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Comparative Study on the Water Vapour Permeability of Textile by a Standard and Novel device

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Abstract

Thermo-physiological properties are very much connected to water vapour and air permeability. There are multiple standards with different working principles to determine the exact performance of any textile material. However, most of these tests are time-consuming and work on the steady state principle, whereas few devices work on heat flux, where results can be obtained much more quickly. The research article covers the testing of 8 unique shirt samples on these devices compared that on a novel device created by the author to see how much the results differ from each other. Lastly, a theoretical approach was used to determine any correlation between air permeability and water vapour permeability. The research work helps in understanding the working of different devices used for water vapour permeability and allows a reduction in time by using a predictive approach with just the results from the air permeability machine.

Key words: *air permeability, water vapour permeability and thermophysiological properties.*

Introduction

Clothing is one of the basic requirements of human beings. It acts as a thermal barrier between the human body and the surrounding environment. One of the pivotal aspects of clothing is thermal comfort. A lot of efforts have been made to define comfort, but an agreeable definition is yet to be devised [1]. Several scientists have defined comfort in their own way [2]. The simplest definition of comfort is the "absence of discomfort". According to Slater, comfort is the pleasant condition of physical, psychological and physiological harmony between the human being and the surrounding climate. Clothing comfort can be segregated into four different types i.e. sensorial or tactile comfort, physiological comfort, fitting comfort and thermo-physiological or thermal comfort [1-4].

Sensorial or tactile comfort is linked to the contact of human skin with clothing i.e. sensations generated in a human being when clothing is worn next to the person's skin. These are feelings of fullness or softness, the creation of static charge, a warm cool feeling, pricking and itching. Physiological comfort is contingent on aesthetic characteristics of the textile substrate, i.e. colour, pilling, drape and luster. Fitting comfort is associated with the size and fitting of the garment [4]. Thermo-physiological comfort is related to the thermal balance of the human body, which is affected by its metabolic rate, physical actions, surrounding climate temperature, along with the thermal and moisture transportation properties of the clothing worn [3]. Heat and moisture transportation in the textile substrate play a crucial role in managing its thermal comfort [5-6]. In a hot climate, if heat loss through conduction, convection and radiation is not sufficient, sweat glands are activated by the human body to release sweat. Accumulated sweat in clothing evaporates slowly till heat lost from the human body can be more than required, and the human body starts to feel cool [7]. Evaluation of water vapour resistance is one of the most important properties associated with thermophysiological comfort. It is the gradient of water vapour pressure across the two sides of the fabric divided by the heat flux per unit area, measured in m^2Pa/W. For colder environments, multilayered fabrics are used to provide thermal comfort to the human body. Under these circumstances, two pivotal characteristics of fabrics are heat and mass transmission [8-10]. Mass transmission can take place in the form of liquid water and water vapour.

Liquid water is transported through fabric through the wetting and wicking process [4]. In case of wetting, solid-air space in the textile substrate is exchanged by a solid-liquid interface. Wetting is evaluated by the contact angle. Evaluation of wicking shows how rapidly and broadly liquid water spreads on the surface of fabric. It is evidenced from literature that heat and water vapour transport properties are contingent on factors like the density, porosity, thickness and water vapour absorbability of fibres etc [11-13]. Fabrics which are breathable allow water vapour to pass through them. However,

these fabrics do not allow liquid water to penetrate. For regulation of the human body temperature, it is essential for skin to generate water vapour, and fabrics must allow the water vapour to pass through them so that it can evaporate from the surface of the fabric. The core temperature of the normal body is almost 37 °C, and the skin temperature varies between 33-35 °C. If the temperature reaches beyond the critical range of 27 °C and 45 °C, it might result in the death of the human being [4]. If the range of temperature of the human body is between 34 °C and 42 °C, it might result in adverse effects such as disorientation and convulsions [14].

Basics of moisture vapour transmission

Moisture vapour is transported through fibrous substrates by the following process:
1) Water vapours pass through the air spaces between fibres by diffusion;
2) Absorption and transmission followed by desorption of the water vapour through the fibres;
3) Water vapours are adsorbed and transmitted along the surface of the fibres;
4) Water vapours are migrated by forced convection [4].

