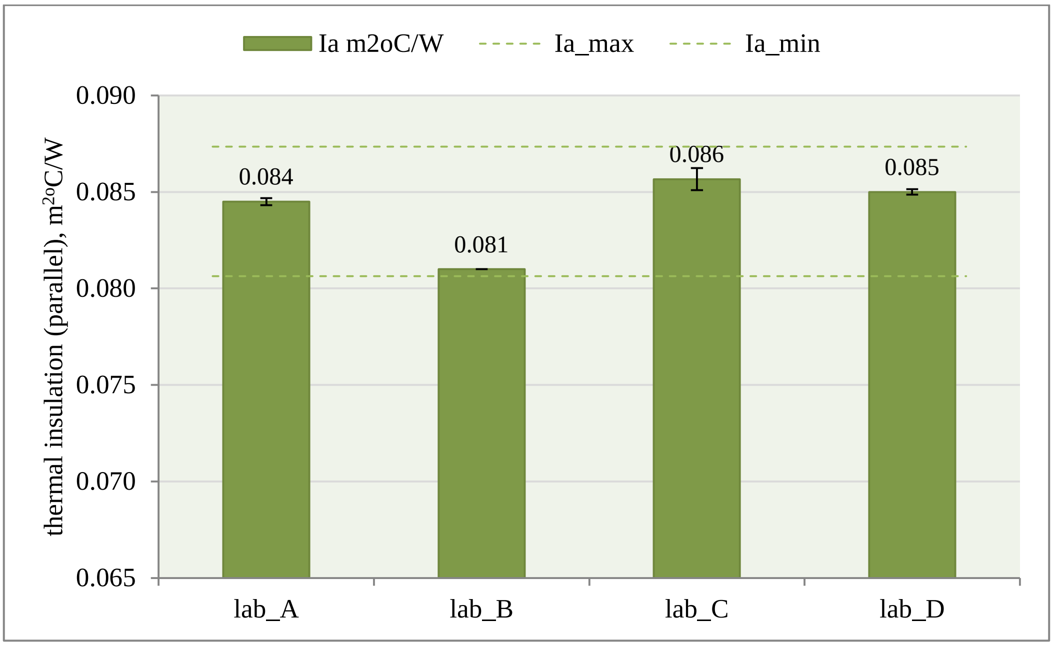

Figure 3. The thermal insulation boundary air layer (I_a) obtained by individual laboratories and reference values with the permissible range 4% error calculated by the parallel method

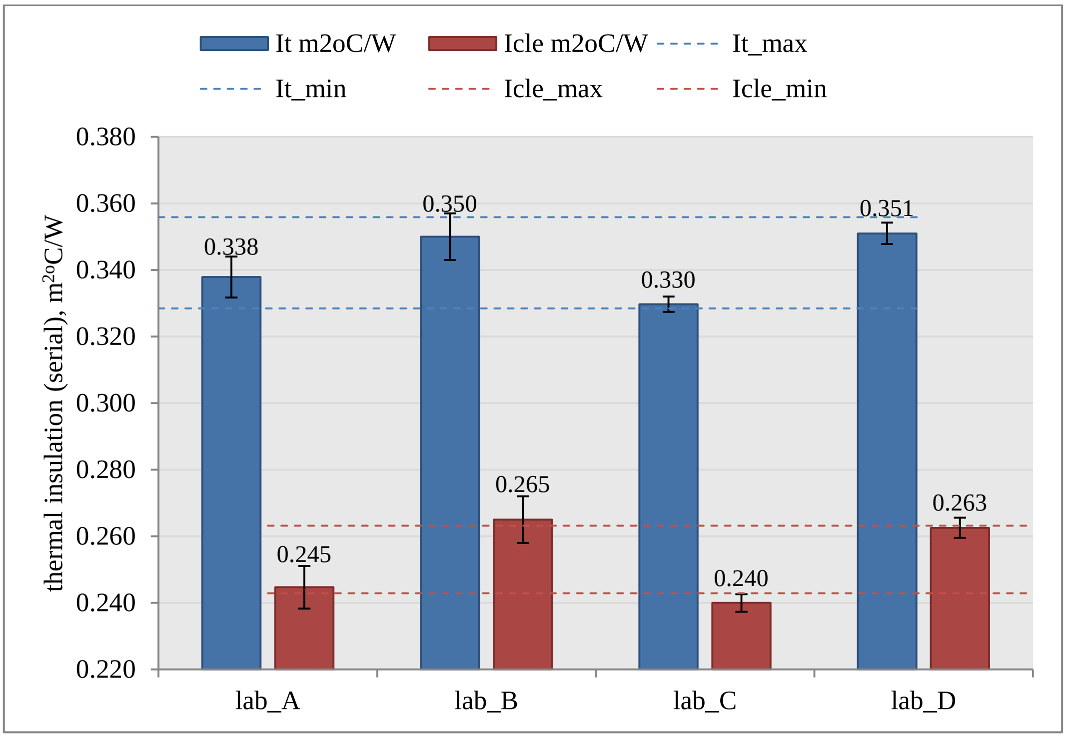

Figure 4. The total thermal insulation (I_t) and the effective thermal insulation of reference clothing (I_{cle}) obtained by individual laboratories and reference values with the permissible range 4% error calculated by the serial method

