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Water vapor resistance measured on sweating thermal manikin and Permetest skin model in the vertical orientation

Frederick Fung[1], Chuansi Gao[2], Lubos Hes[1], Vladimir Bajzik[1,*]

[1] *Department of Evaluation, Faculty of Textile Engineering, Technical University of Liberec, Czech Republic*
[2] *Thermal Environment Laboratory, Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Faculty of Engineering, Lund University, Sweden*

*Corresponding author *E-mail address:* tassfashion@gmail.com

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ABSTRACT

This paper is a comparison of water vapor resistance (R_{et}) measured using the Permetest skin model and Tore sweating thermal manikin, i.e. 2D versus 3D methods; and to study the relationship between them. Three materials and five air gap distances were used for the measurement between these two apparatuses, the test conditions in the climatic chambers were set up according to the ISO standard of each measurement method. Results of the correlation coefficient of three materials showed that they all had a strong increasing trend between the Permetest skin model and the sweating thermal manikin. From the regression analysis, the P-value of all three materials showed that $P < 0.05$ and 100% cotton R^2=0.83, 50% cotton 50% polyester R^2 = 0.91, 100% polyester R^2=0.99. However, R_{et} resulting values from each device slowed down after 12 mm air gap distance.

Keywords
Sweating thermal manikin,
Permetest skin model,
water vapor resistance,
vertical orientation,
air gap distance

1 Introduction

Water vapor resistance (R_{et}) is one of the important parameters in clothing comfort [1-3]; the sweating thermal manikin and the Permetest skin model are apparatuses used by researchers and scientists to test on garments, textile for the value of R_{et} [4-6].

The sweating thermal manikin [7,8] is an anatomically correct, human-like robot that the whole body is divided into segments; each segment of the thermal manikin is a heat zone where the body shell surface temperature can be controlled and adjusted using a computer program to simulate human body heat for thermal comfort of clothing tests (Fig. 1). Because of the human form, thermal manikin can measure convective, radiative and conductive heat losses in all directions over the whole surface or a defined, local surface area [9]. From one-segment of copper manikin, which was invented and used by the U.S. military for researching on thermal heat transfer through protective clothing ensembles in 1941 [10], to multi segments made of plastic or metal, thermal manikin has been developed and been re-invented in many different ways [11-15]; for examples, from dry to wet (sweating) thermal manikins, female and baby manikins, head, hand and foot manikins, breathable manikin for medical research purposes, fabric manikin - Walter for giving R_{ct}/R_{et} results in the same test, and even inflatable manikin [16]. In sweating thermal manikin, small holes are embedded in particular segments on the body that can secrete water to simulate the sweating glands on the human body and some models can perform simple movements like cycling and walking activities. When testing for evaporative resistance (R_{et}), the manikin will be put on a tight fabric skin which is moisture permeable to evenly spread out moisture, and clothing simply hangs on top of the skin, results are directly recorded in the computer program. Though thermal manikin is considering one of the most accurate apparatus for testing thermal and evaporative resistance of clothing system, it still has rooms for improvements. For example, researchers are still debating heat loss or mass loss method should be used when testing for R_{et} [17]; it is difficult to detect and to control the skin surface temperatures [18,19], etc.

The Permetest is one of the smallest skin models among others; like Alambeta and Thermo Labo [20,21]. The concept of the Permetest is derived from the Hohenstein skin model – sweating guarded hot plate (SGHP) – which is to measure evaporative resistance of fabric by generating a unidirectional heat flux through the sample, then the evaporative heat loss is recorded in the steady state [22-24]. However, maintaining the hot plate perfectly flat with even and constant heat; and preventing heat loss by insulation still have a discrepancy [25-29].