The study of scientific literature highlighted that researchers have focused on resolving the problems of reliable determination of the vapour permeability characteristics of textile substrates [15-24]. The development of a textile substrate with essential moisture transmission properties is of urgent need. The selection of the experimental procedure is very important during assessment of the moisture transmission parameters of a textile substrate or clothing assembly. Heat and moisture transfer through fabric is evaluated in two states i.e. a steady state and transient state.

Steady state experimental outcomes provide reliable heat and mass transfer data

for non-active cases. However, they are not able to exhibit heat and moisture transfer processes in actual wearing circumstances [5]. A number of test conditions, the design of devices, and approaches facilitate extensive learning of the vapour permeability process [25].

Determination of moisture vapour transmission through fabric is a very sensitive process and requires a lot of time. However, it is a very effective process. Several standard methods are employed for determination of the moisture vapour transmission of textile substrates. Some of these methods are as follows [26-28]:
1) The sweating guarded hot plate method, skin model (ISO 11092);
2) Sweating manikins;
3) PERMETEST apparatus;
4) The evaporative dish method or control dish method (BS 7209);
5) The upright cup method;
6) The inverted cup method.

Sweating guarded hot plate

This equipment employs skin model for evaluation of the thermo-physiological comfort of clothing according to the ISO 11092 standard [30-31]. This methodology imitates the transportation of moisture through textile substrates and clothing assemblies when worn next to the skin of a human body. Determination of the water vapour resistance of a textile substrate is performed by evaporative heat loss in a steady state condition. The temperature of the guarded hot plate is kept at 35 °C at standard atmospheric conditions for testing in a chamber kept at 65% R.H. and 20 °C. The water vapour resistance (R_{et}) of fabric is measured by **Equation (1)**:

$$R_{et} = \frac{(P_m - P_a)A}{H - \Delta H_c} - R_{et0} \qquad (1)$$

Where, A is the area of the test plate; P_m the saturation water vapour's partial pressure at the surface of the measuring unit; P_a the water vapour's partial pressure of the air in the test chamber; H the

amount of heat supplied to the measuring unit; ΔH_c the correction factor, and R_{et0} is the constant of equipment [4].

Thermal sweating manikins

The thermal manikin was first developed during World War II by America. Afterwards, a number of manikins were developed. For the last 20 years, Empa has developed heated sweating body parts and a whole body sweating thermal manikin (Sweating Agile thermal Manikin, SAM). These have been employed in clothing research to evaluate water vapour resistance and insulation properties under steady state conditions. On the other hand, there has also been investigation of the effects of clothing, posture, wind and climate on local heat flux from different parts of the body [39-42].

The first thermal manikin, "Walter", was made of water and high strength breathable textile substrate to maintain the thermal regulation system of the human body. Walter is not expensive and achieves high accuracy.

The key systems of "Walter" are:
1) A water circulation system;
2) A control and measurement system;
3) A system for the imitation of a "walking" motion.

The sweating heated TORSO [43] consists of a cylinder with an external diameter of 30 cm, divided into two guard sections at the end and a determination section in the centre. Each segment is operated with either constant power or temperature. Water is utilised for stimulating heat at a controlled rate through 54 sweat outlets spread over the surface of the evaluation section.

Fan and Chen [41] mentioned a new perspiring fabric for a thermal manikin replicating gaseous perspiration by moisture transportation through "skin" made of a breathable fabric. The manikin was

$$Relative\ water\ vapor\ permeability\ (\%) = \frac{Loss\ of\ heat\ by\ placing\ fabric\ on\ measuring\ head}{Loss\ of\ Heat\ from\ bare\ measuring\ head} \times 100 \qquad (2)$$

$$Water\ vapour\ permeability\ (WVP) = 24\ M/A.T\ (gm^2/day) \qquad (3)$$

$$Relative\ water\ vapour\ permeability\ index\ (\%) = (WVP)f \times 100/\ (WVP)r \qquad (4)$$

Equations (2), (3) and (4).

utilised to measure the moisture vapour resistances and thermal insulation of clothing assemblies, and established high reproducibility and accuracy.