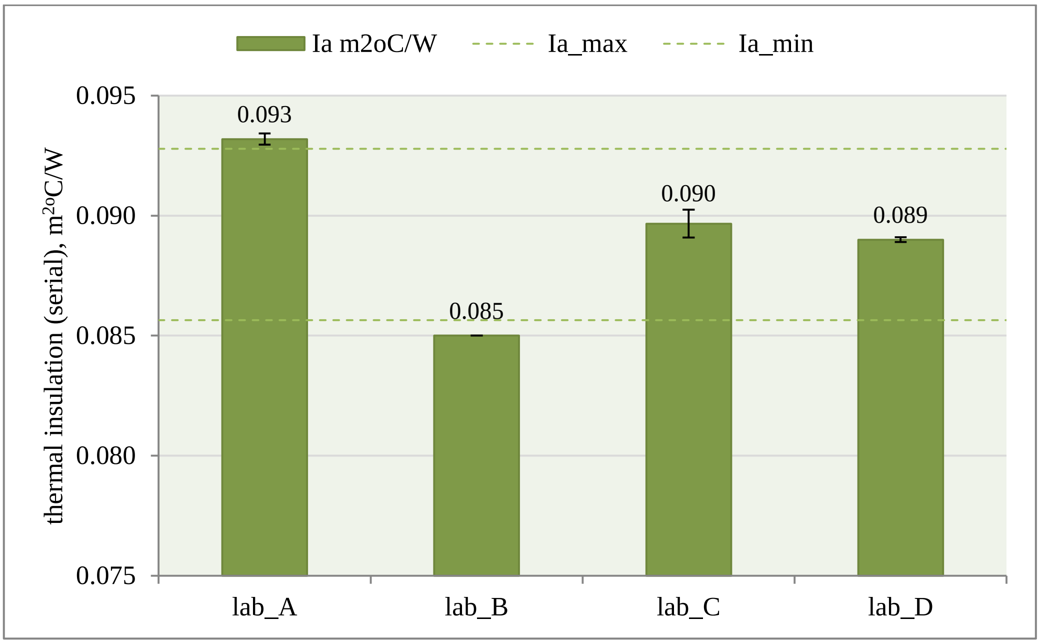

Figure 5. The thermal insulation boundary air layer (I_a) obtained by individual laboratories and reference values with the permissible range 4% error calculated by the serial method

The percentage difference was calculated between the results of the individual value and the reference value to check if individual values were within the acceptable range (Table 3).

Table 3. The percentage difference between the results of the individual values and the reference value (a difference of over |4|% is marked in red)

	lab_A	lab_B	lab_C	lab_D
parallel method				
I_a m^{2o}C/W	-0.6%	3.6%	-2.0%	-1.0%
I_t m^{2o}C/W	-0.4%	-2.1%	5.0%	-2.6%
I_{cle} m^{2o}C/W	-0.3%	-4.2%	7.7%	-3.2%

serial method				
I_a m^{2o}C/W	-4.5%	4.7%	-0.5%	0.6%
I_t m^{2o}C/W	1.2%	-2.3%	3.6%	-2.7%
I_{cle} m^{2o}C/W	3.3%	-4.7%	5.2%	-3.8%

With regard to the parallel method, the above presented dependencies show that the values exceeding the error threshold of 4% were observed 3 times (for I_t excess over the 4% limit occurred twice, for I_{cle} only once). For the serial method, the values over the error threshold of 4% were observed 4 times in total (excess over the 4% limit occurred twice for I_a and twice for I_{cle}). In addition, taking into account standard deviations of individual values, the number of values exceeding the error threshold of 4% was reduced by 1 (Table 8 Appendix 1).

The parameters of the climatic chamber were controlled throughout all the tests. The mean values of the air temperature t_a, relative humidity RH and air velocity V_a were as follows: for the laboratory A: 20.7±0.1^{o}C, 50±1%, 0.40±0.05m/s, for the laboratory B: 20.0±0.1^{o}C, 40±1%, 0.40±0.05m/s, for the laboratory C: 10.3±0.1^{o}C, 50±1%, 0.45±0.05m/s, for the laboratory D: 10.3±0.1^{o}C, 45±1%, 0.44±0.05m/s. They were recorded by sensors in the climatic chamber where the measurements were taken.

Wet heat exchange – evaporative resistance

The PT study made it possible to calculate the evaporative air resistance R_{ea} for the manikin dressed only in special fabric skin. It also allowed the calculation of the total evaporative resistance R_{et} and the effective evaporative resistance R_{ecle} of tested clothing for isothermal conditions (t_a=$t_{manikin}$=34^{o}C). The mean values, standard deviations and the required range of each value with permissible error of 10% are shown in Table 9 (Appendix 1).

The graphs (Figures 6-7) show the results divided in accordance with the parallel method.

