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DERIVATION OF EVAPORATIVE RESISTANCE R_{et} OF CLOTHING FROM ITS THERMAL RESISTANCE R_{ct} MEASURED ON DRY THERMAL MANIKIN AND FROM R_{ct}/R_{et} CORRELATIONS DETERMINED ON A VERTICAL SKIN MODEL

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SUMMARY OF THE THESIS

Title of the thesis: Derivation of evaporative resistance R_{et} of clothing from its thermal resistance R_{ct} measured on dry thermal manikin and from R_{ct}/R_{et} correlations determined on a vertical skin model

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Abstract

Sweating thermal manikin is considered the best machine for testing thermal insulation (R_{ct}) and evaporative resistance (R_{et}) of clothing because manikin's human form can be put on the ready-to-wear garment for testing in a 360-degree environment. It does not like the sweating guarded hot plate (SGHP), so-called skin model; the testing material has to be in a two-dimensional format. However, the sweating thermal manikin cost is very expensive and not commonly owned by research institutes or clothing companies. To solve this issue, a dry thermal manikin (non-sweating, more affordable and popular among many research institutes) is used together with the Permetest skin model to predict the R_{et} for the clothing. The research aims to use the R_{ct} result from a dry thermal manikin and the correlation of the vertically oriented skin model (Permetest) to develop a model equation that can calculate the R_{et} without using the wet thermal manikin.

Four popular clothing materials were chosen (cotton, polyester and their blends plus polypropylene as counter sample) and sewn into shirts in different sizes equivalent to different air gap sizes. Shirts were tested on the dry manikin. Results were analyzed and correlated to the same materials and same air gap distances in a vertically oriented skin model (Permetest) by choosing the best-fit line for all the data as the basic equations to develop the final model equation to predict the R_{et} of the clothing without using the sweating thermal manikin.

Keywords: *Sweating thermal manikin, Permetest skin model, Vertical-horizontal orientation, Evaporative resistance, Clothing comfort, Air gap size, Correlation coefficient*

Abstrakt

Potící se tepelný manekýn je považován za nejlepší zařízení pro testování tepelné izolace (R_{ct}) a výparného odporu (R_{et}) oděvů, protože na manekýna ve formě lidské postavy lze snadno obléci trojrozměrný konfekční oděv při jeho testování. Tuto možnost neposkytuje tepelný model lidské kůže – skin model, neboť zkoušený materiál se zde nachází dvourozměrném formátu. Náklady na pořízení tepelného manekýna s možností pocení jsou však velmi vysoké a proto tato zařízení jsou jen zřídka instalovány ve výzkumných ústavech nebo oděvních společností. Ke stanovení R_{et} u zkoušených oděvů je v této práci použit suchý tepelný manekýn (cenově dostupnější a oblíbený v mnoha výzkumných ústavech) společně s českým tepelným modelem lidské kůže (skin modelem) Permetest. Výzkum v této práci si klade za cíl použít výsledek R_{ct} ze suchého tepelného manekýna a korelaci vertikálně orientovaného modelu kůže (Permetest) k vytvoření modelové rovnice, která umožní vypočet R_{et} bez použití potícího se tepelného manekýna.

K experimentům byly vybrány čtyři oblíbené oděvní materiály (bavlna, polyester a jejich směsi plus polypropylen) a použity k výrobě do košil v různých velikostech odpovídajících různým velikostem vzduchové mezery. Košile byly testovány na suchém manekýnu. Výsledky byly analyzovány a korelovány se stejnými materiály a stejnými šířkami vzduchových mezer ve vertikálně orientovaném skin modelu. Poté byly nalezeny nejvhodnější závislosti pro všechna data potřebná pro sestavení základních rovnic sloužících k prezentaci finální modelové rovnice umožňující cílový výpočet a predikci výparného odporu R_{et} oblečení bez použití potícího se tepelného manekýna.

Klíčová slova: *Teplá figurína pocení, model kůže Permetest, Vertikálně-horizontální orientace, Odpařovací odpor, Pohodlí oblečení, Velikost vzduchové mezery, Korelační koeficient*

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1. Introduction

Thermophysiological comfort, thermal insulation (R_{ct}) and evaporative resistance (R_{et}) are two important parameters that influence the body heat balance during various activities. These two parameters are most commonly measured by thermal manikin and sweating guarded hot plate so-called skin model.

Thermal manikin [1-3] is an anatomically correct, human-like robot that the whole body is divided into segments which are the heat zones, and the heat can be controlled and adjusted using a computer program to simulate human body heat to test the heat transfers from the manikin body through clothing system to the environment. Thermal manikins have two major types: dry and wet (built-in sweating system). The sweating thermal manikin models have small holes embedded in particular segments connected to the water pump inside the manikin to secrete water to simulate the human body's sweating glands. Because of the human form, thermal manikin (dry/wet) can measure the radiation, conduction and convection in 360 degrees in real life [4]. However, when testing the R_{et}, even following the ISO 15831 standard of procedures, the 4mm thick wet-skin (made of a material containing a microporous structure that evaporates the water vapor to simulate human sweating) put on the sweating thermal manikin because of the evaporation of the surface temperature is difficult to control, it is always lower than the manikin shell temperature [5]. Also, the sweating holes only built-in areas, like chest, back, some parts of legs and arms, it takes a long time for water to spread out on the wet-skin. The direct contact of wet skin on clothing may moisten and influences the water vapor permeability of the clothing, decrease the evaporative resistance [6-7] and lower the accuracy of the repeatability and lab-to-lab data comparison. Also, the long hours of preparation and observing time for each test and the maintenance fee of sweating thermal manikins are relatively more expensive than the dry thermal manikin (non-sweating thermal manikins). Dry thermal manikins are often simpler to use, more affordable and used in more places worldwide.

Sweating guarded hotplate (SGHP) - a skin model is an apparatus with a hotplate installed in an enclosed space. Heat is released from the porous hotplate simulating human skin and through a permeable membrane to the material put on the hotplate to test for the R_{ct}/R_{et} by sensors installed inside the closed environment. Results will then be collected and shown on the computer program connected to the skin model [8-9]. The procedure of testing materials on SGHP is standardized in ISO 11092: 2014 [10-11], yet; it can only test materials in two-dimensional form and on a flat surface in a particular size; also, the flatness, the range of temperature and the insulation of the hotplate are still challenging the developers for improvement. *Table 1* is presented the advantages and disadvantages between sweating thermal manikin, sweating guarded hotplate and the Permetest skin model in the next page.

Table 1. The sweating thermal manikin is in wet-skin (in blue) prepared for water vapor resistance tests and sweating guarded hotplate is put inside the climatic chamber before any sample testing; and Permetest skin model is in the vertical orientation

			
Instrument	Sweating Thermal Manikin	Sweating Guarded Hotplate	Permetest Skin Model
Shape	Human form	Rectangular form	Rectangular form
Dimension (approx.)	Height-170cm, Chest-94cm, Waist- 88cm	Length-77cm, Width-67cm, Height-43cm	Length-54cm, Width-23cm, Height-13cm
Weight	Unknown	62 kg	7 kg
Materials	Plastic shell and metallic frame for body parts and joints. Wet-skin is 4mm thick material containing a microporous structure	Metal	Metal
Body Movements	Yes	No	No
Heat zones Control	Yes	No	No
Total heated measured area	1.774 m^2	645 cm^2	50.265 cm^2
Measuring Method	3D – Ready-to-wear garments	2D – Flat surface of textile or garments (cut size)	2D – Flat surface of textile or garments (non-destructive)
Sample Thickness	From 0 mm up	0 – 50 mm	0 – 16 mm
Preparation Time	One day	One day	15 - 30 minutes
Measuring Time	1 hour or more	1 hour or more	1-5 minutes in each test
ISO Standard	15831	11092	11092
Price	Very Expensive	Expensive	Affordable
Climatic Chamber	Needed	Needed	No
Orientation Versatility	Possible	Impossible	Possible
Rct/Ret Test	Yes	Yes	Yes
Principle of Instrument	To measure total heat loss between the manikin shell temperature and the ambient temperature through the air gap and the test sample garment	To measure the power required to maintain the flat hotplate measurement area at a constant temperature	To measure the power needed to keep the flat hotplate measurement area at a constant temperature
Other Problems	-Wet skin (4mm thick) temperature is difficult to control when measuring R_{et} -Costly maintenance fee -A large climatic chamber needed	-Problem when measuring samples with an air gap, the center area will drape -Uneven temperature on a hotplate - smoothness/thickness of hotplate uneven	-Limited water reservoir for R_{et} measure -Limited sample height, only 16mm -Only a small area is tested

Either sweating thermal manikin or any skin models follows the Fourier's law Eq (1). Fourier's law is the law of heat conduction, and it states that "the heat flux resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign" [12]. When in a one-dimensional, steady-state with no heat generated, this observation may be expressed as:

$$\acute{q}_x = -\lambda(dT/dx) \tag{1}$$

where $\acute{q}_x$ is the heat flux (W/m^2), dT/dx is the temperature gradient (K/m) and the minus sign confirms heat flows from higher to lower temperature. λ is the thermal conductivity of the material (W/m·K). When Fourier's law is combined with the principle of conservation of energy, it becomes the essential reference for analyzing thermal conduction problems. Newton's law of cooling*[1] Eq(2) is a discrete analogue of Fourier's law and Fick's laws of diffusion*[2] Eq (3-4) are its concentration and pressure analogues [13].

$$Q = \alpha \cdot A(T_s - T_\infty) \tag{2}$$

where Q is the heat flow rate from the body to the ambient fluid area (W), α is the heat transfer coefficient ($W/m^2 \cdot K$), A is the surface area where the heat transfer takes place (m^2), Ts and T_∞ are the body and ambient temperature respectively (K).

$$m^* = - D_c(dc/dx) \tag{3}$$
$$m^* = - D_p(dp/dx) \tag{4}$$

where m^* is the amount of substance that will flow through a unit area during a unit time interval ($mol/m^2 \cdot s$), D_c is the concentration diffusivity (m^2/s), D_p is the pressure diffusivity (Pa/s), dc is the amount of substance per unit volume (mol/m^3), dp is the amount of pressure per unit volume (kg/m^3), dx is the distance/length (m). Also, one-dimensional heat transfer through fabric or other materials by conduction is governed by Fourier's Law of thermal conduction as in Eq (1) [14-15].

*[1]Newton's law of cooling states that the rate of heat loss of a body is directly proportional to the difference in the temperatures between the body and its surroundings.
*[2]Fick's law of diffusion states that the diffusion rate is proportional to both the surface area and concentration/pressure difference and is inversely proportional to the thickness of the membrane.

2. Objectives of Research

Knowing the relationship/correlation of the dry thermal manikin and the hotplate skin model is important when there is a need to test garment systems with difficult access to the sweating thermal manikin; the correlation can solve the immediate problem plus saving time and cost of labour.
However, in a standard operation regime, the hotplate skin model serves to determine the R_{ct}/R_{et} of a single-layered fabric placed horizontally and flat on the porous measuring surface, which simulates the human skin. When there is a need to test garment systems with vertical gaps using a standard skin model, serious problems arise; for example, the testing surface area is usually large. The tests involving air gaps are practically impossible because textile material will drape/deform around the center area. The effective air gap gets reduced, then the measurement suffers from a big error. Moreover, vertical measurements are also impossible in standard skin models. Their large size in the vertical direction will cause an uneven distribution of water within the apparatus's porous measuring plate. On the contrary, the Permetest skin model has a small diameter (8cm) testing plate and a slightly curved surface to allow a very secure and close contact with material even with an air gap distance of up to 16mm and still keeps the material flat for testing. The portable size of Permetest also gives it the advantage of turning a horizontally (H) oriented test into a vertically (V) oriented test in a second.
The research aims to develop an equation that can calculate the evaporative resistance (R_{et}) result by using the data obtained from the dry thermal manikin and the correlation of R_{ct}/R_{et} of the vertically oriented Permetest skin model. The research is divided into two parts in Chapter 4:

First part: Analysis of Air Gap Sizes Related to Free Convection and the Water Vapor Transfer in Air Gaps in Clothing (Section 4.1, page 6)

Second part: Experiments, Results and Analysis for the Thermal Manikin and the Vertical Skin Model, also the Vertical and Horizontal Air Gaps comparison by means of Permetest skin model. The procedures are as follow:

1. Materials and Apparatuses (Section 4.2, page 8)
2. R_{ct}/R_{et} – Methods (Section 4.3, page 11)
3. Analysis of the Thermal Manikin and the Permetest Skin Model (Section 4.4, page 19)
4. R_{ct}/R_{et} on the H/V Oriented Permetest Skin Model (Section 4.5, page 20)
5. Analysis of the H/V Oriented Permetest Skin Model (Section 4.6, page 24)
6. Determination for the Best Fit Equation Models for the R_{ct}/R_{et} Data from the H/V Oriented Permetest Skin Model Results (Section 4.7, page 25)

3. Review of the Current State of Problem

Literature related to research employing thermal manikin and hotplate skin model, in general; is divided into three main groups:

1. Analysis of clothing for fabric mechanical, thermal and comfort properties and protective clothing using thermal manikin or hot plate skin model [16-28]; in a single layer or multi-layers [29-31]; in dry/wet state [32-38] and different atmospheric conditions to evaluate human behaviours in protective clothing [39-42]. This group is the largest group of research literature using the thermal manikin and the hotplate skin model among the three groups.
2. Reports on new development or re-designed on the thermal manikin and the hotplate skin model, for examples; invented a higher temperature range of the hotplate for thermal conductivity tests, better insulation materials and insulation installation of the apparatus, new arrangement of electric wire to stabilized the constant the heat flow, new material for the hotplate to maintain the perfect flatness of the plate and so on for the sweating guarded hotplate [43-50]. In thermal manikin development, a new invention of the female fabric sweating thermal manikin – Wenda improved breathable manikin for medical purposes and inflatable manikin for thermal properties measurement [51-52].
3. Evaluation of sweating guarded hotplate and thermal manikin and comparing these two apparatuses [53-57]. Articles in this group are limited, especially comparing the hotplate skin model to the thermal manikin; like Matusiak et al. compared thermal resistance results of nine different materials between the Alambeta thermal tester model and the thermal manikin. However, the research is only provided the results from thermal resistance but no evaporative resistance results. Satusumoto et al. compared quasi-clothing heat transfer between a vertical hotplate and the thermal manikin and concluded that "the vertical hot plate was more accurate than the thermal manikin because the manikin could not reproduce the same setup of construction factors like precise air space sizes." Only the schematic is shown in the article, which is not enough clearance to understand how this apparatus operates in the experiment. Also, there is no mention of any recognized procedure standard is applied to the vertical skin model test. More, using space bars between the manikin and the clothing to keep the exact air gap distance which is not practical in reality, for gravitation and mechanical properties of the fabric are always exist and influence the drape of the clothing, which are important factors for thermal resistance measurement.