PERMETEST apparatus

This instrument is the patent of Prof. Hes, employed for determination of the water vapour permeability of textile substrates, soft polymer foils, non-woven webs and garments. The principle of this equipment is based on the sensing of heat flux by calculation of the evaporative heat resistance. In the case of isothermal conditions, the temperature of the measuring head is maintained at room temperature. Heat provided to maintain a constant temperature with and without fabric mounted on the plate is evaluated (*Equation (2)*).

This method can be utilised according to both the BS 7209 and ISO 11092 standards [4].

Evaporative dish method

It is also called the gravimetric method, which is employed to measure water the vapour transmission rate through a textile substrate. The test specimen is secured over the open mouth of a dish containing water and placed in a standard atmosphere. After a certain period of time, the total system retains its equilibrium state. Then the weight of the dish is recorded sequentially, and the rate of water vapour transfer through the sample is determined. Water vapour permeability is measured in a steady state condition. The relative permeability of the specimen is measured by comparing the experimental test results with a reference fabric (*Equations (3)* and *(4)*).

Where, *M* is the loss in mass (g) of water vapour through the fabric specimen, *T* the time between weighing (h), *A* the internal area of the dish (m²), and (*WVP*)*f* and (*WVP*)*r* are the water vapour permeability of the test fabric and reference fabric, respectively.

Upright cup method

In this method, the textile substrate is positioned and sealed over a cup, 2/3rd of which is filled with water, and then it is put in a wind tunnel at standard atmospheric conditions on a weighing balance, and the deviation in mass of the fabric is calculated at time intervals [29]. Water vapour transmission is calculated by *Equation (5)*.

Table 1. Specification of materials.

Sample shirts	
Sr #	Material composition
1	94% Lyocell / 6% elastane
2	100% cotton
3	81% silk / 14% nylon / 5% elastane
4	95% viscose bamboo / 5% elastane
5	100% organic cotton
6	100% linen
7	82% silver-plated polyamide / 18% elastane
8	74% Lyocell / 19% Smartcel sensitive (zinc) / 7% elastane

Table 2. Air permeability, thickness and surface density values of specimens

T-shirts		Air permeability, mm/s	Thickness, cm	Surface density, g/m²
No.	Material composition			
1	94% Lyocell / 6% elastane	31(±1.5)	0.069(±0.01)	179(±4.9)
2	100% cotton	30(±1.9)	0.128(±0.04)	210(±5.5)
3	81% silk / 14% nylon / 5% elastane	85(±2.5)	0.121(±0.03)	182(±4.6)
4	95% viscose bamboo / 5% elastane	7(±0.8)	0.075(±0.01)	234(±7.2)
5	100% organic cotton	17(±1.2)	0.088(±0.04)	154(±5.9)
6	100% linen	149(±6.9)	0.085(±0.03)	195(±2.6)
7	82% silver-plated polyamide / 18% elastane	83(±5.2)	0.056(±0.02)	131(±4.5)
8	74% Lyocell / 19% Smartcel sensitive (zinc) / 7% elastane	24(±3)	0.069(±0.01)	195(±6.5)

$$Water\ vapour\ transmission = \frac{24 \times M}{A \times T}$$

(5)

The water vapour transmission rate is measured in (g/m²/day), *M* – change in mass (g), *T* – testing time (h), and *A* – test area (m²).

Inverted cup method

In this method, the cup is kept in an inverted position along with a super hydrophobic membrane employed to secure the cup. The sample to be tested is kept over this membrane. The inverted cup method was invented for utilising waterproof samples, as fabrics which allow the passage of liquid water may not be inverted because of leakage. The calculations used for this method are same as those of the upright cup method [29].

▮ Experimental work

In this research 8 knitted shirts with different fibre content were selected. The choice of the selection was based on the common use of this garment in research papers and by the general public. Also, an important part of the research was to compare the devices, but it was not necessary to keep the same material, structure or thickness. Details of all material are listed below in *Table 1*.