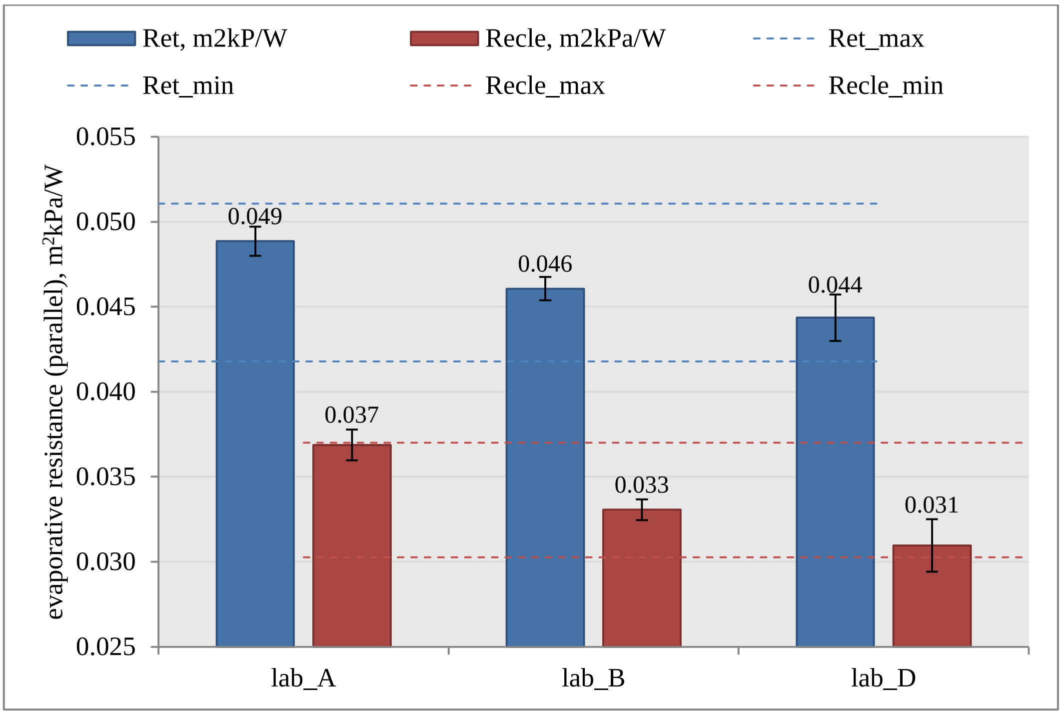

Figure 6. The evaporative resistance (R_{et}) and the effective evaporative resistance R_{ecle} of reference clothing obtained by individual laboratories and reference values with the permissible range 10% error calculated by the parallel method

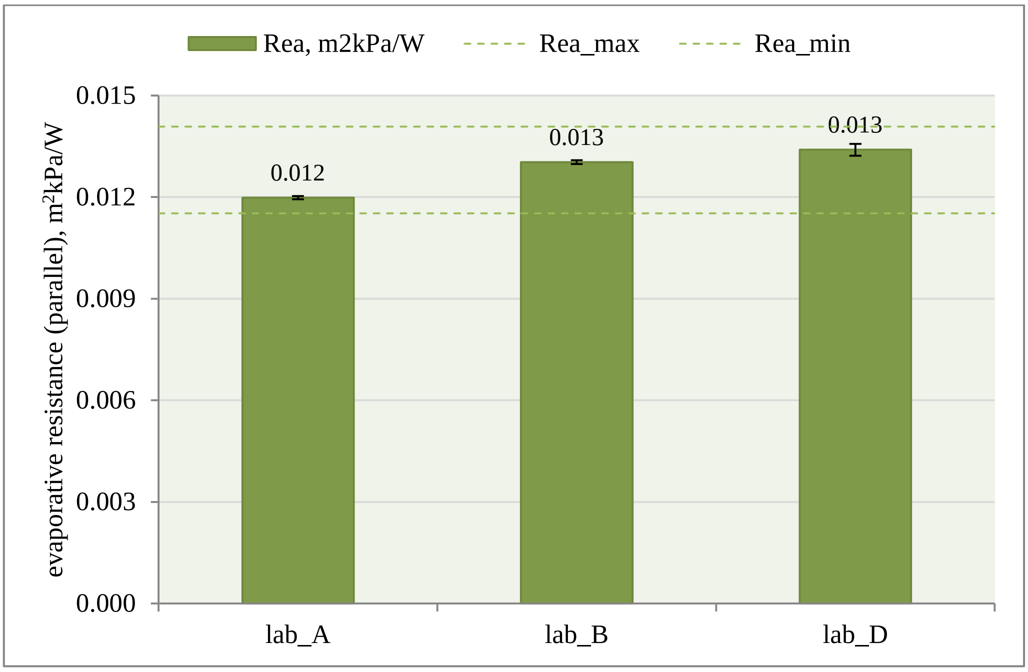

Figure 7. The evaporative resistance of boundary air layer (R_{ea}) (for a manikin dressed only in special skin) obtained by individual laboratories and reference values with the permissible range 10% error calculated by the parallel method

The percentage difference (calculated between the results of the individual and the reference value) showed that all values were in the acceptable range (Table 4).