4. Experiments and Results

4.1 Analysis of Air Gap Sizes Related to Free Convection and the Water Vapor Transfer in Air Gaps in Clothing

4.1.1 Air Gap Sizes Related to Free Convection

In thermophysiology, thermal resistance (R_{ct}) when in the steady-state under non-isothermal condition, the total thermal resistance (Rct_t) is equal to the boundary layer of the body (Rct_m) plus the thermal resistance of the air gap (Rct_g) between the body and the clothing, and the thermal resistance of the clothing (Rct_f). It can be defined by Eq (5) and the unit of R_{ct} is m².K/W. The air gap resistance (Rct_g) is defined in Eq (6), where h (m) is the thickness and λ (W/m.K) is the thermal conductivity of the air.

$$Rct_t = Rct_m + Rct_g + Rct_f \quad (5)$$

$$Rct_g = h/\lambda \quad (6)$$

When the effective thermal resistance (Rct_{eff}) is required, total thermal resistance minus the body boundary layer is the answer as in Eq (7).

$$Rct_{eff} = Rct_t - Rct_m \quad (7)$$

When evaporative resistance (R_{et}) in steady-state under isothermal condition (in non-isothermal conditions, clothing insulation may dramatically change due to moisture absorbent, therefore; isothermal conditions should be used [58-60]), the total evaporative resistance (Ret_t) is similar to Eq (5), the boundary layer of the body (Ret_m) plus the evaporative resistance of the air gap (Ret_g) and the evaporative resistance of the clothing (Ret_f). It can be defined by Eq (8), and their unit is m².Pa/W. The air gap evaporative resistance (Ret_g) is defined in Eq (9) where Dp (W/m.Pa) is the water vapor thermal diffusivity [61].

$$Ret_t = Ret_m + Ret_g + Ret_f \quad (8)$$

$$Ret_g = h/Dp \quad (9)$$

The effective evaporative resistance (Ret_{eff}) is the total evaporation resistance minus the body boundary layer of the evaporative resistance as in Eq (10).

$$Ret_{eff} = Ret_t - Ret_m \quad (10)$$

When heat is transferred in natural convection, Rayleigh number*[3] is applied. Rayleigh number is a dimensionless number associated with free or natural convection [62-63]. When the Rayleigh number is used in fluid mechanics, it characterizes the fluid's flow regime to determine a laminar flow or a turbulent flow. Rayleigh number (Ra) is defined as Eq (11):

$$Ra = Gr*Pr = [g.\beta\ (T_1 - T_2)\ L^3/\ a.v]*Pr \quad (11)$$

where g is the acceleration due to the Earth's gravity which is 9.81m/s², β is the thermal expansion coefficient (*equals to 1/T where T is the absolute temperature K*), T_1 (K) is the measuring head temperature, T_2 (K) is the ambient temperature, L (m) is the length, a (m²/s) is thermal diffusivity, v (m²/s) is the kinematic viscosity. The equation is the product of the Grashof number*[3] (Gr), the

ratio relationship between buoyancy and viscosity within a fluid, and the Prandtl number*[3] (*Pr*), the ratio relationship between momentum diffusivity and thermal diffusivity [64].
The critical value of Rayleigh number (*Ra*) is 1708 [65-66], where the flow is unstable and this transition period will turn laminar flow into turbulent flow [67-68]. However, there is no fluid motion when $Ra < 1000$, and the heat transfer is only by conduction rather than convection [69-70]. In the research experiments, air gap size is from 0 –16mm. g = 9.81, T_1 = 32ºC (305K), T_2 = 22ºC (295K), $\beta = 1/T$ = (305+295) / 2K = 300K, L = (0.004 to 0.016) m, $a = 19*10^{-6}$m²/s, $\nu = 15.7*10^{-6}$m²/s (values of *a* and *ν* are checked from Tables, both at 300K), and *Pr* (Prandtl number) is 0.7. By using the Eq (11); results are in *Table 2.*

Table 2. Rayleigh number for air gap size 0-16mm, values in red are for reference only

unit in m	Rayleigh number (*Ra*)
0	0
0.004	49
0.008	393
0.010	767
0.011	1021
0.012	1326
0.016	3143

Results show that from 0-10mm, *Ra* is under 1000. When $Ra = 10^3$, conduction is the dominant mechanism for heat transfer, indicating no free convection in these narrow air gaps; then convection is introduced when the air gap size increases at 11mm.

*[3]Similarity Theory [71-74] is when two physical phenomena, processes or systems are similar if, at corresponding moments at corresponding points in space, the variables' values that characterize the state of one system are proportional to the corresponding quantities of the second system. For any set of similar phenomena, all the corresponding dimensionless characteristics have the same numerical values. Rayleigh, Grashof and Prandtl numbers are dimensionless numbers that similarity theory can be applied to.

4.1.2 Water Vapor Transfer in Air Gaps in Clothing

As already mentioned, heat in narrow gaps inside clothing systems is transferred by pure conduction unless the Rayleigh number (*Ra*) exceeds 1000. Due to relatively low-temperature drops in clothing worn under common conditions, heat transfer by radiation is neglected. According to Eq (5), radiation heat flow in these conditions should not exceed 10 to a maximum of 15% of the total heat flow [75]. Regarding the transfer of water vapor in the narrow gaps inside clothing systems, its mechanism should be principally the same; due to the similarity between heat and mass transfer. However, in this study, the water vapor transfer is the driving force in the air given by the difference of water vapor partial pressures is low.
Moreover, testing of evaporative resistance (R_{et}) of clothing by the sweating thermal manikins, as well as the R_{et} tests executed on vertically oriented Permetest skin model in this study, were carried out under isothermal conditions, which means that the thermal manikin shell temperature or the porous hotplate of the Permetest device was holding on the same temperature as the fabric sample, thus creating the air gap characterized by its thickness *h* (m) and the evaporative resistance Ret_g (m².Pa/W which is related to power) determined by the modified Ret_g* (m^2.s.Pa/kg, which is related to mass).
The term *DP* (kg/m.s.Pa) presents the water vapor diffusion coefficient in the air related to the water vapor partial pressure, which in some papers is called water vapor diffusion permeability [61]. This term will also be used in the study.

Due to low driving force (low difference of water vapor partial pressures) and isothermal conditions that water vapor transfer in the gaps investigated by the vertical skin model would not be influenced by the free convection based on differences of water vapor density. However, contrary to the common *Ra* number, where the limit for free convection initiation is known, nothing similar was published to initiate free convection based on differences in water vapor density. At present, there is no dedicated EU standard for measuring this quantity, highlighting the fact that more research is needed in this field.

Hence, for the beginning, let us suppose the water vapor transfer in narrow closed gaps in the vertical skin model is based on pure diffusion. In this case, the water vapor diffusion permeability *Dp* in these gaps should approximate to the standard values published in the literature - Schirmer, R.: Die Diffusionszahl von Wasserdampf-Luft-Gemischen und die Verdampfungsgeschwindigkeit, Beiheft VDI-Zeitschrift, Verfahrenstechnik (1938), H. 6, p. 170-177 [76] .

$$DP = 2306.10^{-5}\, P_o \,.\, P_a^{-1} .\, R_v^{-1} (T/273.15)^{0,81} \text{ (kg/m.s.Pa)}$$

Here, R_v is water vapor gas constant 4615 J /kg.K, T is the ambient temperature in Kelvins P_a and P_o mean the testing and the ambient pressure in Pascals (100,000 Pa), respectively. According to EN ISO 13788:2012 for standard laboratory conditions used in the study we get:

$$DP = 2,0.10^{-10} \text{ (kg/m.s.Pa)}$$

In the next step, the effective water vapor diffusion permeability level will be determined by measuring the vertically oriented skin model and compared with the theoretical value. Evaporative resistance Ret_g* (m².Pa/W) related to thermal effects of the evaporation, which was experimentally determined by a vertical skin model for air gaps varying from 0 to 16 mm, can be converted into evaporative resistance Ret_g* (m².s.Pa/kg) by an equation Eq (12) according to the ISO 11092:

$$Ret_g* = R_{et}.L \qquad (12)$$

where L presents the heat for evaporation of water, 2450,000 J /kg (at 22°C). Thus, for certain gap 10 mm (h) created by the studied fabric sample with R_{et} = 15 (m².Pa/W), the Ret_g* value will be $3,675.10^7$ (kg/m².s.Pa). This evaporative resistance Ret_g* shall correspond to the gap of the above thickness h as Eq (13):

$$Ret_g* = h/ DP_{\boldsymbol{eff}} \qquad (13)$$

where the DP_{eff} is the effective vapor diffusion permeability in the studied gap in clothing, then the DP_{eff} value can be calculated as:

$$DP_{\boldsymbol{eff}} = h/ Ret_g* = 0,01 / 3,675 .10^7 = 2,72.10^{-10} \text{ (kg/m.s.Pa)}$$

As expected, the theoretical level of water vapor diffusion permeability in pure diffusion is slightly lower than the value of DP = $2,0.10^{-10}$ (kg/m.s.Pa). Then it can be concluded that in water vapor transfer in the studied gaps prevails the diffusion, just for the gaps thicker than 12 mm, certain effects of free convection can be observed.

4.2 Materials and Apparatuses

Seven materials were prepared for the research, but only four of them (in shade areas) were used for the thermal manikin tests due to limited access to the facilities. Materials' properties are presented in *Table 3* and their photomicrographic images are shown in *Figure 1a-g*. All materials were washed to get rid of the finishing, hang dried and iron-flatted before use. Two apparatuses were used: Tore – the thermal manikin and the Permetest skin model (in vertical orientation) and their features are presented in *Table 4*.

Table 3. Properties of materials

	100% Cotton	***80/20% Cotton /Polyester***	***70/30% Cotton /Polyester***	***50/50% Cotton /Polyester***	***35/65% Cotton /Polyester***	***100% Polyester***	***100% Polypropylene***
Structure	Plain Weave	2/2 Basket Weave	Plain Weave	Plain Weave	Plain Weave	Plain Weave	2/2 Right Twill
Thickness (mm)	0.37	0.55	0.58	0.33	0.23	0.43	0.63
Weight (g/m^2)	154	225	226	159	102	156	252
Fabric Density Warp/Weft (per cm)	26/22	24/14	16/14	26/24	24/28	16/22	32/34
Air Permeability ($l/m^2/s$)	277	234	241	272	523	564	74
Absorption Rate Top/Bottom (%/s)	13/36	21/34	24/43	12/39	8/19	8/20	61/10
Porosity (%)	73	72.8	73.8	66.8	68.8	73.3	55.6
Drapability (%)	34	30	32	39	43	43	10

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

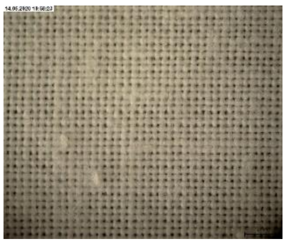
	Tore – Non-Sweating Thermal Manikin	***Permetest Skin Model***
Shape	Human form	Rectangular form
Dimension	Height-170cm, Chest-94cm, Waist- 88cm	Length-54cm, Width-23cm, Height-13cm
Weight	32kg	7kg
Materials	Plastic form shell, inside supported by the metal frame for body parts and joints	Metal
Total heated measured area	1.774 m^2	50.265 cm^2
Measuring Method	3D – Ready-to-wear garments	2D – Flat surface of textile or garments (non-destructive)
Measuring Time	20 minutes of steady-state out	1 to 5 minutes in each measurement in average

	of 40 minutes total measuring time in average	
ISO Standard	15831	11092

a. 100% Cotton

b. 80% Cotton 20% Polyester

c. 70% Cotton 30% Polyester



d. 50% Cotton 50% Polyester

e. 35% Cotton 65% Polyester

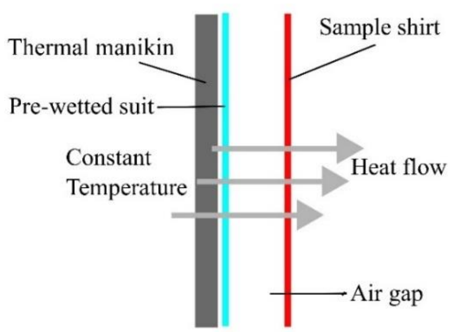
f. 100% Polyester

g. 100% Polypropylene

Figure 1a-g. Photomicrographic images of seven materials by Promicra

Tore at Lund University, Sweden is a Swedish-made thermal manikin. The entire figure is divided into 17 segments and each segment is evenly embedded with the wire temperature sensors to measure the surface temperature, which can be adjusted individually for each segment by a computer program to simulate human body heat for heat transfer testing through clothing to the environment (*Figure 2*). The heat input is the heat loss from the manikin [77], and the process is directly recorded by the computer program (Sensirion and Picolog) at the adjustable interval of each minute. When testing, Tore will be put inside the climatic chamber where different ambient conditions can be achieved. Wet skin will be put on the manikin when testing for evaporative resistance.

The Permetest skin model (developed by Hes) was chosen among all other small-size skin models like the Thermo Labo [78] because of its portability and capability to test materials in horizontal and vertical orientations [79-80]. Permetest skin model is composed of two parts; on one side is the measuring mechanism with digital monitoring panels, control nobs and an electric fan which is responsible for wind speed; on the other side is the wind channel with a sliding opening on the top and the hotplate is installed at the bottom side and is connected to a set of the lifting mechanism. Permetest skin model is a non-destructive device with a small diameter (8cm) testing plate and a slightly curved surface to allow a very secure and close contact with materials even with air gap distance up to 16mm and still keeps the material flat for testing. A sensor is embedded beneath the hotplate that results are directly recorded using a computer and the device software. Similar to regular sweating guarded hot plate, the Permetest skin model is following the procedure of ISO 11092, and the principle is that the heat power sensing by maintaining constant temperature supply to the measuring head is measured with and without fabric sample (*Figure 3*) when testing on thermal resistance R_{ct}. When testing R_{et}, sample textile/clothing, without being cut into a certain testing size like other skin models, is put on the small circular hotplate covered by a thin layer of vapor-permeable membrane function as the wet skin inside the wind channel for testing. The measuring head where the supplied water evaporates is measured (the measuring head's partial saturated pressure with and without sample). The partial pressure of the ambient atmosphere is also measured under the isothermal condition.