Initially all the samples were tested for their thickness using Standard ASTM D1777 – 96(2019), surface density using Standard ASTM D3776, and air permeability using FX3300 and Standard EN ISO 9237. Values of the air permeability, thickness and density of the fabrics are given in *Table 2*.

For the water vapour permeability, 3 standard methods (listed below) and one novel technique were used:
1) Evaporative dish method or control dish method (BS 7209);
2) A sweating guarded hot plate, skin model (ISO 11092);
3) A thermal manikin (ASTM F2730-10);
4) A novel device, name: H-test.

Working principle of H-Test device

A portable device to analyse the comfort performance of car seats has always been the dream of car seat producers. The complication of design and the testing method makes it hard to have a portable device which can measure the comfort performance of a car seat even in uncontrolled condition. Some factors like moisture permeability under different conditions, and the negative heat of absorption of the material affect the measurement. In this research a first prototype design of a device was made, and later in the future more advances can be made in the technology.
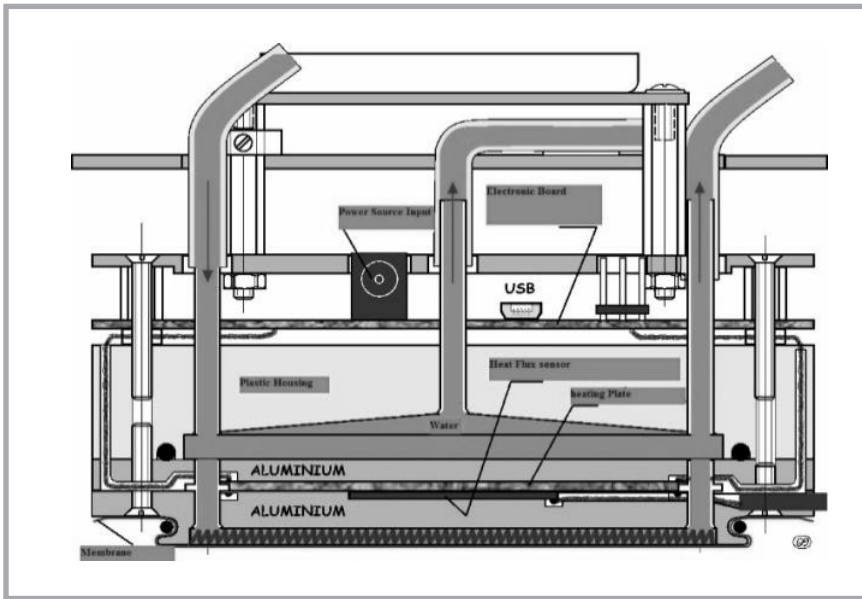
Figure 1. Schematic diagram of the new device.

For this experiment a special heat flux sensor was embedded in a measuring head insulated from the outside. The heat transfer can be increasing or decreasing and can be in the form of convective, radiative or conductive heat transfer. Heat flux through a thermal resistance layer will create a temperature gradient. Under a temperature gradient, the two thermopile junction layers will be at different temperatures and will therefore register voltage. The heat flux is proportional to this differential voltage.

Distilled water was added from tubes above the measuring head and heated to 35 °C. A special microporous membrane (Cellophane) is used on the measuring head to restrict the water drops and allow only water vapour to pass. The device was connected to a computer through a USB port, and values of the heat flux temperature of the water and temperature of the surface were provided by the software. Heat flux sensors measure heat transfer through the surface, expressed in kW/m². A schematic diagram of the device is shown in *Figure 1*, and the measuring head and parts of the device are shown in *Figures 2* and *3*, respectively.

The newly fabricated device is portable, can be used to obtain thermal and comfort related properties, and can be applied directly on any material. Also, the new device takes much less time, is portable, and can be used on any part of samples. However, the device needs further testing to compare results under different ambient conditions. It is an initial prototype. Water vapour permeability obtained through the gravimetric method, thermal manikin, and sweat guarded hot plate, and heat flux values from the H-Test are mentioned in *Table 3*.

The difference in the unit is not a matter of concern as different devices work on completely different working principles, and it is only important if the trend of each sample is comparable to another device's measurement.