Table 4. The percentage difference between the results of the individual value and the reference value

	lab_A	lab_B	lab_D
parallel method			
R_{ea}, m^2kPa/W	6.4%	-1.8%	-4.6%
R_{et}, m^2kP/W	-5.2%	0.8%	4.5%
R_{ecle}, m^2kPa/W	-9.6%	1.7%	7.9%

The microclimate parameters (in the climatic chambers) were controlled throughout the tests. The mean values of the air temperature t_a, relative humidity RH and air velocity V_a were as follows: 33.2±0.1^{o}C, 49±1%, 0.40±0.05m/s for the laboratory A, 34.0±0.1^{o}C, 40±1%, 0.40±0.05m/s for laboratory B, and 34.0±0.1^{o}C, 47±1%, 0.39±0.05m/s for laboratory D. They were recorded by sensors in the climatic chamber during the tests.

Statistical calculations

In compliance with ISO 5725-2[11] and ISO/IEC GUIDE 43-1:1997[12] the following parameters were determined in the interlaboratory studies: the reproducibility standard deviation S_R, the reproducibility relative standard deviation RSD_R, the coefficient of variation *V* and the reproducibility limit *R*. The parameters were calculated for the dry heat exchange (I_a, I_t, I_{cle}) with the serial and parallel method and the results are summarised in Table 5.

Table 5. Statistical calculations for the dry heat exchange

		DRY HEAT EXCHANGE _parallel			DRY HEAT EXCHANGE _serial		
		I_a	I_t	I_{cle}	I_a	I_t	I_{cle}
number of measurements	*n*	10	10	10	10	10	10
mean value	$\overline{X}$ [m^{2o}C/W]	0.084	0.304	0.220	0.089	0.342	0.253

minimum value	$X_{\min}$ [m^{2o}C/W]	0.081	0.288	0.202	0.085	0.327	0.237
maximum value	$X_{\max}$ [m^{2o}C/W]	0.086	0.315	0.234	0.093	0.355	0.270
gap	$R_x = X_{\max} - X_{\min}$ [m^{2o}C/W]	0.005	0.027	0.032	0.008	0.028	0.033
reproducibility standard deviation	$S_R = \sqrt{\frac{1}{n-1}\sum_{n=1}^{n}\left(X_i - \overline{X}\right)^2}$ [m^{2o}C/W]	0.002	0.011	0.012	0.003	0.011	0.013
reproducibility relative standard deviation	$RSD_R = \frac{S_R}{\overline{\overline{X}}}$	0.024	0.035	0.055	0.035	0.031	0.050
coefficient of variation	$V = \frac{S_R}{\overline{\overline{X}}} \cdot 100$ [%]	2.4	3.5	5.5	3.5	3.1	5.0
reproducibility limit	$R = 2.8 \cdot S_R$ [m^{2o}C/W]	0.006	0.030	0.034	0.009	0.030	0.035

The coefficient of variation in the dry heat exchange for I_a I_t and I_{cle} remained within the range between 2% and 5% (for the serial and parallel calculation method).

The above mentioned values were also determined for the wet heat exchange (R_{ea}, R_{et}, R_{ecle}). The results are shown in Table 6.

Table 6. Statistical calculations for the wet heat exchange

	WET HEAT EXCHANGE _parallel

	R_{ea}	R_{et}	R_{ecle}
n	7	7	7
$\overline{X}$ [m^{2}kPa/W]	0.013	0.046	0.034
X_{min} [m^{2}kPa/W]	0.012	0.043	0.030
X_{max} [m^{2}kPa/W]	0.014	0.049	0.038
R_x [m^{2}kPa/W]	0.002	0.006	0.008
S_R [m^{2}kPa/W]	0.001	0.002	0.003
RSD_R	0.048	0.043	0.077
V [%]	4.8	4.3	7.7
R [m^{2}kPa/W]	0.002	0.006	0.007

The coefficient of variation of the wet heat exchange for R_{ea} R_{et} and R_{ecle} was in the range between 4% and 8%.

According to ISO/IEC GUIDE 43-1:1997[12], the conducted tests and the obtained results can be evaluated by the means of z-scores |z|. The standard specifies the following division of results: $|z| \leq 2$ satisfactory, $2 < |z| < 3$ questionable and $|z| > 3$ unsatisfactory. The indicator |z| was calculated using the following formula:

$$|z| = \left| \frac{X_i - \overline{X}}{S_R} \right| \quad (7)$$

Figures 8-10 present z-scores calculated for individual laboratories for the dry and wet heat exchange.