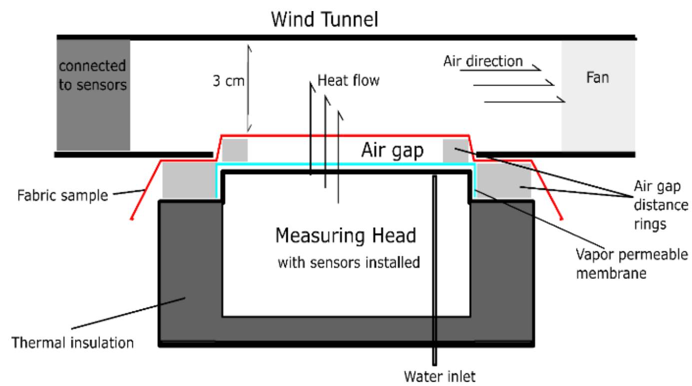


Figure 2. Principle of the thermal manikin ***Figure 3. Principle of Permetest skin model***

4.3 R_{ct}/R_{et} – Methods

4.3.1 Thermal Manikin - Samples

Four materials that were 100% cotton, 50/50% cotton/polyester, 100% polyester, and 100% polypropylene were chosen and were made into long sleeve shirts in five sizes with 1cm overlapping double taped closure center back. Each size was approximately equivalent to a different air gap distance of 0, 4, 8, 12, 16mm. The first shirt was tight-fitted by the molding method [81], and the shirt patternmaking procedures are shown in *Figure 5a-f.*

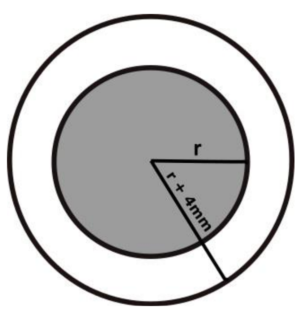


Figure 4. The grey area is the torso of the thermal manikin and air gap distance is added to the radius of the torso that will become the ease allowance of the clothing for the thermal manikin

Based on the first set of shirt patterns, assuming the torso of the thermal manikin was a circular column, ease allowance (air gap distance) would add onto the radius of the circumference of the torso which was then become the ease allowance for the front and back patterns of the shirt and so on (*Figure 4*). First size sample (0mm) by tape measure, the chest circumference of the manikin is 940 mm, hence; using Eq (14) the radius of the chest is 149.68 mm. Based on the clothing pattern of the first sample with 0mm air gaps, the clothing pattern of other sizes each will have an increase in the radius of the manikin body circumference. The increase in the radius is 0; 4, 8, 12, 16 mm. Hence, the total increase of the pattern sizes is calculated as Eq (15):

$$\textit{Manikin Body Circumference (MBC)} = 2\pi.r \tag{14}$$

$$\textit{Grading Size of Shirt} = 2\pi.(r + i) \tag{15}$$

where: *i* is the increase of the radius: 0, 4 and 8 mm and so on. The increase of the body circumference from each of the samples will be divided equally and distributed to the front and back on the pattern pieces as shown in *Table 5*.

Table 5. The total increase in each sample's circumference and the increase in each sample's front and back pattern pieces

Sample	Radius increase and Total increase in Sample's Circumference	Equal amount increases in the Front piece and Backpiece
Sample 1	r=149.7mm (no increase), 940mm Chest circumference	0
Sample 2	r+4mm=153.7mm, (968.3-940) mm	28.3mm/2=14.1mm
Sample 3	r+8mm=157.7mm, (993.5-940) mm	53.5mm/2=26.8mm
Sample 4	r+12mm=161.7mm, (1018.7-940) mm	78.7mm/2=39.4mm
Sample 5	r+16mm=165.7mm, (1044-940) mm	104mm/2=52mm

A total of twenty combinations of shirts of four materials with 0, 4, 8, 12, 16mm 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 because of the gravity and the mechanical properties of the materials; for example, on the shoulder areas might have 0 mm air gap distance. All shirts were sewn with a fine 100% polyester thread (Polysheen® No. 40) with a fine machine sewing needle (Schmetz 70/10). The stitched seams were pressed open under a press cloth with high heat to melt/expand the polyester thread to minimize needle holes' size to reduce heat loss.

Figure 5a. Tore - Dry 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. The 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

4.3.2 Thermal Manikin - Climatic Chamber and Experiment Procedures

During the experiment, the thermal manikin was put in the climatic chamber at Lund University (dimensions: 2400 height x 2360 width x 3200 length mm). The chamber can be adjusted from 5 to 60 ºC and the temperature standard deviation (SD) from the set value is less than ±2 ºC. The relative humidity in this chamber can be adjusted from 10 to 95%, depending on the temperature and the humidity SD from the set value is less than ±5%. Air velocity can be adjusted between 0.1 and 0.7 m/s. R_{ct} tests were in non-isothermal condition, the manikin's surface temperature was set and maintained at 34±2 ºC. The ambient temperature was set and maintained at 22±2ºC (checked against the average of three temperature measurements taken at 0.1, 1.1 and 1.7m above the level

of the sole of the manikin's foot) with 0.145 ± 0.060 m/s air velocity aimed at the manikin's back (measured at 1.2m above floor level). The relative humidity inside the chamber was maintained at 50±5%. in a hanging/standing position and followed the standard procedures ISO 15831[82]. R_{et} tests were in isothermal condition, thermal manikin skin temperature remained at 34±2 ºC and a pre-wet skin would put onto the manikin (wet-skin temperature difficult to determine); the ambient temperature was 34ºC ± 2, relative humidity was 50% ± 5, and wind speed was 0.145 ± 0.060 m/s. The experiment for the thermal and evaporative resistance are including two steps: First step for the R_{ct} test, the thermal manikin is measured naked in non-isothermal condition; and for the R_{et} test, a pre-wet skin which is a tight-fitting skin (thickness 0.9 mm, 95% cotton, 5% elastane) covered the manikin's entire body except for the hands and feet, is measured under isothermal condition (despite the pre wet-skin method not being standardized, it has been presented in a variety of publications and was used for sweat simulation [83-85] in heat and mass transfer studies).
The naked manikin or the manikin wearing the pre-wet skin is tested three times to take the mean value for later calculations. Second step is explained in the following: Each of the 20 shirt combinations was tested three times for the thermal insulation (R_{ct}) and the evaporation resistance (R_{et}). For each test, one shirt would be put on the thermal manikin (or on top of the pre wet-skin in R_{et} tests) and followed the air gap size and material order. For example, 1st round – 1st test, 0mm/cotton, next 0mm/cotton-polyester blended, next 0mm polyester, next 0mm/polypropylene; then 1st round – 2nd test, 0mm/cotton and so on until three tests on 0mm shirts were completed. 2nd round – 1st test, 4mm/cotton and so on. This order allowed shirts to be recovered, relaxed, and dried before the next test because each test will take about an hour in average.

4.3.3 Thermal Manikin - R_{ct} Results

The heat loss method (using the global calculation method) was used to determine both the total thermal resistance Rct_t (m².K/W) and the effective thermal resistance Rct_{eff} (m².K/W). The resulting data were 20 minutes taken out from the steady-state time, approximately 40 minutes on average (resultant sample in Appendix 7). Eq (16) and (17) are for calculating the R_{ct} results as follow:

$$Rct_t = (Ts - To / HLt)*A \tag{16}$$

$$Rct_{eff} = Rct_t - Rct_s = Rct_g + Rct_f \tag{17}$$

where Rct_t is the total thermal resistance including Rct_s, Rct_g, Rct_f (all in the unit m².K/W), which are the boundary layer of the thermal manikin, the thermal resistance of the air gap and the material, respectively. Ts and To are the temperature (K) of the thermal manikin shell and the ambient temperature inside the climatic chamber, respectively. HL_t (W) is the total heat loss and A (m²) is the surface area involved in the experiment. When the effective thermal resistance Rct_{eff} (m².K/W) is needed, total thermal resistance Rct_t minus the naked thermal manikin resistance is in Eq (17).

Table 6. Effective R_{ct} results from the thermal manikin tests

	Arithmetic Mean of Effective R_{ct} (m²K/W)							
	100% Cotton	CV %	50/50% Cotton/Polyester	CV %	100% Polyester	CV %	100% Polypropylene	CV %
0mm	0.07	2	0.08	4	0.06	2	0.09	10
4mm	0.1	6	0.09	3	0.08	6	0.11	2
8mm	0.1	6	0.11	1	0.09	4	0.13	6
12mm	0.09	29	0.11	3	0.09	6	0.13	8
16mm	0.12	6	0.12	5	0.11	2	0.14	4

Results of the effective R_{ct} from the combinations of four materials and five air gap distances from 0 -16mm are presented in *Table 6*. Some interesting observations were that one pair of results shared the same mean value from each material and air gap combination. These scenarios may be caused by the shirt draping on the thermal manikin, creating a heterogenous (uneven) air gap between the manikin and the shirt but somehow having the same mean value because the three tests' original values of each sample were all different.

In *Figure 6*, cotton/polyester blend, 100% polyester, and polypropylene show a similar trend from 0 to 8mm air gap distance, and R_{ct} is in a linear relation but then slows down after 12mm. Only 100% cotton reacted differently and slightly dropped at 12mm the rise quickly at 16mm.

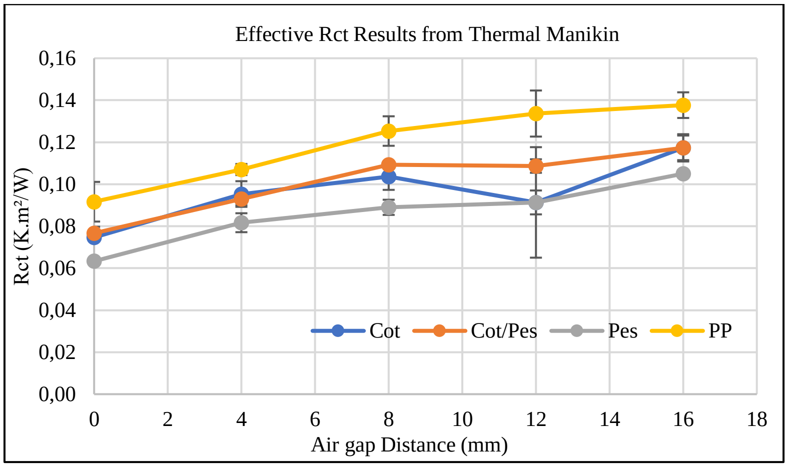


Figure 6. Comparison of the R_{ct} results from the thermal manikin tests of four materials

4.3.4 Thermal Manikin - R_{et} Results

The resulting data were 20 minutes taken out from the steady-state time, approximately 40 minutes on average. Eq (18) and (19) are for calculating the R_{et} results as follow:

$$Ret_t = (\, Ps - Po \,/\, HLt\,)\, A \tag{18}$$

$$Ret_{eff} = Ret_t - Ret_s = Ret_g + Ret_f \tag{19}$$

where Ret_t (m².Pa/W) is the total evaporative resistance including Ret_s, Ret_g, Ret_f (all in the unit of m².Pa/W), which are the wet skin layer of the thermal manikin, the evaporative resistance of the air gap and the material, respectively. *Ps* and *Po* are the saturated water vapor pressure (Pa) of the thermal manikin wet skin and the ambient water vapor pressure in the climatic chamber, respectively. When the effective evaporative resistance Ret_{eff} (m².Pa/W) is needed, total evaporative resistance Ret_t minus the wet skin evaporative resistance is in Eq (19).

Table 7. presented the effective R_{et} results from the combinations of the air gaps and the materials. However, this time only cotton has one pair of the same result in 0-4mm and 8-10 mm. Since R_{et} tests were in isothermal condition, there was no temperature difference, only water vapor pressure and it became the cushion layer between the thermal manikin and the shirt. Absorptivity of synthetic fibre like polyester and polypropylene are lower than natural fibre cotton, so when in narrow air gaps, moisture absorbed by the cotton fibre and stick onto the thermal manikin and

Table 7. Effective R_{et} results from the thermal manikin tests

	Arithmetic Mean of Effective R_{et} (m^2.Pa/W)							
	100% Cotton	CV %	50/50% Cotton/Polyester	CV %	100% Polyester	CV %	100% Polypropylene	CV %
0mm	4.9	36	5.87	10	1.73	19	4.63	11
4mm	4.9	21	6.2	9	4.27	12	8.23	6
8mm	10.27	11	10	16	6.47	11	10.73	14
12mm	10.27	27	10.87	5	10.23	10	15.27	17
16mm	11.83	15	13.03	2	12.13	7	13	9

resulted in similar mean values even though the original R_{et} resulting data of cotton were different from 0 to 16mm. The cotton properties through the thickness and drapability may also contribute to similar results in different air gap distances.

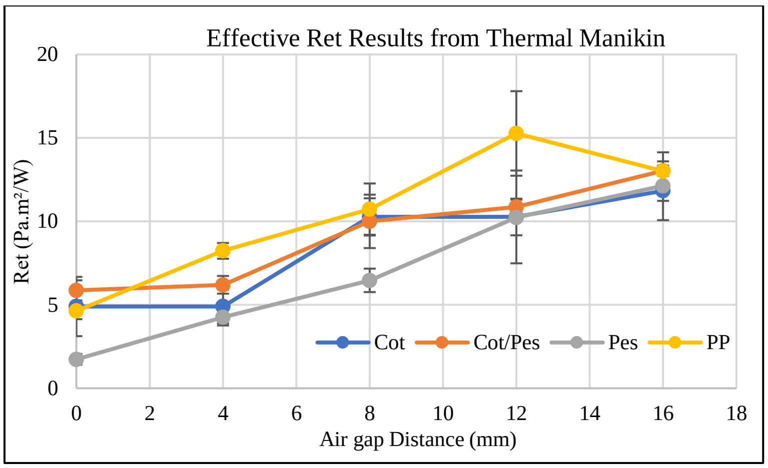


Figure 7. Comparison of the R_{et} results from the thermal manikin of four materials

Two trends were displayed in *Figure 7*: cotton – cotton/polyester and polyester – polypropylene trends. The first trend steady from 0 to 4mm, then quickly rise to 8mm and steady at 12 mm then slowly rise to 16mm; the second trend started to increase steadily from 0 mm until 12 mm then slowed down. Polyester and polypropylene are synthetic fibres, absorptivity is relatively lower than cotton and may not be influenced by the water vapor moisture so that the trend goes steadily; cotton and cotton blends have natural fibres which may have a better absorptivity property that may affect the stability of the vapor pressure between the air gaps from 0 to 16mm and resulting in rising, stabilized and increasing this regime.

4.3.5 Vertically Oriented Permetest Skin Model – Samples

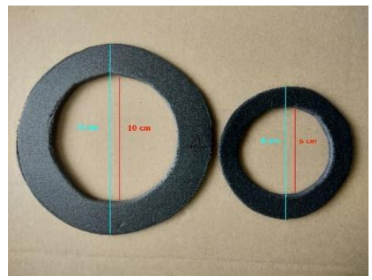
Like the thermal manikin tests, four materials were used directly without cutting into a particular size and shape. Each test area of the material was randomly chosen and marked after the test not to be used again on the same day.

4.3.6 Vertically Oriented Permetest Skin Model – Climatic Chamber and Experiment Procedures

The experiment was processed in the climatic chamber and was set up at 50-55% in relative humidity, wind speed at 1m/s and ambient temperature at 20-22°C in an isothermal condition for

R_{et} tests. For the R_{ct} tests, the non-isothermal condition was applied, and the hot plate measuring head would increase 10°C more than the ambient temperature. All experiment procedures followed ISO 11092 [20]. Air gap distance was applied using 100 percent foamed polyethylene in 2, 4 and 5mm thickness rings and their combinations (*Figure 8a-d*). 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 manikin's vertical air gaps.

Figure 8a. Permetest skin model in the vertical orientation



b. Sizes of outer and inner rings

c. Showing outer rings were stacked on the base of the hotplate

d. Showing inner rings were placed inside the wind channel on the hotplate

4.3.7 Vertically Oriented Permetest Skin Model – R_{ct} Results

Each determination of the R_{ct} 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} (W/m^2) reaches the steady-state, the result of the first step is given by the Eq (20), where Rct_o (m^2.mK/W) presents thermal resistance of the boundary layer above the measuring surface of the apparatus:

$$q_{eto} = (TPs - TPo) / Rct_o \tag{20}$$

Here, *TPs* (mK) means the surface temperature of the measuring head, and *TPo* (mK) is the ambient temperature in the measuring channel of the Permetest skin model. The second step characterizes the heat flow passing through the measuring head of the apparatus covered by the tested sample:

$$q_{et} = (TPs - TPo) / (Rct_o + R_{ct}) \tag{21}$$

for the case without the distance ring in Eq (21) or with distance ring in Eq (22)

$$q_{etg} = (TPs – TPo) / (Rct_o + R_{ct} + Rct_g) \quad (22)$$

which creates the additional air gap resistance Rct_g (m^2.mK/W). $Rct_g = h/\lambda$, where λ (W/m.K) is the thermal conductivity of the air. The required thermal resistance of the sample R_{ct} yields solution of Eq (20) and Eq (21). The required total thermal resistance of the sample R_{ct} plus air gap resistance Rct_g yields the solution of Eq (20) and Eq (22). When the thermal resistance of the sample R_{ct} is deduced from the achieved value, we obtain thermal resistance Rct_g of the air gap.