To compare all results, including the air permeability, in one table, it is necessary to narrow down the values, for example the results of the gravimetric method are converted from g/m²/d to kg/m²/h and the air permeability from mm/s to m/s.

Air permeability, water vapour permeability and heat flux values from the H-Test are displayed in *Table 4*.

Yet, it is hard to compare each result, for which opted for the approach that the air permeability and water vapour permeability are very much connected to classical textile material.

Different devices use different sets of units, which makes the results look very different, but eventually they are all convertible to SI units.

Correlation of water vapour permeability with air permeability

Breathability/permeability parameters measure and evaluate the sample size (m²) in terms of gas volume pressure in cubic metres per second (m³/s). In thermodynamics this quantity is used for volume flow density m³/(m².s) = m/s.
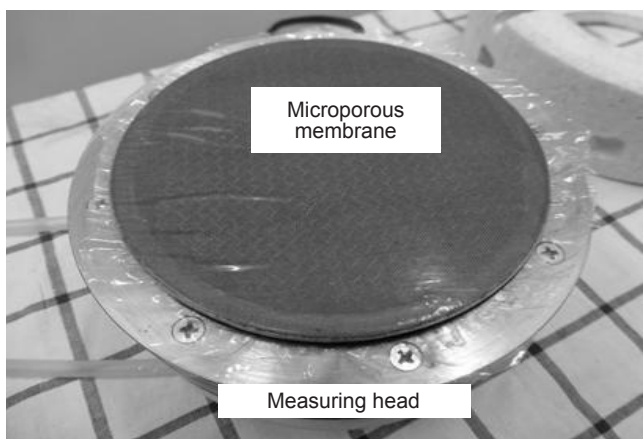

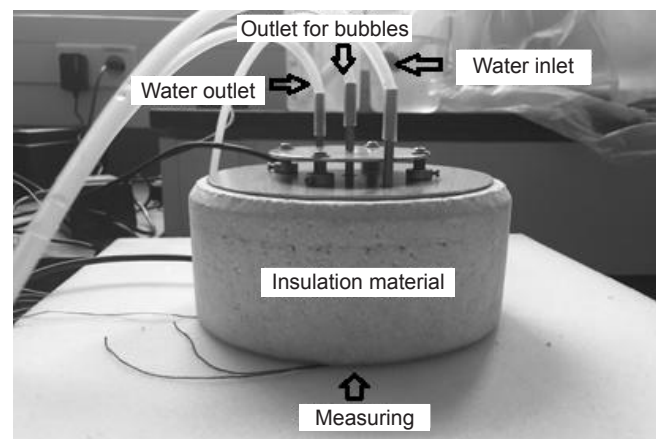**Figure 2.** Measuring head of the new device.

Figure 3. Parts description of the new device.

However, it is probably unnecessary to introduce another name in the textile field.

In order not to have to perform the above recalculations of the volume flow according to the state at the time of measurement, we recommend using the mass flow density because mass is an objective reality, independent of the state of the gas at the time of measurement. For this mass unit "kg" can be used, which makes it $kg/(m^2.s)$

Breathability to air

This is the breathability of fabrics to air as the volume pressure of a uniform surface. To compare the different results, it is necessary to convert the data to a suitable standard. For unknown reasons, the air permeability value of the sample is usually given for only one pressure difference before and after the sample measured. For further use, it would be more appropriate to set the so-called flow characteristic, i.e. the dependence of the air pressure on more set pressure drops "Δp (Pa)", with f being the force.

$$V \ (m^3/s) = f \ (\Delta p \ (Pa)).$$

From the results it is possible to determine the trend that requires dependence, or two other parameters of breathability, which can be further used for numerical simulation of sample flow.

Resistance to water vapour flow

In contrast to the air flow through the sample in the previous section, the resistance to the passage of water vapour of the sample was measured here. Water of a given phase (35 °C) was separated from the sample by cellophane, which was not permeated by liquid water and maintained it at the selected level; but it allowed (saturated) water vapour to permeate. Cellophane certainly put up some resistance to the vapour, which was considered constant under the given measurement conditions. Thus, the resulting resistance was measured for two resistors in series (cellophane + sample). Therefore, the resistance to the passage of pairs was probably determined and not their permeability; although the conversion from resistance to permeability is simple, see below.