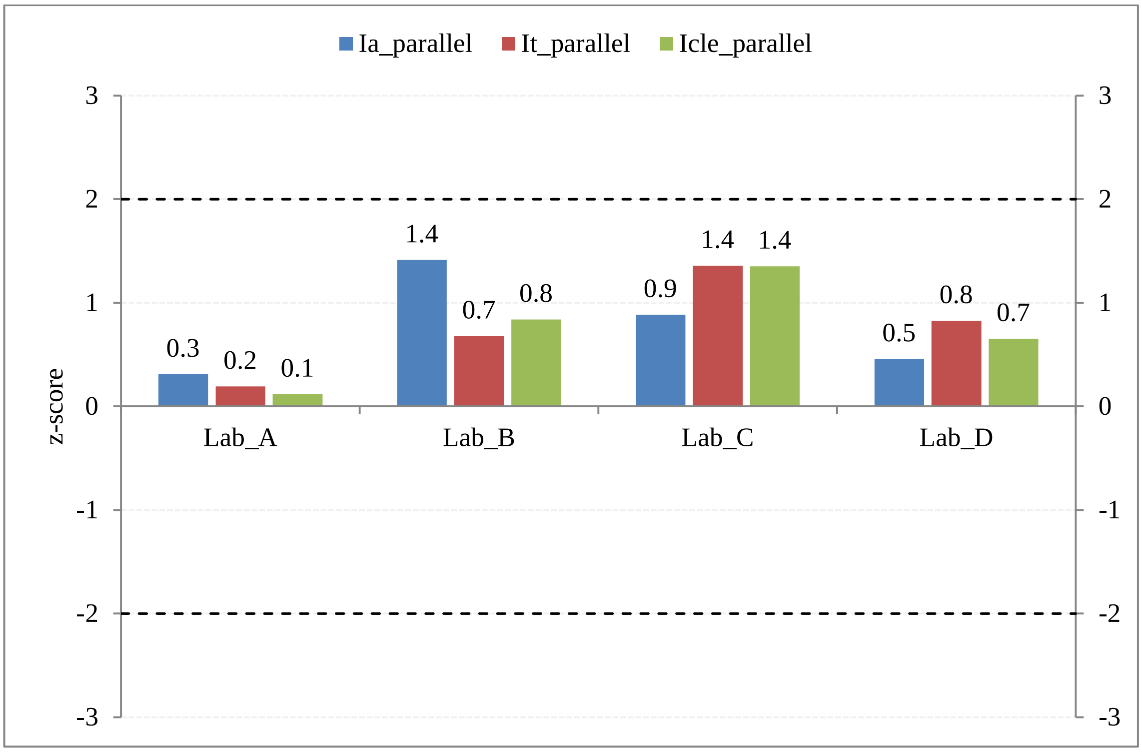

Figure 8 Z-scores calculated for laboratory A, B, C and D for dry heat exchange (parallel method: I_a – thermal insulation of boundary air layer, I_t – total thermal insulation of reference clothing, I_{cle} – effective thermal insulation of reference clothing)

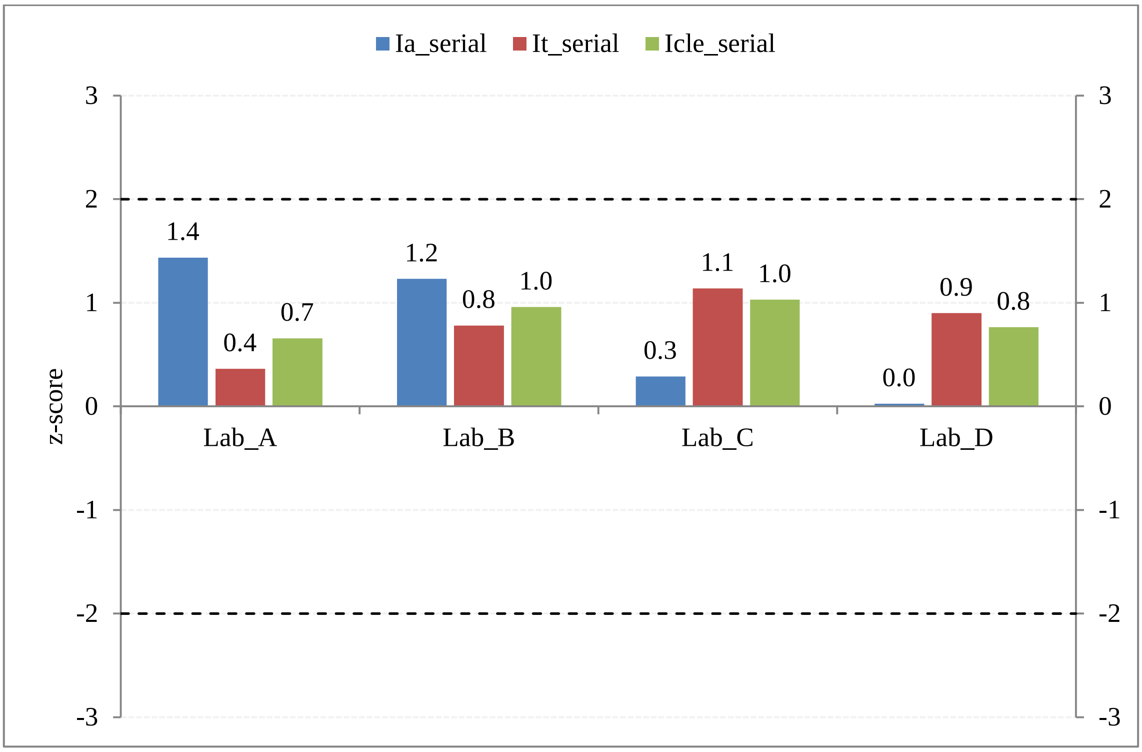

Figure 9 Z-scores calculated for laboratory A, B, C and D for dry heat exchange (serial method: I_a – thermal insulation of boundary air layer, I_t – total thermal insulation of reference clothing, I_{cle} – effective thermal insulation of reference clothing)