The Permetest skin model (developed by Hes) works on the principle of heat power sensing by maintaining constant heat supply to the measuring head is measured with and without fabric sample (Figure 2). When testing R_{et}, sample textile/clothing (without cutting) is put on the small circular hotplate which is covered by a thin layer of vapor permeable membrane function as the wet skin inside the wind channel for testing (Fig. 3a-e). The measuring head where the supplied water gets evaporated is measured; the partial saturated pressure of the measuring head with and without sample, and the partial pressure of the ambient atmosphere are also measured under the isothermal condition. A lot of articles have already published regarding these two apparatuses testing on different garments and materials like protective clothing, knitted fabrics, testing garments in multi-layers; mass, thickness, dry and wet state of materials; footwear materials and even using manikin and Permetest to test on different parameters of the same material [30-35]. These experiments showed that physical and mechanical properties like drapability, air permeability, porosity, thickness and so on of materials/clothing influence the results of R_{et}. For example, over- or underestimation of heat loss caused by condensation when low permeability clothing is tested in low ambient temperature [36-38]. However, this paper is focused on finding out the correlation between the Permetest skin model and the thermal manikin these two apparatuses. Knowing the correlation of these two apparatuses is useful to predict the R_{et} when there is no access to the manikin, and also save time and labor cost. The only limitations of the research are 1) the maximum air gap thickness is 16 mm, a limit of the Permetest; 2) only three materials were tested; 3) after 12 mm air gap distance, R_{et} started to slow down or stabilized.

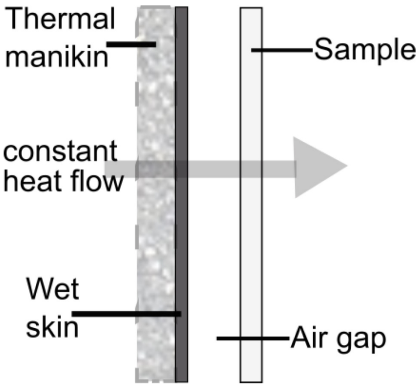


Fig. 1 Principle of thermal manikin

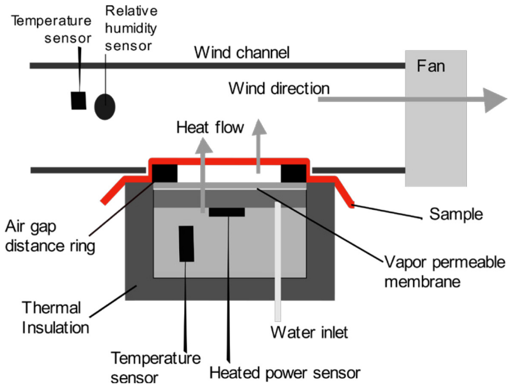


Fig. 2 Principle of Permetest skin model

2 Method

Two apparatuses were used for the experiment, Permetest skin model and the sweating thermal manikin. Tested samples were woven materials shown in Table 1. Samples were washed to minimize the finishing on the materials, hang dry then iron flat before used for tests. Five air gaps between 0-16 mm were applied during tests which were 0, 4, 8, 12 and 16 mm. Each material was tested three times on each apparatus with the combinations of five air gap distances

Table 1. Properties of materials

Material	**100% Cotton**	**50/50% Cotton/Polyester Blended**	**100% Polyester**
Type	Plain	Plain	Plain
Weight (g/m²)	156	159	159
Thickness (mm)	0.30	0.38	0.43
Fabric Density Warp/Weft (per cm)	26/22	26/26	24/16
Air Permeability (l/m²/s)	234	272	579
Absorption Rate (%/s) Top/Bottom	13.33/35.50	11.81/39.24	7.81/20.07
Porosity (%)	66	71	73
Drapability (%)	34	39	43

2.1 Permetest skin model

Materials were used directly without cutting. Air gap distance was applied by using 100 percent foamed polyethylene in 2, 4 and 5 mm thickness rings and their combinations (Fig.3a-e). To balance the thickness of the air gap distance created by the stack of rings and to maintain the smooth air current flew inside the wind channel, two types of rings were cut: outer rings were put around the base of the hotplate for counter thickness; inner rings were placed inside the wind channel on the hotplate to create the air gap distance. The outer ring was 12cm in diameter on the outer circle and 10cm on the inner circle, width 2cm. The inner ring was 8cm in diameter on the outer circle and 6cm on the inner circle, width 2cm. Each material was tested three times under 0, 4, 8, 12, 16 mm air gap distance in a vertical orientation to simulate the vertical air gaps on the manikin and in an isothermal condition. As required in the ISO 11092 [39], the climatic chamber was set up at 50-55% in relative humidity, wind speed at 1m/s and air temperature at 22-24 °C.