Table 8. Effective R_{ct} results from Permetest skin model in the Vertically Oriented position

Arithmetic Mean Values of Effective R_{ct} (m^2.mK/W)								
Vertical Air gap	100% Cotton	CV %	50/50% Cotton/Polyester	CV %	100% Polyester	CV %	100% Polypropylene	CV %
0mm	8.7	9	11.5	13	7.8	11	12	6
4mm	65.5	14	46.1	3	54.8	2	54.7	15
8mm	94.5	3	69	2	74.9	2	89.5	1
12mm	95.2	2	73.8	5	90.1	3	93	7
16mm	106.5	11	82.2	17	101.1	5	90.2	5

The resulting data in *Table 8* show each material rises from 0mm quickly to 8mm, then slows down at 12mm. *Figure 9* is presenting the visual of the data.

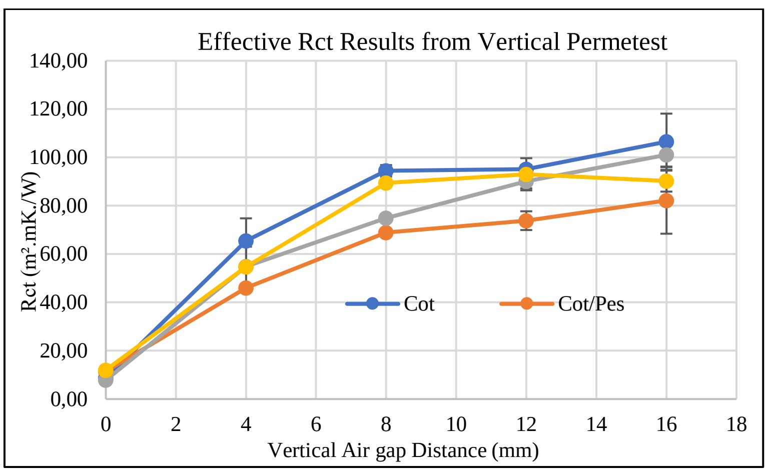


Figure 9. Comparison of the R_{ct} results from Vertically Oriented Permetest of four materials

4.3.8 Vertically Oriented Permetest Skin Model – R_{et} Results

Each determination of the 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 (23), where Ret_o (m^2.Pa/W) presents the evaporative resistance of the boundary layer above the measuring surface of the apparatus:

$$q_{eto} = (PPs – PPo) / Ret_o \quad (23)$$

Here, *PPs* (Pa) means partial pressure of the saturated water vapor above the hotplate, and *PPo* (Pa) is the partial pressure of the water vapor in the measuring tunnel of the testing apparatus. The second step characterizes the heat flow passing through the measuring head of the apparatus covered by the tested sample:

$$q_{et} = (PPs - PPo) / (Ret_o + R_{et}) \tag{24}$$

for the case without the distance ring in Eq (24) or with distance ring in Eq (25)

$$q_{etg} = (PPs - PPo) / (Ret_o + R_{et} + Ret_g) \tag{25}$$

which creates the additional air gap resistance Ret_g* (m^2.Pa.s/kg). $Ret_g* = h/DP$, *DP* (kg/m.Pa.s) presents the water vapor diffusion coefficient in the air related to the water vapor partial pressure, which had been mentioned in *section 4.1.2*. The required evaporation resistance of the sample R_{et} yields solution of Eq (23) and Eq (24). The required total evaporative resistance of the sample R_{et} plus air gap resistance Ret_g* yields solution of Eq (23) and Eq (25). When the evaporative resistance of the sample R_{et} is deduced from the achieved value, we obtain evaporation resistance Ret_g* of the air gap.

Table 9. Effective R_{et} results from Permetest skin model in the Vertical Oriented position

Arithmetic Mean Values of R_{et} (m².Pa/W)								
Vertical Air gap	100% Cotton	CV %	50/50% Cotton/Polyester	CV %	100% Polyester	CV %	100% Polypropylene	CV %
0mm	3.4	13	3.6	15	1.5	4	3.2	4
4mm	8.2	2	6.1	4	7.4	3	5.7	2
8mm	12.9	2	11.5	4	14.1	3	9.5	2
12mm	22.5	4	22.2	4	20.7	3	17.3	12
16mm	25.5	11	26.2	4	24.5	10	18.6	7

Similar to effective R_{ct} results, effective R_{et} results presented in *Table 9*, showing each material's evaporative resistance rose from 0mm quickly up to 12mm then slowed down to 16mm. When comparing *Figure 9, 10 to Figure 6, 7*; it seems that the results from the Permetest skin model are more uniformity than the thermal manikin results, and it may cause by the even air gap distances

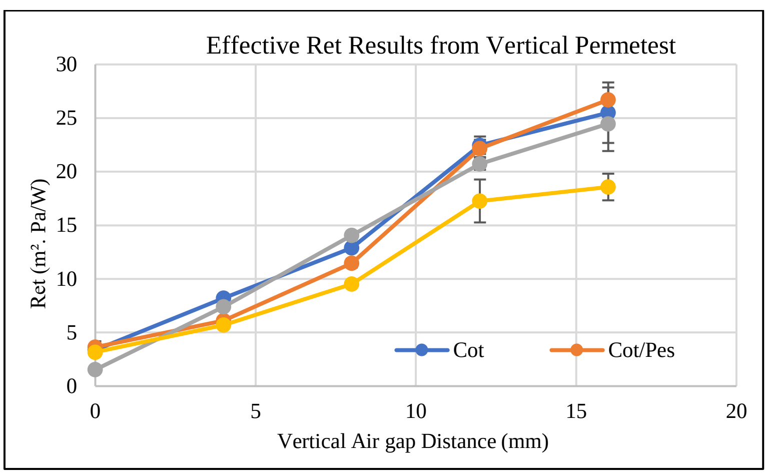


Figure 10. Comparison of the R_{et} results from Vertically Oriented Permetest of four materials

created in Permetest but not the uneven and unpredictable air gap space between the thermal manikin and the shirt.

4.4 Analysis of Thermal Manikin and Permetest Skin Model (Vertical Orientation)

Results from the thermal manikin and the Permetest skin model were analyzed using three statistical methods: correlation coefficient (r), R^2 and two-way ANOVA with replication.

4.4.1 Correlation coefficient (r) -- The Thermal Manikin and the Vertically Oriented Permetest skin model

Table 10. The correlation coefficient (r) of Thermal Manikin Vs. Vertically Oriented skin model

Manikin Vs Permetest (r)	100% Cot	50/50% Cot/Pes	100% Pes	100% PP
R_{ct}	0.83	0.97	0.96	0.97
R_{et}	0.90	0.96	1.00	0.94

Results presented in *Table 10* showing all four materials have a very strong and positive trend (close to +1) between the thermal manikin and the vertically oriented Permetest skin model in both thermal (R_{ct}) and evaporative resistance (R_{et}).

4.4.2 R^2 - Regression between the Thermal Manikin and the Vertically Oriented Permetest skin model

The R^2 results in *Table 11*, each material from thermal and evaporative resistance are showing strong correlations between the thermal manikin and the Permetest skin model, which means that every changing value of thermal manikin can be highly explained by the value of the Permetest skin model or vice versa.

Table 11. The correlation determination (R^2) of Thermal Manikin Vs. Vertically Oriented skin model

Manikin Vs Permetest (R^2)	100% Cot	50/50% Cot/Pes	100% Pes	100% PP
R_{ct}	0.70	0.94	0.91	0.95
R_{et}	0.80	0.91	1	0.88

4.4.3 Two-way ANOVA -- The Thermal Manikin and the Vertically Oriented Permetest skin model

In both R_{ct} and R_{et} results from 100% cotton, 50/50% cotton/polyester blend, 100% polyester, 100% polypropylene showed that the ***p-value < 0.01*** means a significant difference between the thermal manikin and the vertically oriented Permetest skin model. The result is logical because the thermal manikin and the vertically oriented Permetest skin model are fundamentally different: from sizes and shapes to test methods, ISO standard and so on (*Table 1*).

4.5 R_{ct}/R_{et} on Horizontally/Vertically Oriented Permetest Skin Model

To understand the difference between the vertically and the horizontally oriented air gap distance, the Permetest skin model was chosen for the task because of its versatility of position orientation, portability in size, and the R_{ct}/R_{et} test relatively in shorter time.

4.5.1 Methods and Experiments - Samples

Seven test materials were chosen and their properties were presented in *Table 3.* They were woven and blended fabric between 100% cotton and 100% polyester, plus one polypropylene for counter reference. All test materials were washed, hang-dry, iron flat before used.

4.5.2 Climatic Chamber and Experiment Procedures

Each test material would be tested five times randomly and non-destructively (without cutting into size and shape) for R_{ct}/R_{et} with the combinations of five different air gap distances and the vertical/horizontal orientation in the Permetest skin model. Each test area would be marked after testing to prevent repetition. The experiment would follow ISO 11920 and the climatic chamber set up and apply the air gap distance rings. Please refer to the previous *section 4.3.6.*

Table 12. The arithmetic mean values of 7 materials results from R_{ct}/R_{et} and the combinations of Horizontal/ Vertical orientation and air gap distances

100% Cotton								
Air gap Distance	***R_{ct} (m^2.mK/W)***				***R_{et} (m^2.Pa/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*10.8*	*12*	*9.5*	*15*	*2.8*	*5*	*2.5*	*6*
4mm	*53.5*	*8*	*60.4*	*4*	*6.2*	*3*	*5.4*	*2*
8mm	*112.8*	*3*	*82.1*	*4*	*15.9*	*10*	*12.4*	*2*
12mm	*147.6*	*4*	*130.8*	*3*	*22.1*	*0.4*	*18*	*1*
16mm	*129.2*	*8*	*123.8*	*10*	*25.4*	*5*	*28.6*	*10*
20% Polyester								
Air gap Distance	***R_{ct} (m^2.mK/W)***				***R_{et} (m^2.Pa/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*13.2*	*9*	*13.3*	*11*	*4.1*	*7*	*3.7*	*5*
4mm	*65.6*	*6*	*61.9*	*2*	*6.6*	*2*	*6.3*	*2*
8mm	*116.4*	*9*	*80*	*5*	*15.9*	*8*	*13.5*	*2*
12mm	*113.3*	*8*	*108.7*	*2*	*26.6*	*4*	*20*	*11*
16mm	*123*	*7*	*123.1*	*10*	*33*	*9*	*30.8*	*9*
30% Pes								
Air gap Distance	***R_{ct} (m^2.mK/W)***				***R_{et} (m^2.Pa/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*15.4*	*11*	*13.6*	*9*	*3.8*	*8*	*3.6*	*3*
4mm	*68*	*2*	*64.5*	*2*	*7*	*6*	*6*	*3*
8mm	*122.3*	*5*	*80.2*	*8*	*17.8*	*9*	*13.3*	*2*
12mm	*124.8*	*3*	*113.9*	*4*	*25.5*	*6*	*20.9*	*5*
16mm	*131.9*	*3*	*132.5*	*10*	*26.7*	*3*	*26.6*	*4*
50% Polyester								
Air gap Distance	***R_{ct} (m^2.mK/W)***				***R_{et} (m^2.Pa/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*13.4*	*4*	*13.1*	*8*	*2.9*	*7*	*2.7*	*7*

4mm	*74.1*	*3*	*62.9*	*4*	*6.1*	*3*	*5.4*	*4*
8mm	*120.9*	*5*	*87.7*	*4*	*16.8*	*8*	*12.2*	*2*
12mm	*140.8*	*12*	*113.5*	*3*	*24.5*	*6*	*18.3*	*3*
16mm	*117.4*	*5*	*123.8*	*5*	*25.8*	*2*	*25.6*	*9*
65% Pes								
Air gap Distance	***R_{ct} (m^2.mK/W)***				***R_{et} (m^2.Pa/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*11.6*	*7*	*11.3*	*14*	*2.2*	*5*	*2*	*10*
4mm	*72.4*	*3*	*64.5*	*4*	*5.7*	*4*	*5.2*	*2*
8mm	*131.1*	*4*	*91.2*	*5*	*15*	*11*	*12.2*	*2*
12mm	*147.3*	*9*	*129.2*	*9*	*24.4*	*7*	*19.3*	*5*
16mm	*121*	*7*	*120.3*	*9*	*25.7*	*2*	*23.4*	*4*
100% Polyester								
Air gap Distance	***R_{ct} (m^2.mK/W)***				***R_{et} (m^2.Pa/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*5.8*	*7*	*7.4*	*14*	*1.7*	*6*	*1.3*	*15*
4mm	*68.9*	*11*	*56.8*	*8*	*5.6*	*4*	*4.8*	*2*
8mm	*116.3*	*3*	*90.2*	*2*	*13.2*	*2*	*12.1*	*2*
12mm	*138.2*	*3*	*109.4*	*3*	*25.6*	*4*	*18.3*	*5*
16mm	*143.6*	*7*	*131.9*	*6*	*25.1*	*2*	*25*	*5*
100% Polypropylene								
Air gap Distance	***R_{ct} (mK.m^2/W)***				***R_{et} (Pa.m^2/W)***			
	H	***CV %***	***V***	***CV %***	***H***	***CV %***	***V***	***CV %***
0mm	*15.6*	*11*	*15.7*	*5*	*4.3*	*5*	*3.6*	*6*
4mm	*73.6*	*8*	*69.8*	*3*	*7.5*	*3*	*6.5*	*2*
8mm	*138.2*	*5*	*95.3*	*5*	*16*	*10*	*14*	*2*
12mm	*162.6*	*2*	*140.3*	*12*	*27.4*	*0.4*	*20.4*	*1*
16mm	*140.1*	*5*	*120.8*	*3*	*26.5*	*5*	*24.4*	*10*

4.5.3 Results

Results from R_{ct}/R_{et} tests of seven materials in vertically/horizontally oriented air gaps are presented in *Table 12* above. The resulting data show that there are two common trends:

- R_{ct}/R_{et} rises quickly from 0mm until 12mm, slowing down or dropping from 12mm air gap distance in both horizontal and vertical orientations. *Table 13 and 14* are presenting the difference between vertically and horizontally oriented air gap results in both R_{ct} and R_{et}. The percentage of difference is calculated by the Eq (26) as follow:

$$(H - V/ H)* 100 \tag{26}$$

  Where H and V are horizontal/ vertical air gap results from R_{ct}/R_{et}.
- Vertically oriented test results are slightly lower than the horizontally oriented test results in most cases. Visual comparisons are presenting in *Figure 14-15.*