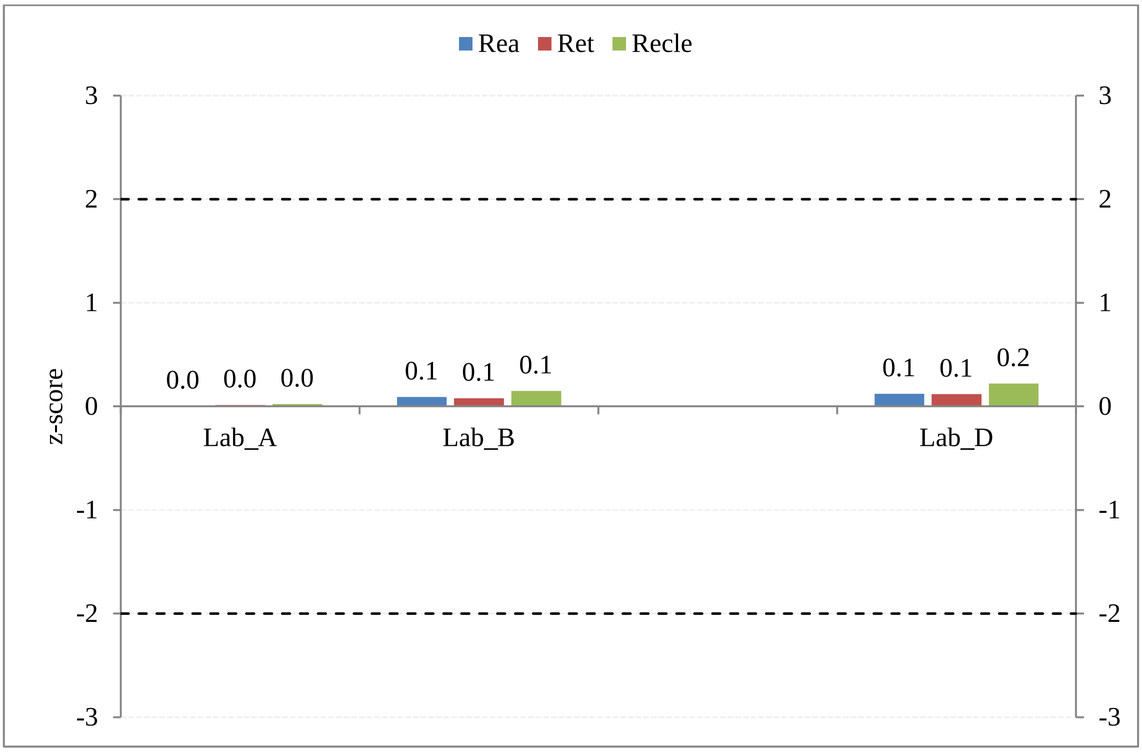

Figure 10 Z-scores calculated for laboratory A, B and D for wet heat exchange (parallel method: R_{ea} – evaporation resistance of boundary air layer, R_{et} – total evaporation resistance of reference clothing, R_{ecle} – effective evaporation resistance of reference clothing

The values were assessed on the basis of z-score results. It was found out that all laboratories participating in the PT study fell within $|z| \leq 2$ satisfactory.

Discussion and conclusions

According to EN ISO 15831 standard[8], the reproducibility limits (*R*) for total thermal insulation calculated according to the parallel and serial model should fall within <7%, whereas according to ASTM F2370-10[10], basing on interlaboratory testing, the reproducibility limit for evaporative resistance R_{ecl}, for data taken at different laboratories, was 0.008 m^2kPa/W (which equaled *R* 50%).

In the framework of the SUBZERO project, the interlaboratory study was organised. With the participation of 8 different laboratories, it aimed to measure thermal insulation of 4 different clothing ensembles. The study revealed that the coefficient of variation was less than 9% both with the parallel and serial model[5]. The calculated reproducibility limit of thermal insulation tests (for cold protective ensemble – clothing designed for use in the ambient temperature of -50^oC) was *R* 15% for serial and parallel methods[13].

The interlaboratory study organised by KSU[7] with 6 different thermal manikins determined thermal resistance (insulation value) and evaporative resistance of 5 clothing ensembles. Depending on an ensemble (ensemble 1: I_{t_mean} 0.176 $m^{2o}C/W$; ensemble 5: I_{t_mean} 0.390 $m^{2o}C/W$), reproducibility of thermal resistance measurements made between laboratories was in range of 0.111-0.161 $m^{2o}C/W$ (*R* 63% and 41%, respectively)[7]. The reproducibility of evaporative resistance measurements was in wide range of 0.020-0.250 m^2kPa/W (*R* 80% and 153% respectively)[7].