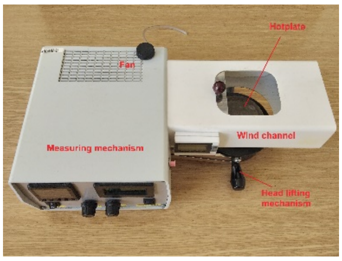
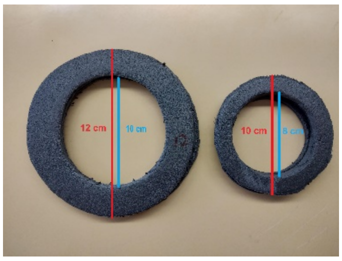
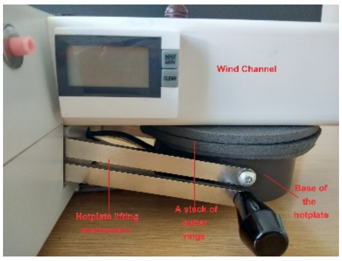


Fig. 3 (a) Permetest skin model in the horizontal orientation

(b) Permetest skin model in the vertical orientation



(c) Sizes of outer and inner rings



(d) Showing outer rings stacked on the base of the hotplate

(e) Showing inner rings placed inside the wind channel on the hotplate

Each determination of evaporation resistance R_{et} of a sample consists of two steps: first test without sample, second test with air gap distance ring of thickness h covered by a sample. When the heat flow q_{eto} reaches the steady state, the result of the first step is given by the Eq. (1), where R_{eto} presents resistance of the boundary layer above the measuring surface of the instrument:

$$q_{eto} = (P_s - P_o)/R_{eto} \quad (1)$$

Here, P_s means partial pressure of the saturated water vapour and P_o is the partial pressure of the water vapour in the measuring channel of the testing instrument. The second step characterises the heat flow passing through the measuring head of the instrument covered by the tested sample:

$$q_{et} = (P_s - P_o)/ (R_{eto} + R_{et}) \quad (2)$$

for the case without the distance ring in Eq. (2) or with distance ring in Eq. (3)

$$q_{etg} = (P_s - P_o)/ (R_{eto} + R_{et} + R_{eg}) \quad (3)$$

which creates the additional air gap resistance R_{eg}. R_{eg} = h/D, where D is the coefficient of diffusion of water vapour in air, which can be found in tables. The required evaporation resistance of the sample R_{et} yields solution of Eq. 1 and Eq. 2. The required total evaporation resistance of the sample R_{et} + air gap resistance R_{eg} yields solution of Eq. 1 and Eq. 3. When from the achieved value the evaporation resistance of the sample R_{et} is deduced, we obtain evaporation resistance R_{eg} of the air gap.

2.2 Sweating thermal manikin

Tore is the thermal manikin used in the experiments. A close-fitted shirt (approximately 0 mm air gap, Fig. 4 a-f) was made by the molding method [40]. Based on this shirt, 4, 8, 12, 16 mm air gap distance was added into the shirt pattern circumference as wearing allowance. All shirts were sewn by a fine 100% polyester thread (Polysheen® No. 40) with a fine machine sewing needle (Schmetz 70/10). The sewn seams were pressed open under a press-cloth with high heat to melt/expand the polyester thread to minimize the size of needle holes to reduce heat loss. A total of fifteen combinations of shirts of three materials with 0, 4, 8, 12, 16 mm built-in air gap distance were made. The air gap distance around the torso when the shirt was put on the manikin might not be the same as desired, for example; on the shoulder areas might have 0 mm air gap distance. Each of the 15 shirts combinations was tested three times for evaporation resistance on a heated thermal manikin with pre-wetted skin in an isothermal condition. ISO 15831 was followed. The climatic chamber was set up at 50% in relative humidity, wind speed at 0.145 m/s and air temperature at 34 °C.