Table 13. R_{ct} -Difference between Horizontally and Vertically Oriented Air gaps

	R_{ct} - Difference between Horizontally and Vertically Oriented Air gaps (%)						
	Cot	20Pes	30Pes	50Pes	65Pes	Pes	PP
0mm	12	-0.8	11.7	2.2	2.6	-27.6	-0.6
4mm	-12.9	5.6	5.1	15.1	10.9	17.6	5.2
8mm	27.2	31.3	34.4	27.5	30.4	22.4	31
12mm	11.4	4.1	8.7	19.4	12.3	20.8	13.7
16mm	4.2	-0.1	-0.5	-5.5	0.6	8.1	13.8

Table 14. R_{et} -Difference between Horizontally and Vertically Oriented Air gaps

	R_{et} - Difference between Horizontally and Vertically Oriented Air gaps (%)						
	Cot	20Pes	30Pes	50Pes	65Pes	Pes	PP
0mm	10.7	9.8	5.3	6.9	9.1	23.5	16.3
4mm	12.9	4.5	14.3	11.5	8.8	14.3	13.3
8mm	22	15.1	25.3	27.4	18.7	8.3	12.5
12mm	18.6	24.8	18	25.3	20.9	8.3	25.5
16mm	-12.6	6.7	0.4	0.8	8.9	0.4	7.9

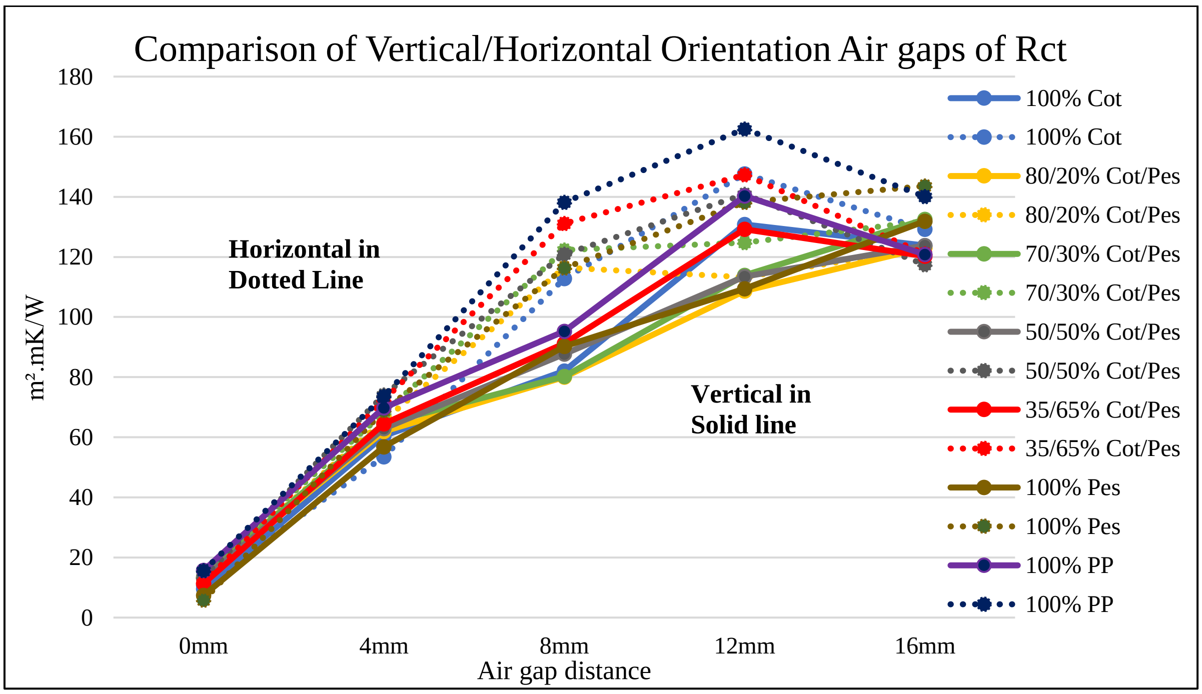


Figure 11. Visual comparison of the vertically and horizontally oriented air gaps of R_{ct}

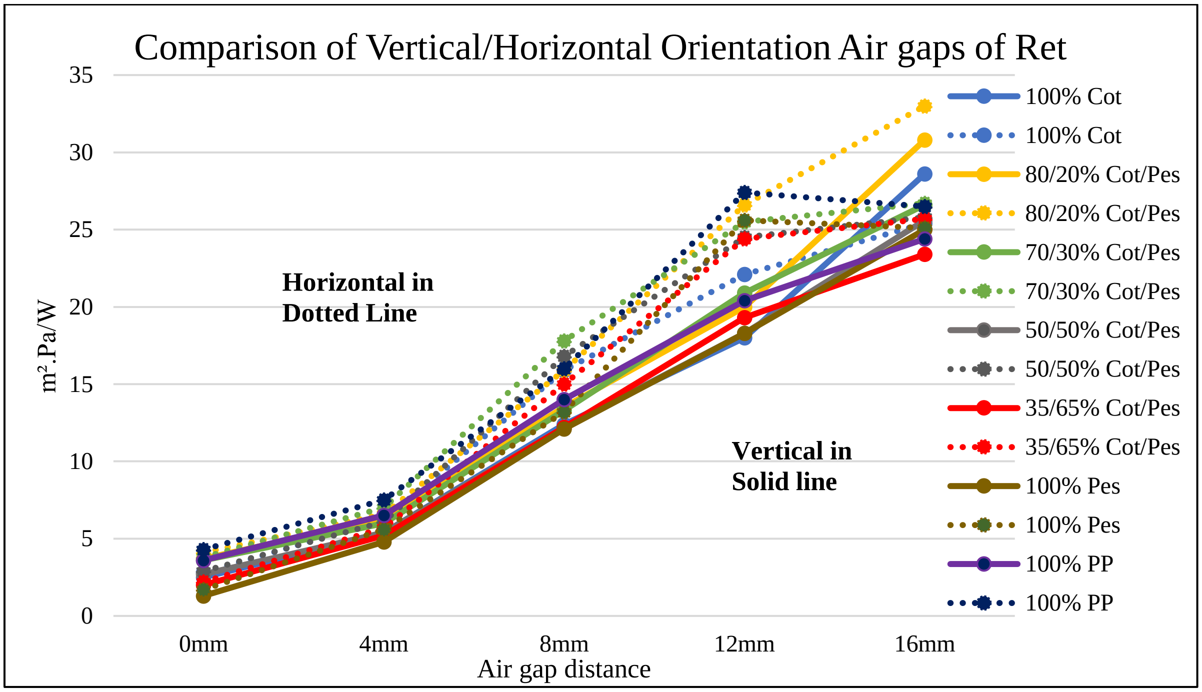


Figure 12. Visual comparison of the vertically and horizontally oriented the air gaps of R_{et}

4.6 Analysis of the H/V Oriented Permetest Skin Mode

Results from the seven tested materials were analyzed using three statistical methods: correlation coefficient (r), R^2 and two-way ANOVA with replication.

4.6.1 The Correlation Coefficient (r) of the Vertically and the Horizontally Oriented Permetest Results from Seven Tested Materials

Table 15. Correlation coefficient (r) results of R_{ct}/R_{et} and the combinations of Horizontally/ Vertically Oriental air gap distances from 7 materials

100% Cotton						80/20% Cotton/Polyester					
R_{ct}			R_{et}			R_{ct}			R_{et}		
	H	V		H	V		H	V		H	V
H	1		H	1		H	1		H	1	
V	**0.97**	1	V	**0.96**	1	V	**0.94**	1	V	**0.98**	1
70/30% Cotton/Polyester						**50/50% Cotton/Polyester**					
R_{ct}			R_{et}			R_{ct}			R_{et}		
	H	V		H	V		H	V		H	V
H	1		H	1		H	1		H	1	
V	**0.94**	1	V	**0.98**	1	V	**0.95**	1	V	**0.97**	1
35/65% Cotton/Polyester						**100% Polyester**					
R_{ct}			R_{et}			R_{ct}			R_{et}		
	H	V		H	V		H	V		H	V
H	1		H	1		H	1		H	1	
V	**0.96**	1	V	**0.99**	1	V	**0.99**	1	V	**1.00**	1
100% Polypropylene											
R_{ct}			R_{et}								
	H	V		H	V						

H	1		H	1	
V	**0.97**	1	V	**0.98**	1

Each material's correlation coefficient r (Table 15) shows a very strong and positive trend from all seven materials; the r is almost +1.

4.6.2 R^2 - Regression between the Vertically and the Horizontally Oriented Permetest Results from Seven Tested Materials

Table 16. Regression results of R_{ct}/R_{et} and the combinations of Vertically/Horizontally Oriented air gap distances from 7 materials

Vertical Vs. Horizontal R^2	*100% Cotton*	*80/20% Cotton/ Polyester*	*70/30% Cotton/ Polyester*	*50/50% Cotton/ Polyester*	*35/65% Cotton/ Polyester*	*100% polyester*	*100% polypropylene*
R_{ct}	0.94	0.89	0.88	0.89	0.92	0.98	0.95
R_{et}	0.92	0.97	0.95	0.93	0.99	1	0.96

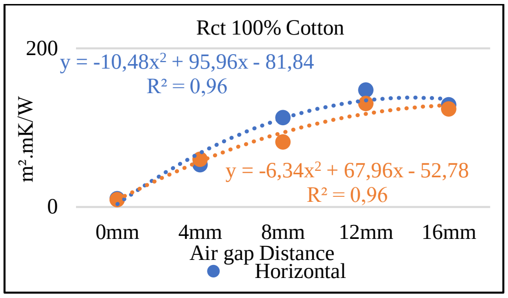
The regression from the R_{ct}/R_{et} test results (*Table 16*) from seven materials is very strong, and most of the $R^2$are over 0.9, which means the vertically oriented Permetest can predict the Rct/Ret results for the horizontally oriented Permetest or vice versa.

4.6.3 Two-way ANOVA with five repetitions results from Vertically and Horizontally Oriented Permetest from Seven Materials

Results from R_{ct} and R_{et} of all seven materials show that the ***p-value < 0.01*** means there is a significant difference between the vertically and the horizontally oriented Permetest skin model. The reason is that even the experiments were done by using the same Permetest skin model. However, the vertical and horizontal orientation of the apparatus was causing some difference in the resulting values. R_{ct} experiments were done under non-isothermal conditions, and the driving force was the temperature difference. Hot air rises and cool air falls naturally in the vertical air gap, but in the horizontal air gap, the air has to travel through a distance inside the wind channel before exiting. R_{et} experiments were done under isothermal conditions, and saturated vapor pressure is the driving force. Water vapor molecules are concentrated at the bottom and rising to the wind channel's top in the horizontal air gap. However, when it is in the vertical orientation, the rising water vapor molecules may escape through the fan that will cause R_{et}'s lower values. It also leads to the R_{ct}/R_{et} results that the vertically oriented values always seem lower than the horizontally oriented values from the air gap distance 0 - 16mm (*Figure 11,12*).

4.7 Determination for the Best Fit Equation Models for the R_{ct}/R_{et} Data from the H/V Oriented Permetest Skin Model Results

The resulting data from thermal resistance (R_{ct}) of seven materials with the combinations of air gap distances and vertical/horizontal orientations showed a polynomial equation fitted better than the linear equation, $R^2 > 0.95$. However, data from evaporative resistance (R_{et}) of seven materials with the combinations of air gap distances and vertical/horizontal orientations showed that data fitted better in the linear equation and the $R^2 > 0.98$ except 100% polyester $R^2 = 0.90$. Some samples are presented in *Figure 13a-d*.



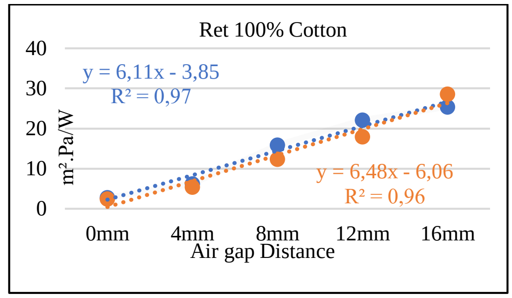
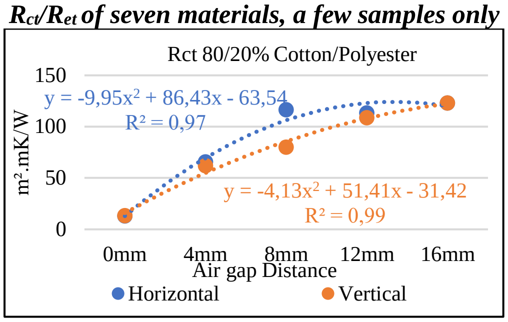
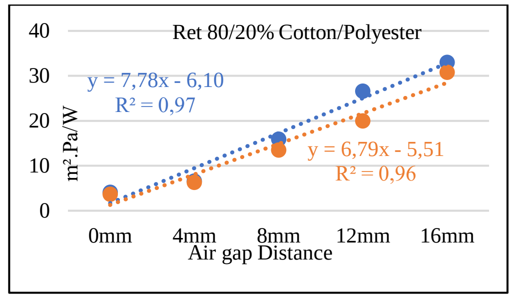


Figure 13a-d a. The best-fit model for data from the R_{ct}/R_{et} of seven materials, a few samples only

b.





c. ***d.***

5. Conclusion

The thermal manikin is considered the best apparatus for measuring thermal and evaporative resistance for the clothing system because the apparatus's human form can detect the radiation, conduction, and convection in the 3D environment. However, the expensive cost, the long preparation time for the test, and a big climatic chamber are needed for the apparatus because not many companies nor researchers can access it. More, the uncertainty of the wet skin temperature of the sweating thermal manikin and error may be caused by wet skin direct contact to clothing; and the condensation build-in under the clothing when in the cold ambient can also cause over or underestimation of the results and so on lead to an alternative method for the thermophysiological measure is needed.

The Permetest skin model is portable, versatile in a vertical or horizontal orientation and a fast thermophysiological measuring device due to its small measuring head. The experiments showed that a very strong correlation between the thermal manikin and the vertically oriented Permetest skin model in R_{ct}/R_{et} of the combinations of four materials (100% cotton, 50/50% cotton/polyester, 100% polyester and 100% polypropylene) and five air gap distances (0, 4, 8, 12, 16mm), the R^2 of the R_{ct} is range from 0.70 – 0.95 and R_{et} is from 0.80 - 1. Also, their arithmetic mean of correlation coefficient in R_{ct} and R_{et} are both over 0.9. With these results, correlation tests between vertically and horizontally oriented Permetest skin model were set up with the combinations of seven materials and five air gap distances (0, 4, 8, 12, 16mm), and the R^2 of the R_{ct} is range from 0.88 – 0.98 and R_{et} is from 0.92 - 1.; their arithmetic means of correlation coefficient in R_{ct} and R_{et} are both over 0.9. The correlation coefficient and R^2 showed that the vertically and horizontally oriented Permetest experiments have a strong relationship and a strong positive trend. Since a strong relationship between thermal manikin and the vertically oriented Permetest skin model, and a strong correlation between the vertically and horizontally oriented Permetest skin model implying that the horizontally oriented Permetest skin model also has a strong relationship with the thermal manikin.