The changed parameter is defined as the steady heating power required to make a steady passage of water vapour through the fabric surface at a given pressure drop. After setting the basic SI units into the following breakthrough units and the result is simple – it is the inverse of the flow velocity

$$m^2.Pa/W = m^2.N/m^2/(N.m/s) = s/m.$$

Where, m^2 is the area of the sample, Pa the water vapour pressure, W the energy used in J/s, and N is the SI unit of force in Newtons.

It is logical that the breathability of the monitored layer for the medium and the pressure resistance of the same layer are inverse values. If the same/converted values of the same quantities are reported in the same units, it would be possible to compare the breathability of the sample monitored for moisture and air.

■ Conclusions

It can be concluded from our research that water vapour permeability from different devices/standards are comparable, especially in terms of behavioral trends, but the absolute values are very different. The novel device also shows very promising results; the device measures the heat flux, which is directly related to the moisture trying to escape through the textile material. The correlation between air and water vapour permeability is very good and just by knowing the air permeability, it is possible to predict the water vapour permeability of material. The breathability units in textile measurements must be standardised to meet international thermodynamics SI units. In the future, the research will continue with extreme ambient conditions. Also, it is derived that water vapour resistance is the inverse of air permeability in terms of standard units.

Table 3. *Water vapour permeability and heat flux values of different specimens.*

T-shirts		Water vapour permeability-gravimetric method, g/m²/d	Ret-thermal manikin, m².pa/W	Ret-SGHP, m².pa/W	Heat flux-H-TEST, W/m²
No.	Material composition				
1	94% Lyocell / 6% elastane	4333(±28)	62.03(±2.4)	3.1(±0.2)	14(±1.2)
2	100% cotton	3996(±31)	31.26(±3.1)	4.4(±0.09)	24(±2.4)
3	81% silk / 14% nylon / 5% elastane	4214(±17)	67.09(±4.2)	1.9(±0.08)	9(±0.9)
4	95% viscose bamboo / 5% elastane	4090(±35)	62.55(±5.7)	3.6(±0.14)	17(±1.4)
5	100% organic cotton	3967(±25)	61.06(±1.9)	3.3(±0.11)	15(±1.7)
6	100% linen	4669(±14)	114.72(±10.9)	2.4(±0.17)	8(±1.1)
7	82% silver-plated polyamide / 18% Elastane	4410(±28)	67.58(±5.4)	1.7(±0.5)	12(±1.4)
8	74% Lyocell / 19% Smartcel sensitive (zinc) / 7% elastane	3937(±45)	54.85(±7.5)	2.75(±0.4)	11(±2.4)

Table 4. *Air permeability, water vapour permeability and heat flux values of specimens from the H-Test.*

T-shirts		Air permeability, mm/s	Water vapour permeability-gravimetric method, kg/m²/d	Ret-thermal manikin, m².pa/W	Heat flux-H-TEST, W/m²
No.	Material composition				
1	94% Lyocell / 6% elastane	31(±1.5)	4.333	62.03(±2.4)	14(±1.2)
2	100% cotton	30(±1.9)	3.996	31.26(±3.1)	24(±2.4)
3	81% silk / 14% nylon / 5% elastane	85(±2.5)	4.214	67.09(±4.2)	9(±0.9)
4	95% viscose bamboo / 5% elastane	7(±0.8)	4.09	62.55(±5.7)	17(±1.4)
5	100% organic cotton	17(±1.2)	3.967	61.06(±1.9)	15(±1.7)
6	100% linen	149(±6.9)	4.669	114.72(±10.9)	8(±1.1)
7	82% silver-plated polyamide / 18% Elastane	83(±5.2)	4.41	67.58(±5.4)	12(±1.4)
8	74% Lyocell / 19% Smartcel sensitive (zinc) / 7% elastane	24(±3)	3.937	54.85(±7.5)	11(±2.4)

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