Fig. 4 (a) Tore – sweating thermal manikin

(b) The molding method -- duct tape was applied on top of the plastic shrink wrap which was tightly wrapped around the torso of the manikin for protection and easy unmolding

(c) Unmolded front and back pieces and were divided into small segments according to the contour lines on the manikin's torso

(d) Unmolded arm piece from shoulder to wrist and cut into small segments

(e) Arm piece was converted into two-dimensional sleeve patterns

(f) The finished shirt was completed with bodice and sleeves and was closed in the center back

For each 40 minutes observation, 20 minutes of steady state was taken for calculating the result as in Eq. (4), where P_{aS} is the manikin skin water vapor pressure (only torso and arms); P_{aA} is the ambient air water vapor pressure; HL is the heat loses of the torso and arms only.

$$R_{et} = P_{aS} - P_{aA} / HL \quad (4)$$

3 Results

Resulting data in Table 2 were analyzed by three methods: a) Correlation coefficient in Table 3; b) Linear regression (Fig. 5a-c); c) 2-way ANOVA.

Table 2. R_{et} results from the Permetest skin model and the thermal manikin

Mean values of evaporative resistance of materials (Pa*m²/W)						
Air gap distance	100% CO		50/50% CO/PES		100% PES	
	Permetest	Manikin	Permetest	Manikin	Permetest	Manikin
0 mm	3.50	4.90	3.70	5.87	1.40	1.73
4 mm	5.30	4.90	6.10	6.20	4.60	4.27
8 mm	10.70	10.27	11.50	10	9	6.47
12 mm	19.40	10.27	22.20	10.87	16.70	10.23
16 mm	21.90	11.83	26.70	13.03	19.60	12.13

Results from the Permetest skin model and the thermal manikin showed that when the air gap distance increases, the evaporative resistance increases and the increasement slows down after 12 mm air gap distance in both apparatuses. An interesting thermal manikin R_{et} results from 100% cotton, it showed that 0 and 4 mm; 8 and 12 mm air gap distances had the same mean values. The original data showed that results from these four air gap distances were different but the values were very close. However, these results may also cause by the thickness, drapability, porosity and evaporation of the fabric itself, further investigation needed.

a) Correlation coefficient of Permetest skin model and the thermal manikin

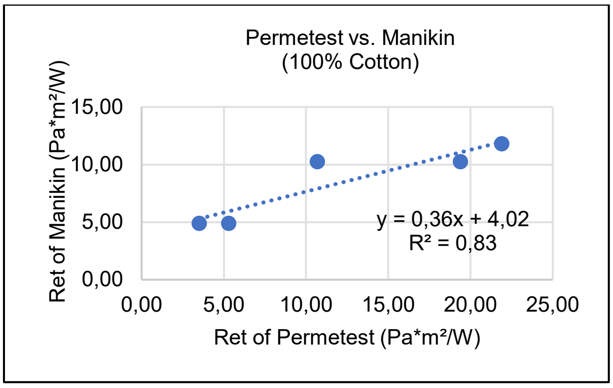
Table 3. Values of correlation coefficient from three materials

Correlation Coefficient	**100% Cotton**		**50/50% Cotton/Polyester**		**100% Polyester**	
	Permetest	Manikin	Permetest	Manikin	Permetest	Manikin
Permetest	1		1		1	
Manikin	0.91	1	0.95	1	0.997	1

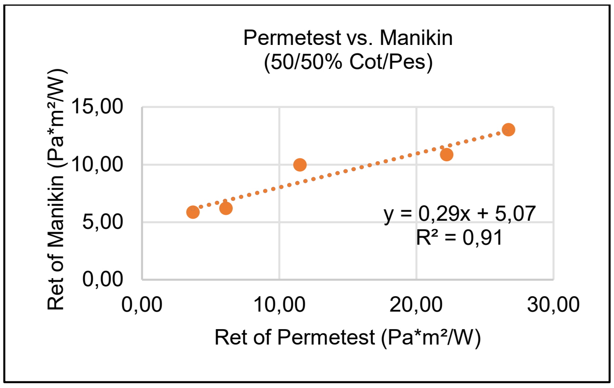
Results from all three materials showed that their correlation coefficient (r) values between the Permetest skin model and the thermal manikin had a very strong positive trend. For the results from 100% polyester, the r is almost 1.