To further develop the relationship between the thermal manikin and the Permetest skin model, the best-fit equation for the R_{ct}/R_{et} must be determined. From ***Section 4.7*** R_{ct} data fit better in polynomial so that: $R_{ct} = a_1X^2 + b_1X + c_1$, when $0 = a_1X^2 + b_1X + (c_1 – R_{ct})$, then

$$X = -b_1 + [b_1^2 - 4a_1(c_1 – R_{ct})]^{½} /2a_1 \tag{27}$$

Here, X is the hypothetical height (h) in millimetre. From ***Section 4.7*** R_{et} data fit better in linear so that: $R_{et} = a_2X + b_2$, when substitute Eq (27) to X

$$R_{et} = a_2\{-b_1 + [b_1^2 - 4a_1(c_1 – R_{ct})]^{½} /2a_1\}+ b_2 \tag{28}$$

$$\boldsymbol{R_{et} = 1/2(a_2/a_1)\{[b_1^2 - 4a_1(c_1 – R_{ct})]^{½} – b_1\} + b_2} \tag{29}$$

5.1 Validation

First, using the **Eq (29)**, constants from the vertically oriented Permetest (*Table 17*) and the actual R_{ct} results from the thermal manikin to calculate the R_{et}. The results are presented in *Table 18*. Second, comparing the actual R_{et} test results to the calculated results and analysis. *Table 19* is presented the comparison results. Sample shirts were made of four materials which were 100% cotton, 50/50% cotton/polyester blend, 100% polyester and 100% polypropylene.

Table 17. Constants from Polynomial of R_{ct} and Linear of R_{et}

R_{ct} (m²·mK/W) = $a_1X^2 + b_1X + c_1$							**R_{et} (m²·Pa/W)** = $a_2X + b_2$			
Constant	**a_1**		**b_1**		**c_1**		**a_2**		**b_2**	
Orientation	H	V	H	V	H	V	H	V	H	V
100% Cotton	*-10.48*	*-6.34*	*95.96*	*67.96*	*-81.84*	*52.78*	*6.11*	*6.48*	*-3.85*	*-6.06*
80/20% Cotton/ Polyester	*- 9.95*	*-4.13*	*86.43*	*51.41*	*-63.54*	*31.42*	*7.78*	*6.79*	*-6.10*	*-5.51*
70/30% Cotton/ Polyester	*-10.20*	*-3.33*	*90.18*	*48.69*	*-65.86*	*28.52*	*6.43*	*6.09*	*-3.13*	*-4.19*
50/50% Cotton/ Polyester	*-13.94*	*-5.57*	*111.08*	*60.63*	*-86.64*	*40.40*	*6.42*	*5.87*	*-4.04*	*-4.77*
35/65% Cotton/ Polyester	*-15.48*	*-8.06*	*122.24*	*76.66*	*-99.78*	*57.96*	*6.57*	*5.69*	*-5.11*	*-4.65*
100% Polyester	*-10.06*	*-4.86*	*94.88*	*59.30*	*-79.36*	*45.34*	*5.44*	*5.47*	*-4.56*	*-5.35*
100% Polypropylene	*-14.37*	*-9.12*	*120.03*	*82.80*	*-95.98*	*59.68*	*6.43*	*5.55*	*-2.95*	*-2.87*

Table 18. R_{et} calculated results by using Eq (29), R_{ct}* results from the thermal manikin (Table 6) and constants from the vertically Oriented Permetest skin model ** Unit which is used in thermal manikin software Kevin (K) is converted to milli-Kevin (mK) before calculation, and the resultant unit is in **m²·Pa/W***

COT	Test 1 (m²·Pa/W)	Test 2 (m²·Pa/W)	Test 3 (m²·Pa/W)	Mean (m²·Pa/W)	SD	CV %
4mm	10.47	9.06	9.79	9.77	0.71	7.2
8mm	11.23	10.3	10.3	10.61	0.54	5.1
12mm	6.84	10.98	10.73	9.52	2.32	24.4
16mm	11.72	11.23	12.3	11.75	0.54	4.6
Cot/PES	Test 1	Test 2	Test 3	Mean	SD	CV %

4mm	9.51	9.76	9.26	9.51	0.25	2.6
8mm	16.59	10.75	10.84	12.73	3.35	26.3
12mm	10.92	10.51	16.59	12.67	3.40	26.8
16mm	12.04	11.16	11.32	11.51	0.47	4.1
PES	Test 1	Test 2	Test 3	Mean	SD	CV %
4mm	8.15	8.58	8.91	8.55	0.38	4.5
8mm	9.08	9.49	8.91	9.16	0.30	3.3
12mm	8.83	9.49	9.74	9.35	0.47	5.0
16mm	10.38	10.62	10.38	10.46	0.14	1.3
PP	Test 1	Test 2	Test 3	Mean	SD	CV %
4mm	5.98	5.68	5.92	5.86	0.16	2.7
8mm	6.98	6.52	7.32	6.94	0.40	5.8
12mm	6.92	7.21	8.11	7.41	0.62	8.4
16mm	7.27	7.94	7.72	7.64	0.34	4.5

Table 19. The comparison of the actual R_{et} values (m^2Pa/W) calculated from the Eq (29) (based on the Skin model experiments) and R_{et} values measured on thermal manikin wearing a pre-wetted suit

*By the ISO 15634,2004, the comparative precision of total arithmetic mean: Serial model 6.8%, Parallel model 5.3%

	Arithmetic Mean		*Difference	
COT	Manikin (m^2.Pa/W)	Eq 29 (m^2.Pa/W)	in (%)	Eq 29/Manikin (m^2.Pa/W)
4mm	4.9	9.77	99	4.87
8mm	10.27	10.61	3	0.34
12mm	10.27	9.52	7	0.75
16mm	11.83	11.75	1	0.08
	Arithmetic Mean		Difference	
Cot/PES	Manikin (m^2.Pa/W)	Eq 29 (m^2.Pa/W)	in (%)	Eq 29/Manikin (m^2.Pa/W)
4mm	6.2	9.51	53	3.31
8mm	10	12.73	27	2.73
12mm	10.87	12.67	17	1.8
16mm	13.03	11.51	12	1.52
	Arithmetic Mean		Difference	
PES	Manikin (m^2.Pa/W)	Eq 29 (m^2.Pa/W)	in (%)	Eq 29/Manikin (m^2.Pa/W)
4mm	4.27	8.55	100	4.28
8mm	6.47	9.16	42	2.69
12mm	10.23	9.35	9	0.88
16mm	12.13	10.46	14	1.67
	Arithmetic Mean		Difference	
PP	Manikin (m^2.Pa/W)	Eq 29 (m^2.Pa/W)	in (%)	Eq 29/Manikin (m^2.Pa/W)
4mm	8.23	5.86	29	2.37
8mm	10.73	6.94	35	3.79
12mm	15.42	7.41	52	8.01
16mm	13	7.64	41	5.36

Reasons for 4 mm has the biggest difference may be caused by the following explanations:

1- Air gap spacing (*Figure 14*). When the sample shirt was draped on top of the pre-wetted suit, a narrower air gap (smaller shirt size) had a higher possibility to contact the pre-wetted suit directly due to the properties of the material; like stiffness, resiliency, moisture absorbent, porosity and so on that would cause creasing or wrinkles which would increase the contact point/area. Contact points or areas influence spacing between the sample shirt and the pre-wetted suit that will decrease the actual evaporative resistance R_{et} of the shirt. On the other hand, a bigger size shirt has a bigger air gap. This air spacing between the pre-wetted suit and the sample shirt acted like a cushion layer that would prevent the material stick to the pre-wetted suit layer to create contact areas. However, from 10 mm to 12mm, the air gap spacing is big enough that free convection will start. This phenomenon will influence the results on R_{et} and make it unpredictable.

2- The air gap thermal conductivity (λ) of 4mm is about 0.025; however, the average λ of materials used in the experiment is 0.04, which is higher than the air gap that may cause unpredictable outcomes when the air gap is small. *Table 20* presented the results of thermal conductivity of each material by means of Alambeta device.

3- Smaller air gap increases the probability of sample shirt contact directly to the thermal manikin wearing the pre-wetted suit, which will moisten the sample shirt and wetness will decrease the water vapor permeability, hence; decreases the evaporative resistance R_{et} [16].

4- First validation, labor errors may involve.

The above reasons conclude that the **Eq (29)** may not be suitable for air gap size 4mm or smaller. Further validation is needed.

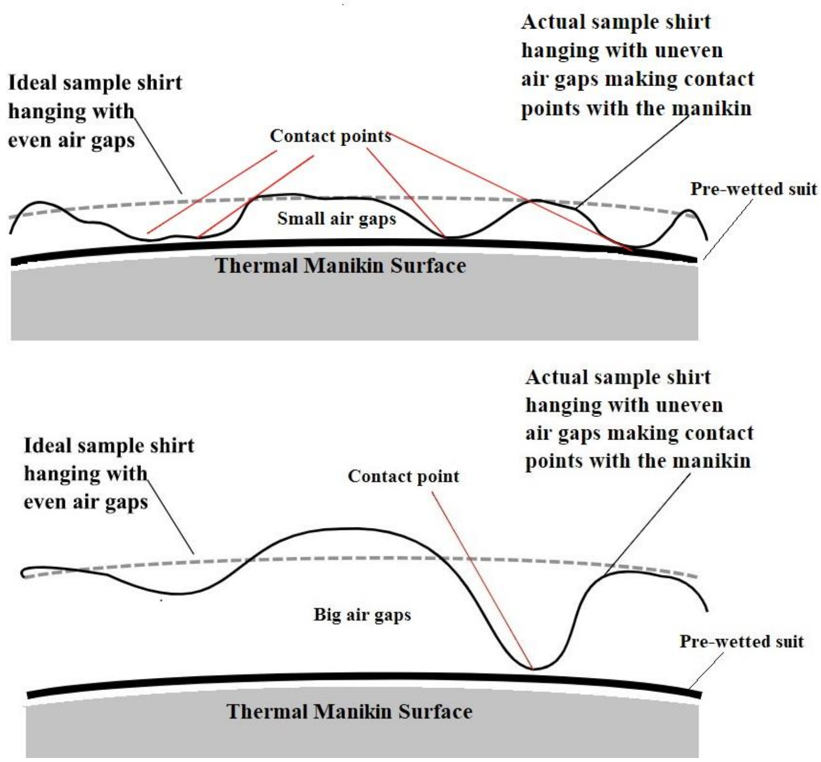


Figure 14. Cross-sections of a small and a big air gap between the thermal manikin wearing a pre-wetted suit and a sample shirt

Table 20. Thermal conductivity of four materials tested by Alambeta device

unit in (**W/m·K**)	Test 1	Test 2	Test 3	Test 4	Test 5	**Mean**
100% Cot	0.037	0.037	0.036	0.037	0.04	**0.037**
50/50% Cot/Pes	0.041	0.042	0.039	0.038	0.037	**0.039**
100% Pes	0.043	0.045	0.045	0.046	0.044	**0.045**
!00% PP	0.052	0.047	0.048	0.05	0.05	**0.049**

6. Future Scope of Work

- Phase 2 – Second validate, same materials (only cotton and polyester due to limited time) with the same setup, procedures and apparatuses. Air gap distance/shirt allowance will be 5mm and 10mm. Each shirt will be tested five times for R_{ct} and R_{et}. Results will be used in **Eq (29)** for the validation and the comparison to the first validation and analysis.
- Phase 3 -- Same setup, procedures, apparatuses and air gap distance/shirt allowance will be 0, 4, 8, 12, 16mm. Each shirt will be tested five times for R_{ct} and R_{et}. Thicker natural and synthetic materials will be chosen, for example, denim and broadcloth versus synthetic corduroy and satin. Results will be analyzed and compared to the first experiment.

7. References

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8. List of Publications by the Author

List of Publications in Research Journals

- Fung, F. T.; Hes, L.; Unmar, R.; Bajzik. V.; 'Thermal and Evaporative Resistance measured in a Vertically and Horizontally Oriented Air Gap by Permetest Skin Model' Industria Textila Journal, April 2021. **Impact factor: 0.784**
- Fung, F T.; Hes, L.; and Bajzik, V.; 'A Study of Air Permeability Influences on Pattern Cutting', Vlakna a Textil – Fibres and Textiles, VaT 4, volume 26, December 2019. Recorded in **Scopus**
- Fung, F. T.; Krucinska, I.; Draczynski, Z; Hes, L.; Bajzik, V.; 'Method of Patternmaking for Sweating Thermal Manikin for Research Experiment Purposes', Vlakna a Textil – Fibres and Textiles, VaT 1, volume 27, March 2020. Recorded in **Scopus**
- Fung, F. T.; Kalaoglu, F.; Altay, P.; Hes, L.; Bajzik, V.; 'Measuring Movement Ease for Clothing Pattern by means of Special made Shirt', Vlakna a Textil – Fibres and Textiles, VaT 2, volume 27, June 2020. Recorded in **Scopus**
- Fung, F T.; Hes, L.; and Bajzik, V.; 'Review of Men's Shirt Pattern Development for the Last 100 Years – Part 1. The Bodice' Vlakna a Textil – Fibres and Textiles. VaT 3, volume 27, September 2020. Recorded in **Scopus**
- Fung, F. T.; Gao, C.; Hes, L.; Bajzik. V.; 'Water Vapor Resistance Measured on Sweating Thermal Manikin and Permetest Skin Model in the Vertical Orientation' Journal of Communications in Development and Assembling of Textile Products, (CDATP), September 2020. **DOI: https://doi.org/10.25367/cdatp.2020.1**
- Fung, F T.; Hes, L.; and Bajzik, V.; 'Review of Men's Shirt Pattern Development for the Last 100 Years – Part 2. Sleeve and Cuff' Vlakna a Textil – Fibres and Textiles. VaT 4, volume 28, March 2021. Recorded in **Scopus**

List of Publications in International Conferences

- Fung, F. T.; Havelka, A.; 'Small Increasement in Clothing Pattern Relates to Thermal Insulation in Clothing of Woven Fabric' International Ph.D. Students Day, CEC 2017, Liberec, Czech Republic.
- Fung, F. T.; Havelka, A.; 'Effect of Air Permeability on Grainlines, Aged, Washed and Moisted Woven Fabric' won the **3rd prize** of poster presentation, International Ph.D. Students Day, 22nd Strutex 2018, Liberec, Czech Republic.
- Fung, F. T.; Hes, L.; Bajzik, V.; 'Review of Men's Shirt Pattern Development' 47th Textile Research Symposium 2019, Liberec, Czech Republic.
- Fung, F. T., Skenderi, Z., Hes, L., "Alternative Method of Determination of Evaporative Resistance of Socks Measured on Dry Thermal Foot Model" 14th Scientific-Professional Symposium Textile Science and Economy, 26 January, 2022, Zagreb, Croatia

Research Projects

- Member of the student grant competition (SGS) project 2017, 'Increase in Clothing Pattern Relates to Thermal Insulation in Clothing of Woven Fabric', Faculty of Textile Engineering, Technical University of Liberec, Czech Republic.
- Member of the student grant competition (SGS) project 2018- number 21246, 'Estimate Wearing Ease for Movement for Clothing Pattern of Men's Shirt of Woven Fabric', Faculty of Textile Engineering, Technical University of Liberec, Czech Republic.