In the same tests but with the participation of EMPA[14], the reproducibility between laboratories with regard to the above mentioned tests ranged between 0.053$m^{2o}C/W$ and 0.150 $m^{2o}C/W$ (*R* 45% and 44%, respectively)[14]. The reproducibility for evaporative resistance test was in wide range of 0.012-0.219 m^2kPa/W (*R* 80% and 137%, respectively)[14].

In other research, three independent laboratories measured the evaporative resistance of seven clothing ensembles[9]. Tests were carried out with 2 types of thermal manikins: Newton (26 and 34 zones) and Tore (17 zones). The interlaboratory reproducibility, for more permeable samples (R_{et}<0.06 m^2kPa/W) was in the range 12-24%[9] and for less permeable samples reproducibility was in the range 51-53% (R_{et} 0.10-0.30 m^2kPa/W)[9] which also represents a rather high value.

The comparison studies were also conducted by Wang[14]. The studies covered 8 laboratories equipped with 6 thermal manikins of the Newton type, as well as the KEN and TORE type. Six clothing ensembles were tested. The reproducibility standard deviations had a greater variability in the range of 0.0009-0.0183 m^2kPa/W. The calculated interlaboratory reproducibility limit, for more permeable samples (R_{et}<0.04 m^2kPa/W)[14] was in the range 16-33% and for less permeable sample (R_{et} 0.12 m^2kPa/W) reproducibility limit was 41%[14]. Furthermore, the said studies omitted to determine the intensity of sweating required for testing. For example, 7 laboratories applied the sweat rate over 500 $g \cdot m^{-2} \cdot hr^{-1}$, whereas one laboratory applied the sweat rate of 200 $g \cdot m^{-2} \cdot hr^{-1}$.

The authors of the said studies pointed to a number of factors liable to affect the relatively high interlaboratory reproducibility limits (*R*). They enumerated, inter alia,:

difference in construction of used manikin[7,13,17] (heating system[13], dimensions of manikin[13], body shape[9,13], number of segments, shell materials[13]), difference in water supply system[7,9,14,17,18], number of sweating segments[7], not clear test protocol[7,13,17,18] and difference in calculation methods[13,17] but also dissimilarities in terms of sensors calibration of the manikin[9]. The effect of the sample stiffness/fit[9,13] and also thermal parameters in the climatic chamber[7,9,13,17,18] were also noted.

In accordance with the assumptions of the study, the use of one-type of a manikin and a precise clothing instruction[9] should allow for decreasing, at least partly, the dispersion of intra-laboratory test results. In the studies under analysis (for measuring the total thermal insulation I_t), the coefficient of variation (*V*) was below 3.5% (for the serial and parallel method) and the reproducibility limit (*R*) was 9%. The use of one type of a manikin resulted in lowering the coefficient of variation and the reproducibility limit in comparison to the studies by Anttonen[17] (*V*<9%; *R* 15%), McCullough[7] and Richards[13] (*R* 44%). Nevertheless, the value of *R* according to EN 342[6] is even lower (*R*<7%). It needs to be pointed out that the manikins, although of the same type, differed in terms of the number of segments and the total measuring area. Additionally, the discrepancies in the results can be attributed to the conditions under which the dry heat exchange was carried out, which varied and were differentiated according to a given laboratory. All the laboratories studied the total thermal insulation for air flow of 0.4m/s. The differences were noted in relative humidity and ambient temperature. Given the relative humidity range of 40-50% , it was concluded that it did not have a significant influence on the results of the dry heat exchange. Anttonen[17] demonstrated that the influence of humidity (20-80% RH) on the total thermal insulation was negligible. In the PT studies under discussion, two laboratories carried out tests in the ambient temperature of 20-21^{o}C (lab_A, lab_B), while the remaining ones in the ambient temperature equivalent to 10^{o}C (lab_C, lab_D). It seems possible that higher ambient temperatures could have been the reason for failure to satisfy the condition of heat flux >20 W/m^2 on all segments. The phenomenon was defined by Wang[14] as one of sources of error.

As regards the wet heat exchange in the studies discussed in this paper (for measuring the evaporative resistance R_{et}), the coefficient of variation (*V*) was 4.3% (for the parallel method) and the reproducibility limit (*R*) was 0.006 m^{2}kPa/W (*R* 13%). The major factor which differentiated the results was the sweating system. Two manikin had the internal water system (a sweat rate was set at 500 ml$\cdot$m$^{-2}\cdot$hr^{-1}) and one laboratory pre-sprayed the skin to wet it.