b) Linear regression between Permetest skin model and the thermal manikin

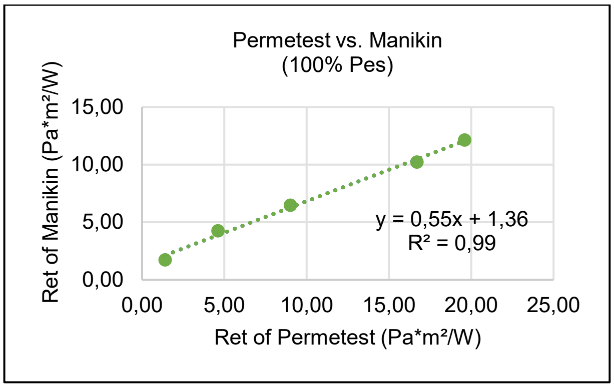
Correlation determination (R^2) of 100% cotton is 0.83, 50/50% cotton/polyester blended is 0.91, and 100% polyester is 0.99 almost 1 to 1 relationship. Results mean that each unit of Ret changes in the thermal manikin is highly related to the changing in the Permetest skin model.



(a)



(b)



(c)

Fig. 5 Regression between Permetest and thermal manikin of 100% cotton (a), 50/50% cotton/polyester blended (b), 100% polyester (c)

c) 2-way ANOVA of Permetest skin model and the thermal manikin with 0 to 16 mm air gap distances in three materials

Results showed that P-value of three materials were: 100% cotton $P<0.05$; 50/50% cotton/polyester $P<0.05$; 100% polyester $P<0.01$ in 95% confidence level. Three materials $P<0.05$ show that there is a significant difference between the results of Permetest and the thermal manikin which is because these two apparatuses are fundamentally different when taking the R_{et} measurement as shown in Table 4.

Table 4. Differences between Tore – the thermal manikin and the Permetest skin model

	Tore – Sweating Thermal Manikin	**Permetest Skin Model**
Shape	Human form	Rectangular form
Dimension	Height 170 cm, chest 94 cm, waist 88 cm	Length 54 cm, width 23 cm, height 13 cm
Weight	Unknown	7 kg
Materials	Plastic form shell, inside supported by the metal frame for body parts and joints	Metal
Total heated measured area	1.774 m²	50.265 cm²
Measuring Method	3D – Ready-to-wear garments	2D – Flat surface of textile or garments (non-destructive)
Measuring Time	20 minutes of steady state out of 40 minutes total measuring time	1 to 5 minutes in each measurement in average
ISO Standard	15831	11092

4 Conclusions

Tore – the sweating thermal manikin and the Permetest skin model were used to examine the evaporative resistance (R_{et}) of the combinations of three materials (100% cotton, 50/50%

cotton/polyester, 100% polyester) and five air gap distances (0, 4, 8, 12, 16 mm). Each apparatus' set up environment was according to a different IOS standard but the method for testing materials was different; materials were made into shirts to be tested on the manikin and were directly tested on the Permetest without cutting. Results were analyzed by three methods: correlation coefficient, correlation determination and the P-value. The correlation coefficient results from all three materials showed a very strong positive increasing relationship between the manikin and the Permetest skin model. The R^2 of the three materials are also very strong that it indicated that the R_{et} values of the manikin are highly predicted by the Permetest skin model and vice versa. However, $P < 0.05$ in all three materials in the two-way ANOVA showed the significant difference between the two apparatuses; it was caused by the different methods of testing materials on each apparatus, 2D versus 3D. Overall, this experiment shows that values of evaporative resistance (R_{et}) can be predicted between the manikin Tore and the Permetest skin model for the 100% cotton, 100% polyester and 50/50% cotton/polyester blended within a narrow air gap from 0 to 12 mm, then the trend will become stabilized or slow down.

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