Curriculum Vitae

FREDERICK FUNG
Email: tassfashion@gmail.com
Mobile: +420-777502793
Nationality: Canadian (HongKonger)

Highlight:

- Over 10 years of teaching experience in clothing design and realization
- Fluent in English, Cantonese, Mandarin Chinese and simple Japanese
- Founder and Director of Tass Fashion Show (Teachers And Students Show)
- Received scholarships for bachelor, master and doctoral degree study, 2010 Canada Olympic costume designer for Opening and Closing ceremony, and Canada Small Business Grant

Special Skills

- Preparation and operation of sweating thermal manikin (Newton and Tore), and the related software: Sensirion and Picolog
- Specialized tailored fit clothing for thermal manikins of any models with specific air gap distance built-in for a particular material for the Rct/Ret test
- Examining and analyzation of clothing/materials
- Operation of Alambeta, Permetest skin model, SGHP-sweating guarded hotplate, M290 Moisture Management Tester (MMT), FX3300 Air Permeability Tester, Planimeter, Promicra
- Skillful in garment construction, patternmaking and clothing design for men and women
- Computer skills including MS Office (Word, Excel, PowerPoint); Graphics software: Gimp 2.1, Inkscape 1.0, Paint; Video Editing software: Handbrake 1.3 and Shortcut
- Experienced event planner; organize, direct and good communication in teamwork

Work Experience

Instructor---Teaching Design Fundamental, Fashion Design, Men's and women's patternmaking and Garment Construction (beginning to advanced), from 6/2007 till 02/2015

Teaching Beginning, Intermediate and Advanced Garment Construction, Men's and Women's Patternmaking, Design Concept and Development, Fashion Design, Final Collection and Portfolio courses. Also responsible for writing course syllabus or programs, lesson plans, teaching material (including handouts, sewing samples, project patterns, research and other course materials), class demonstration, take-home assignments, midterm and final projects, as well as marking assignments, projects and final grading for the class.

- **12/2017---01/2018 Zhejiang Fashion Institute of Technology, China**
- **09/2013---02/2015 Ningbo University, China**
- **01/2010---06/2013 Visual College of Art and Design, Canada**
- **06/2007---12/2009 Art Institute of Vancouver, Canada**

Founder and Director of TASS Fashion 2009/2010/2011/2012/2014
a non-profit organization to promote Vancouver-based artists and fashion designers. Responsible for looking for sponsors, directing and training volunteers to organize and prepare for the show---from graphic design and printing look book, guest list, seating plan, runway, recruiting new talented models, lighting, media, and more. Tass fashion has grown from 7 designers and 200 guests to 35 designers and over 900 guests in the 3rd year at the Round House Community Center in downtown Vancouver, Canada.

Costume Design for Canada Olympic 2010/2, over eight months of preparation for the Opening and Closing ceremony costumes of Olympic Canada 2010. From designs to taking measurements to pattern drafting, fitting, sewing, alteration, to finishing for the Salish tribe representing Canadian's aboriginal tradition.

Garment Production Assistant/ Fabric Manager, 2007 to 2008
CYC Inc. Vancouver Label (Wing + Horn). Help production team to prepare fabric—fabric tests, shrinkage test, panels cutting, estimate labour hours and planning, scheduling and quality control finished garment, in charge of fabric receiving and shipping and distributing garment to international retailers.

******Launched Frederick Fung Label, 2003 to 2006***
*Rewarded with a small business grant from the Business Sector of the Government of Canada to launch the label—**Frederick Fung**, and selling at four different stores in lower Mainland in Vancouver.*

Pattern Maker/Designer Assistant, 2001
Neto Leather Inc./ French Laundry, Vancouver.
Responsible for manual/computer pattern making, grading, sample markers and developed variations of design. Fitting, alteration and editing patterns on the computer. Quality control of samples. Preparation for promotion (brochures, photoshoots, etc.).

Education:
Doctoral Degree of Textile Engineering---Textile Evaluation Department, Technical University of Liberec, Liberec, Czech Republic, since 2016 till now (Scholarship).
Diploma of Fashion Design---Helen Lefeaux, Vancouver, British Columbia, 2000.
Master of Fine Arts---Printmaking major, sculpture minor (Scholarship).
Started at San Francisco Art Institute (1991) then transferred to Fort Hays State University, Kansas, completed in 1994.
Bachelor of Fine Arts---Double major in printmaking and sculpture (Scholarship).
Academy of Art University, San Francisco, California, 1990.
Diploma in Visual Communication--- Graphic design, Lee Wailai Technical Institute, Hong Kong, 1985.

Media and Press:

2014/05 Ningbo Press and Media, China

2012/12 Collection was posted by OOPs Magazine

2012/10 Tass Fashion Look Book 2012

2012/07 interviewed by Source Magazine regarding Spring/ Summer collection

2012/07 Interviewed by OMNI TV, Ming Pao, Chinese Global Media at the VFW Conference at Bing Han

2012/07 Inspiration Speech for VFW Volunteer and Staffs

2011/12 Kira Kira Group Show was promoted by Japanese Magazine

2011/10 Collection was shown on Breakfast TV Vancouver, promoting Men's Fashion Week

2011/08 Tass Fashion Look Book 2011

2010/10 Interviewed by Vancouver Sun, Sunday Fashion Page, Designer of the week

2010/10 Interviewed by Asian magazine, fashion page

2010/10 Interviewed by Scarletblack.wordpress.com fashion blog

2010/02 Canada Olympic Opening and Closing ceremony on major TV Channels

2005/06 Full page interviewed by Vancouver 24Hours promoting my 1st Personal Fashion Show at the Museum of Anthropology in UBC, Canada.

Awards and Shows:

2018/10 Third place in Strutex International Conference Poster Competition, Czech Republic

2014/05 First TASS (Teacher and Student Show) in China, Ningbo University

2012/10 Fourth Annual Tass Fashion Show at Chinese Cultural Center in China Town, Vancouver

2012/09 Vancouver Fashion Week at Chinese Cultural Center in China Town

2012/08 Vancouver Men's Fashion Week at Museum of Vancouver

2012/04 Diffused Group Fashion Show at Ayden Gallery in Tinsel Town, Canada

2011/12 KiriKiri Group Fashion Show at Ayden Gallery in Tinsel Town, Canada

2011/10 Vancouver Men's Fashion Week at the Modern in Gas Town

2011/08 Third TASS Fashion Show at the Round House Community Center in Yaletown, Canada

2010/10 Vancouver Fashion Week in Vancouver downtown Empire Hotel

2010/08 Second TASS Fashion Show at Round House Community Center in Yaletown, Canada

2010/02 Canada Olympic designing costumes for Opening and Closing ceremony

2009/08 First TASS Fashion Show at District Main on Main Street, Vancouver

2007 Personal Fashion Show at Douglas Gallery on Granville Street, Vancouver

2006 Personal Fashion Show in Downtown for Aboriginal Festival, Vancouver

2005 Personal Fashion Show at the Museum of Anthropology in UBC, Vancouver

2005 Group Fashion Show at the Atlanta Club sponsored by Starbuck, Vancouver

2002-2003 Rewarded Canada Small Business Grant to Launch Frederick Fung Label

2000 Group Fashion Show at the Renaissance Hotel at Vancouver downtown.

1992-1994 Master Study Scholarship from the Fort Hays State University in Kansas State, USA

1988-1990 Bachelor Study Scholarship from Academy of Art University in San Francisco, USA

Recommendation of the supervisor

Derivation of Evaporative Resistance of Clothing from its Thermal Resistance Measured on Dry Thermal Manikin and Rct / Ret Correlations Determined on a Vertical Skin Model

Supervisor´s evaluation report on PhD Thesis of Mr. Frederic T. Fung, M.A.

In his Thesis, the candidate presented a new method of determination of thermal and evaporation resistance of clothing by means of thermal manikins. The so called dry thermal manikins serve for the determination of thermal resistance of clothing, whereas the very costly sweating manikins measure the clothing evaporation resistance. Due to irregular moisture distribution absorbed in clothing, which also reduces thermal resistance and water vapour permeability of the tested clothing, the experimental results achievable in these manikins suffer from low reproducibility.

The candidate proposed, theoretically analysed and experimentally verified a novel method, in which thermal resistance data measured on dry manikins are transformed into evaporation resistance of clothing. The transformation procedure is based in comparative measurements of thermal and evaporation resistances in special so - called Skin model, which evaluates heat and mass transfer in simulated vertical air gaps corresponding to real air gaps in the worn clothing. Results of this original and systematic research then were statistically treated, theoretically analysed and then presented as transformation equations, specific to all tested woven fabrics.

The evaporation resistance data determined by these equations then were correlated with data achieved by testing of clothing (made of the studied fabrics) on real sweating manikin in the Lund University in Sweden. For air gaps in the range of 8 to 14 mm (the mostly occurring gaps) the differences did not exceed 15%, which can be accepted as a good result when considering the complexity of the measurements.

It should be emphasized, that no study on similar topic was found in the literature, despite many papers published on manikins. The achieved results were presented on a few conferences and in several papers. Till now, no negative comments to this advanced method were observed. **Application of the presented very innovative method may extend the use of cheaper and easy operable dry manikins in many textile laboratories in the world,** despite certain limitations of this new method.

During his PhD study, the candidate presented lot of creativity, systematic scientific approach, personal precision and admirable experimental skills. Having learned and then carried out complicated operations on Sweating manikins, Skin models and other testers, he also personally tailored all special clothing of the with pre - destined air gaps used for testing on manikins in Sweden and Poland. He can be characterized by a feature typical for real scientists - being never satisfied, wanting to discover the principles, optimizing the theories, repeating many times the measurement in case of doubts.

That is why I am sure Mr. Frederic Fung deserves the PhD title and I am recommending his Thesis for the defence in the Faculty of textile engineering of Technical university of Liberec

Prof. Ing. Luboš Hes, DrSc

In Liberec on Sept. 1st, 2021

Opponents' reviews

Assoc. Prof. Małgorzata Matusiak Ph.D., D.Sc.
Faculty of Material Technologies and Textile Design,
Lodz University of Technology,
Lodz, Poland

Lodz 14.01.2022

Review Report on Doctoral Dissertation

of Frederick Tungshing Fung
entitled: "Derivation of Evaporative Resistance of Clothing from Its Thermal Resistance Measured on Dry Thermal Manikin"
prepared base on appointment of Dean of Faculty of Textile Engineering TUL - Doc. Ing. Vladimr Bajzik, Ph.D.

Supervisor: Prof. Ing. Luboš Hes, Dr Sc. (Czech Republic)

1. General description

The review has been performed on the basis of the Doctoral Dissertation in English. The Dissertation is written on 95 pages including: *Abstracts* (in English, Czech and Chinese) *Introduction*, *Objectives of the Research, Review of the Current State of the Problem, Experiments and Results, Evaluation of Results, Conclusion, Future Scope of Work, References List of Tables*, *List of Figures* and *List of Publications by the Author.* To the dissertation there were attached the *Appendices* containing detailed research results. Together with the Appendices the Ph.D. Thesis contain 118 pages.

2. Importance of the PhD. Thesis for the field of science

The main goal of presented PhD. Thesis was to develop a method for prediction the water-vapor resistance of clothing on the basis of the results from the dry thermal manikin. The motivation to undertake the performed research in a given topic is the fact that measurements with a sweating thermal manikin are difficult to obtain, and the time to prepare the measurement and the measurement itself are long lasting. This means that an assessment of water-vapor resistance is not always possible and profitable for designers and manufacturers of clothing. This limits an ability to meet the expectations of the clothing users in terms of physiological comfort.

In my opinion the investigations performed in the frame of the Ph.D. Thesis are of high importance for the material engineering, especially the engineering of textile materials and apparel products. Positive results of the presented investigations are very important, especially in current situation of the apparel market. They create new possibilities of assessment of comfort-related properties of clothing and in the same time increase the competitiveness of the apparel manufacturers on the market in the age of overproduction of goods.

An elaboration of procedure to measure the textile materials using the vertically oriented Permetest can be also assessed as a very important aspect of the Ph.D. Thesis. It is a modification of existing method. The method and its complete validation is very important for the field of textile metrology. The Ph.D. Thesis laid the foundations for the full development of the proposed method, which so far has not been used anywhere.

A very important input of the Ph.D. Thesis into the textile engineering is an analysis of influence of the air gap size on the heat and moisture transport thru the clothing. Performed investigations confirmed that in the examined range of air gap size the increase of the size of air gaps between the clothing and human being causes an increase of the thermal resistance and water-vapor resistance.

3. The evaluation of the procedure of problem solving, the used method and the fulfilment of the set aim

The Author decided to reach the scientific goal by an elaboration of equation for calculation of the evaporative resistance (Ret) of textiles by using the data from the dry thermal manikin and the correlation of Rct/Ret of the vertically oriented Permetest skin model. The Author started form the theoretical considerations of the heat and mass flow trough textiles. He analysed the phenomena of heat conduction and convection in air spaces under clothing deriving assumption that the conduction is a dominant mechanism for heat transfer. The Author also drew attention to the fact that there is insufficient information in the available literature on the subject matter analysed.

Next, after theoretical consideration, the Author performed a range of measurements using different methods. Some of them are commonly known and accepted all over the word. It concerns mostly the thermal manikin and horizontally oriented Permetest. The measurement by using the vertically oriented Permetest is a new, interesting idea. It can be considered as the Author's contribution to the development of textile metrology. However, it needs detailed and complex validation. In order to characterize the basic properties of the investigated materials the Author applied the commonly known, standardized. Testing methods. All testing devices used in the investigations have been illustrated in the photos.

For the thermal manikin measurements the Author prepared a set of shirts of different size in such a way, that the air gaps between the manikin body and shirt increased systematically from 0 mm till 16 mm. For this purpose he applied the molding method described in the literature. Finally, the measurement results were analysed using the statistical tools like the correlation analysis, determination coefficient analysis, two-way ANOVA and regression analysis.

In my opinion the procedure of problem solving is interesting and innovative. It is appropriate and well justified. The Author assumed that the measurement using the horizontally oriented skin model cannot be fully compared with the results from the thermal manikin because the conditions of measurement and movement of fluid in vertical and horizontal modes differ between each other due to the gravity. This assumption can be assessed as logical and correct. The theoretical considerations are based on the existing knowledge and some necessary assumptions properly explained and justified. The applied testing methods and procedures are appropriate, well described and correctly performed to fulfil the set aim. The statistical tools are correct and rather standard.

4. The evaluation of the results of the PhD. Thesis and the importance of the author's contribution

The results of the measurement and calculations are presented in the form of tables and graphs. Detailed results are presented in the appendices. In the dissertation the Author presents the mean values and dispersion of the results. All obtained results are discussed in details with explanation of some doubts and outliers.

The correlation analysis confirmed a strong and positive correlation between the results of Rct and Ret measurement by means of the thermal manikin and vertically oriented skin model. The analysis confirmed also the strong and positive correlation between the Rct and Ret results from the Permetest measured in vertical and horizontal orientation. Unfortunately, the Author did not provide the information about the statistical significance of stated correlations. Additionally, the results of the two-way ANOVA are not sufficiently presented and discussed. Author did not explain the independent and dependent variables analyzed.