In the studies by Lu[19] with the use of a 34-segment ‘Newton’ sweating thermal manikin and 7 clothing ensembles, the value of evaporative resistance for tests with pre-wetted fabric ‘skin’ was significantly higher than with water supplied sweating. In the latter case, a special cotton fabric skin was pre-wetted. It contained 154% of its dry weight while a uniform water flow rate of 800 $ml\cdot m^{-2}\cdot hr^{-1}$ was set to all segments of manikin[19]. The discussed studies demonstrated the same tendency. A comparison of the manikins with the same number of segments but different sweating systems (lab_A and lab_D) showed that the evaporative resistance for lab_A with pre-wetting applied was higher than R_{et} for lab_D with internal water supplied system. It should be also pointed out that the applied sweat rate affects the value of evaporative resistance. Lu's studies[16] demonstrated that in case of a clothing ensemble with the total insulation value of 1.23 clo (permeability index 0.3) there was a statistical difference between R_{et} for the sweat rate of 400 $ml\cdot m^{-2}\cdot hr^{-1}$ and the values of 800 and 1200 $ml\cdot m^{-2}\cdot hr^{1}$. For sweating set point of 400 $ml\cdot m^{-2}\cdot hr^{-1}$ a higher evaporative resistance of clothing was calculated[16]. According to Lu[16], the reason for this discrepancy in the results was attributable to not fully saturated fabric skin for a sweating rate <400 $ml\cdot m^{-2}\cdot hr^{-1}$. Lu[16] therefore recommended to set a sweat rate for such cases at >400 $ml\cdot m^{-2}\cdot hr^{-1}$. Similar conclusions were also drawn by Wang[14]. When pre-wetted system is used a saturation level of fabric skin may prove problematic and hence affect a measurement error.

The 13% reproducibility limit (*R*) for R_{et} is comparable with the result of studies conducted by Mayor[9] and Wang[14] who used a similar clothing ensemble.

The studies described in this paper demonstrated that the assumed assessment criteria with permissible errors at the intra-laboratory level were too liberal. Furthermore non-compliance with the said criteria was proven in selected cases. When analysed against interlaboratory criteria, however, the same results satisfied the criteria. Alongside this, z-scores calculations for the dry and wet heat exchange yielded satisfactory results for compliance with the provisions of the ISO/IEC GUIDE 43-1 standard. Given the increasing availability of thermal manikins and diversity of their constructions, it seems justifiable to consider establishing assessment criteria for wet and dry heat exchange based on the previously conducted studies, taking into consideration the manikins used, and applying them in future PT.

The studies presented in this article point to a need for standardisation of evaporative resistance experiments conducted with thermal manikins. They furthermore show the importance of the type of a manikin selected for testing which, to a large extent, determines the final outcome of studies. Alongside the type of a manikin, the sweating system and sweating intensity[2,14,16] are equally important. The knowledge on the influence of the above mentioned parameters on the final result is invaluable.

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Appendix 1

Table 7. Mean values with standard deviations from thermal insulation of reference clothing - dry heat exchange

parallel method	lab_A	lab_B	lab_C	lab_D	Mean value, $m^{2o}C/W$	4% of mean value	Required range, $m^{2o}C/W$
I_a $m^{2o}C/W$	0.084 ±0.000	0.081 ±0.000	0.086 ±0.001	0.085 ±0.000	0.084	0.003	0.081 – 0.087
I_t $m^{2o}C/W$	0.306 ±0.002	0.311 ±0.006	0.290 ±0.002	0.313 ±0.001	0.305	0.012	0.293 – 0.317
I_{cle} $m^{2o}C/W$	0.222 ±0.002	0.230 ±0.006	0.204 ±0.002	0.228 ±0.001	0.221	0.009	0.212 – 0.230
serial method	lab_A	lab_B	lab_C	lab_D	Mean value, $m^{2o}C/W$	4% of mean value	Required range, $m^{2o}C/W$
I_a $m^{2o}C/W$	0.093 ±0.000	0.085 ±0.000	0.090 ±0.001	0.089 ±0.000	0.089	0.004	0.086 – 0.093
I_t $m^{2o}C/W$	0.338 ±0.006	0.350 ±0.007	0.330 ±0.002	0.351 ±0.003	0.342	0.014	0.328 – 0.356
I_{cle} $m^{2o}C/W$	0.245 ±0.006	0.265 ±0.007	0.240 ±0.003	0.263 ±0.003	0.253	0.010	0.243 – 0.263

Table 8. The percentage differences include individual laboratory standard deviation (values >|4|% marked in red)

	lab_A	lab_B	lab_C	lab_D
parallel method				
I_a $m^{2o}C/W$	-0.6%	3.6%	-2.0%	-1.0%
I_t $m^{2o}C/W$	-0.4%	-2.1%	4.5%	-2.6%

I_{cle} m^{2}°C/W	-0.3%	-1.7%	6.9%	-3.2%
serial method				
I_a m^{2}°C/W	-4.2%	4.7%	-0.5%	0.6%
I_t m^{2}°C/W	1.2%	-2.3%	3.6%	-2.7%
I_{cle} m^{2}°C/W	3.3%	-2.0%	4.1%	-3.8%

Table 9. Mean values with standard deviations from the evaporative resistance of reference clothing - wet heat exchange

parallel method	lab_A	lab_B	lab_D	Mean value, m^2kPa/W	10% of mean value	Required range, m^2kPa/W
R_{ea}, m^2kPa/W	0.012 ±0.000	0.013 ±0.000	0.013 ±0.000	0.013	0.001	0.012 – 0.014
R_{et}, m^2kP/W	0.049 ±0.001	0.046 ±0.001	0.044 ±0.001	0.046	0.005	0.042 – 0.051
R_{ecle}, m^2kPa/W	0.037 ±0.001	0.033 ±0.001	0.031 ±0.002	0.034	0.003	0.030 – 0.037