On the basis of the measurements by means of the vertically and horizontally oriented Permetest the regression equations have been derived presenting the dependency of the Rct and Ret on the air gap size. The regression equations have been derived separately for each type of investigated materials. It would be very interesting to derive the regression equations on the basis of all results undependably on the type of fabric. It is a pity that Author did not attempt such an analysis and did not present it in the Ph.D. Thesis.

The equations (34) is a final and the most important result of the Ph.D. Thesis. It presents the relationship between the Ret and Rct. This equation has been used for calculation of the Ret according to wet thermal manikin on the basis of the Rct from the dry thermal manikin. This equation has been validated by comparison of the real Ret measured by means of the thermal manikin wearing the pre-wetted suit with the values calculated on the basis of derived equation. The equation has been partially validated. The relative small predicting errors have been achieved for the 8 mm and 12 mm air gaps. For the 0 mm and 4 mm air gaps as well as for the 16 mm and bigger air gaps further investigations are necessary to validate the method.

The Author discussed some potential reasons of big errors for the given air gap sizes. In my opinion, the results are promising. Author presents the future scope of the work. Especially, the Phrase 2 should finally prove the concept.

In my opinion presented theoretical considerations ad experiments are interesting, scientifically and methodically correct, and logically explained. The originality of the performed work, methodology and data analysis confirms a very important Author's contribution to the scientific development in a given scientific area.

5. Other statements concerning the evaluation of the methodicalness, clarity of structure and the language of the Ph.D. Thesis

It can be assessed that the Ph.D. Thesis is well structured and conforms to principles and requests to the structure of scientific thesis. Presented work is based on scientific bases, original, systematic and well described. The bibliography in the Ph.D. Thesis is rather broad. The references include 92 items. Majority of them are very actual. They are mostly the scientific articles published in world-renowned scientific journals, chapters in monographs, standards, and some information from Internet. The selection of references is adequate to the topic of the thesis.

The language is clear and correct although some linguistic errors are present.

In my opinion, the Ph.D. Thesis fulfils the formal requests on appropriate level.

6. The evaluation of the student's publications.

It should be assessed that the student's scientific achievements are at an average level. He is an co-author of 7scientific articles. The number of publications is rather big, the journal are commonly known but the rank of the journals is not very high. The student participated actively in 3 conferences. It is also not to big activity. It can be partially this may be partially justified by the long lasting pandemic situation. It should be expected in the future that the student select also for publication the journals with a higher scientific rank and a higher Impact Factor. It is worth appreciating that the student won the 3rd prize of poster presentation during the International Ph.D. Students Day, 22nd Strutex 2018 in Liberec.

7. Remarks:

- page 50, equation (24) – in my opinion it should be "q_{cto}" instead of the "g_{eto}".
- page 50, equation (25) – instead of "q_{et}" it should be "q_{ct}".
- page 50 equation (26) – it should be "q_{ctg}" instead of the "q_{etg}"

Final Statement

In my opinion, the topic of the Ph.D. Thesis is actual and interesting, especially from the point of view of designing the apparel products ensuring a physiological comfort and well-being of clothing users. The Ph.D. Thesis being reviewed is well structured. It represents high level scientific work. All experiments are properly arranged, and measurement methods are correctly applied. The results are discussed deeply and in a sufficient way. The main goal of the scientific work and its objectives were achieved.

I assess that the Ph.D. Thesis fulfils all requirements posed on theses aimed for obtaining the Ph.D. degree. In my opinion the Ph.D. Thesis is ready to be defended.

prof. Ing. Tomáš Vít, Ph.D.
Technická univerzita v Liberci
Fakulta strojní
Katedra energetických zařízení
Studentská 2, 460 01 Liberec 1

In Liberec on March 15th, 2022

Opponent's opinion of the dissertation

Frederick Tungshing Fung, M.A.

on topic

Derivation of Evaporative Resistance of Clothing from Its Thermal Resistance Measured on Dry Thermal Manikin

The presented dissertation deals with the analysis of heat and mass transfer in the conditions of textile engineering.

Achievement of objectives

The main objective of the thesis is *„To develop an equation that can calculate the evaporative resistance (R_{et}) result by using the data obtained from the dry thermal manikin and the correlation of R_{ct} / R_{et} of the vertically oriented Permetest skin model"*. It is set by the author at the end of the second chapter.

In the opinion of the opponent, the thesis does not show that the objective has been achieved. In Chapter 5, the author presents a formula (with different coefficients for different types of fabrics) that should prove the achievement of the goal. However, author himself admits that the formula is not applicable for gaps smaller than 4 mm. According to the presented data it seems that the applicability is very limited for gaps lower than 8 mm as well. Taking into the account the procedure by which the formula was achieved, the opponent is convinced that the results are not applicable even for gaps larger than 12 mm. The main reason is the fact that natural convection was not taken into account.

Review and analysis of the current state of knowledge

The issue of heat and mass transfer in narrow gaps or cavities is a topical problem, which has many applications in various scientific and engineering fields. Therefore, it is striking that this issue was not addressed in the thesis at all.

It is also surprising that the author does not mention the theory of similarity between heat and mass transfer. The Chilton-Colburn J-factor analogy was developed almost a hundred years ago and its results are still widely used.

The literature review, which focuses mainly on the use of thermal manikin or hot plate skin models, is summarized in 31 lines only. The author presents the list of topics and concepts without providing comment on the information obtained. The opponent considers such an approach to the literature review to be insufficient.

The author works very boldly with the literature sources. He often puts on the same level publications from high quality peer-reviewed journals or textbooks and information from the internet with unclear origins and validation. The author gets beyond the edge of generally accepted physics due to inappropriate sources. It is evident especially in the field of transport phenomena.

Theoretical significance of the thesis

The opponent does not consider himself an expert in the field of textile engineering. He therefore believes that the *Council of the study program sees the benefit of presented thesis for the scientific field*. If this were not the case, the council would certainly intervene during the study and make recommendations on the expected benefits of the work.

The opponent is able to competently assess the area of transport phenomena both from a theoretical and an experimental point of view, including methods used for evaluation and presentation of results.

From the point of view of heat and mass transfer theory, as it is known to the opponent, the work contains a number of fundamental inaccuracies. As a result, these inaccuracies lead to incorrect processing and interpretation of the results. The first oversight lies in the author's interpretation of Rayleigh's number, where the author omitted the physical nature of this parameter. He mistakenly considers the temperature difference to be the driving force of the phenomena, instead of the correct interpretation, which is based on the difference in densities (the term $g\beta\ (T_1 - T_2)$ is of course valid for most technical applications, but this is not the case. It has to be considered that the density of the medium changes due to both temperature and moisture). The value of Ra for heat and moisture transfer problems differs. It does not depend on the width of the gap only as presented in thesis. It is also evident from the results of the experiments where the end of pure conduction region was reached in the case of heat transfer but not in the case of mass transfer.

The second significant mistake, according to the opponent, is the incorrect application of similarity theories. The similarity theory in this case will apply very well to heat / moisture transfer in a narrow air gap and subsequently to heat / moisture transfer in a fabric. However, it is not possible when using such a simplified approach to find similarity for the whole observed phenomenon, i.e., for heat / moisture transfer through at least two different layers.

The third mistake is to present the results of the experiments regardless of theory. The author did not notice that the results of the experiments, as presented, do not correspond to the theory presented by him. Apart from other contradictions, it is obvious at first sight that if heat in a small gap is transferred only by conduction the slope in presented graphs should be significantly higher.

In general, it is inappropriate to present the results in the coordinates of gap width vs. thermal resistance. This approach leads to the loss of information about the influence of other parameters. With a properly performed dimensional analysis, it would certainly be possible to find better coordinates. The use of the „classic" Ra - Nu coordinates is obvious.

The author incorrectly neglects the heat transfer by radiation. Despite the radiation has a significant effect.

Shortcomings can also be found in the evaluation of experimental results. It is not clear how the author used regression analysis and the dependence of what parameters he monitors. It is not clear what type of regression analysis was used. ANATES was probably used correctly, but on a very small data set.

It is not clear why the author uses quadratic correlation to describe heat transfer phenomena. This kind of correlation has no basis in theory. The author does not state what is the reason for quadratic correlation, especially when all the relations he presents are linear.

Practical significance of the thesis

The performed experiments on thermal manikin and Permetest can be considered the greatest benefit of the work. The opponent is aware that the experimental determination of heat flow and mass flow is very demanding with respect to the uncertainty of the measured quantities. It is clear that great care has been taken in the preparation and execution of the experiments and the results obtained are certainly valuable.

During the experiments, the author does not address the issue of measurement uncertainty, which can be relatively large and significantly affect the informative value of the experiments. The measurement uncertainty can be given by the uncertainty of the mannequin surface and ambient air temperatures, which are set with uncertainty of ± 2 °C. This value corresponds to a 25 % uncertainty when calculating the heat flux.

Definition of used measuring equipment is vague. The repeatability of the experiments is contradictory.

The author also does not comment on presented fluctuations (discontinuities) in the measured and calculated values.

It is not clear why the experiment, whose main goal was to verify and apply basic physical principles, was repeated on seven different kinds of fabrics. It has no effect on revealing the nature of the phenomenon. On the contrary, it complicates the experiment and its evaluation.

Comments on used experimental and analytical methods

The basic idea of the dissertation is correct. It brings novelty to the scientific field. The opponent assumes that on the basis of similarity theory it is possible to use the results obtained on the basis of heat transfer for the analysis of mass transfer (here moisture).

The approach to the performed experiments is also correct (some comments in the previous paragraph).

However, the weakness of the thesis lies in the theoretical foundations and in the approach to processing and presentation of results. Due to serious faults in understanding the HMT analogy, the author did not use the potential of the obtained experiments and the presented results must be considered misleading and erroneous.

Statistical methods are applied without further explanation. It is possible to doubt the correctness of the application.

Authors knowledge in the scientific field

The author demonstrated the ability to design and perform an experiment on an existing experimental facility. At the same time, he was able *to design and implement modifications to the experimental equipment so that it could be used for a different type of tests than originally intended.* The author also demonstrated knowledge in the field of textile engineering and material structure, such as calculating fabric drapability.

Knowledge of transport phenomena shows serious shortcomings. The opponent assumes that the committee will take a position on whether this knowledge is necessary for a Ph.D. in the field of textile engineering.

From the number of errors it is possible to select the following:

- p. viii – *dp* is not the amount of pressure per unit volume, units are not correct,
- p. viii – *L* is Latent Heat of Vaporization or Heat of Vaporization or should be Enthalpy of Vaporization,
- p. ix – water vapor gas constant is not 4615 J / (kg · K),
- p. ix – units of β are not [K],
- p. 10, l7 – Fourier's law and heat conduction has nothing to do with conservation of energy,
- p. 10, l9 – Newton's law of cooling is not a discrete analogue of Fourier's law,
- p. 10, formula (4) – mess in units. There is no reason to define different diffusivity in each formula,
- p. 17 – the formula (11) for Gr calculation is wrong,
- p. 17, l11 – T_2 is not an ambient temperature in this case,
- p. 17, l22 – the critical value of Re could not be considered as onset of turbulent flow. Value of 1708 mentioned as onset of so called Bénard cells and has nothing to do with the laminar-turbulent transition,
- p. 18, l4 – units of β is wrong,
- p.19 – Table 3, presented values are wrong because of wrong definition of Gr,
- p.19 – conduction is dominant mechanism for Ra <1000 not Ra = 1000,
- p.19 – 1 / T^* could not be interpreted as the mean absolute temperature of the gas,
- p 19, l8 – moisture air must be considered as a mixture of ideal gasses in this case,
- p 19, l15 – the difference of partial water vapor pressures is driving mechanism for mass transfer but difference of moisture air density is the driving force for the convective motion and for the definition of Ra. Two different mechanisms are mixed here,
- p 20, l8 – radiation heat transfer in the presented temperature ranges should be, and probably is, much higher than 10-15 %. It is clear from presented results of experiments,
- p 21, l8 – water vapor gas constant is not 4615 J / (kg · K),
- p 24, Table 4 – the properties important to evaluate the experiments,
- p 43, Eq. 20 – inconsistent units,
- p 43, Table 7 – calculation of R_{ct} is not defined. Author means R_{cteff} probably,
- p 43, Table 7 – values of CV are calculated from 3-4 measurements. It would be more accurate to state the value of uncertainty, which, only due to the temperature setting will be higher than 25 %,
- p 43, Table 7 – the results do not meet the assumptions and the author does not comment. The author assumes that the increase in thermal resistance is caused only by an increase in the thickness of the air gap. For a 4mm, such an increase in thermal resistance corresponds to 0.15 m2K / W but the experiments show a max of 0.02 m2K / W,

- p 45, Eq. 22 – inconsistent units,
- p 51, Table 9 – the same as Table 7. Results do not correspond to assumptions. The trend is far from being linear,
- p 56, Table 11 – used correlation method is not defined. It is not clear between which quantities the correlation is calculated,
- p 57, Table 12 – from opponent understanding the regression coefficients describe the relationship between a predictor variable and the response. What are the predictor and response variables here?
- p 57 – it is not clear how the ANOVA test was performed,
- p 58, Table 13 – it is not possible to derive the same outcomes from the results of experiments presented in the appendix,
- p 30, Eq. 30 – does not have meaning of "the percentage of difference",
- p 70, graph g – presented polynomial does not fit to the results. Is it correct that thermal resistance is -86.64 m^2 mK / W for 0 mm gap?
- p 73, Eq. 32 – it is not the solution of quadratic function,
- p 77, Eq. 35 – value will be close to Ret in most of the cases.

Formal level of work

English is not the author's native language. Even the opponent does not consider himself a person capable of language proofreading in English. He therefore states that the work is, despite some rough wording, understandable.

Major shortcomings are associated with typography, where there are a number of errors that are an obstacle to understanding. Different units in the corresponding graphs are then a tolerable trifle.

The structure of the dissertation

The thesis has a standard structure. It contains a definition of the goal, a summary of existing knowledge, a theoretical basis for work, design and implementation of experiments and evaluation of results.

A comment on the literature review was made above.

Conclusion

The dissertation contains the results of the author's original experiments. The applicability of the conclusions obtained from the analysis of the results is contradictory.

<u>Contribution of the dissertation</u>:

- The undeniable benefit of the dissertation is in the opening of the question whether it is possible to use the similarity between heat and mass transfer in textile engineering.
- The author's work in the preparation and implementation of a number of experiments is also beneficial.

The shortcomings of the work are in particular:

- Major errors in the theoretical description of the observed phenomenon.
- Errors in the evaluation and statistical processing of experimental results.
- Ignoring the discrepancy of experiments with theory.

Evaluation

Submitted dissertation of Frederick Tungshing Fung, M.A. "*Derivation of Evaporative Resistance of Clothing from Its Thermal Resistance Measured on Dry Thermal Manikin*" contains a number of serious errors and shortcomings in the theoretical area and in the evaluation and interpretation of results as well.

Most of the mistakes and errors are connected to the theory of transport phenomena and its application. It is necessary to emphasize that the field of thermodynamics and transport phenomena is not the main scientific field of the author.

A commission composed mainly of textile engineering experts should decide whether the benefits of the work are sufficient for the textile industry.

I recommend the dissertation Frederick Tungshing Fung, M.A., to defend it in front the committee.

prof. Ing. Tomáš Vít, Ph.D.