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# A New Method for Measuring Water Vapour Transfers Through Fabrics

**A. Marolleau[1,2,3]*, F. Salaün[1], D. Dupont[1,2], H. Gidik[1,2], and S. Ducept[3]**

[1]*ENSAIT, GEMTEX, Lille 59000, France*
[2]*HEI-Yncréa, Lille 59000, France*
[3]*DAMART, Roubaix 59100, France*

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**Abstract:** The Skin Model is modified with a frame in order to model the microclimate which is present between the skin and the clothing. The aim of the study is to design and instrument the system by allowing dynamic control of moisture management as a function of time. Resistive humidity sensors are placed at 4 locations in the frame to measure the transfer rate of water molecules through the fabric layer. After checking the reproducibility of measurement, the influence of physical parameters (weight, thickness, moisture regain and fabric design) and thermo-hydric characteristics of fabrics (air permeability, wetting time, one-way transport index, thermal resistance and water vapour permeability) on the transfer rate is analyzed by applying a multiple linear regression. The statistical analysis suggests that one of the main parameters significantly affecting the moisture management is the moisture regain of the fabrics related to its chemical composition, since high fabric moisture regain values lead to low water vapor transfer through the layer. Furthermore, the textile design (1×1 Interlock or jersey), wetting time (WT) and one-way transport index (R) have a low influence on these hydric transfers. To obtain further information, dynamic vapor sorption (DVS) and desiccant inverted cup methods are introduced. For the DVS, the maximum water sorption at 35 °C was determined by the mass difference between 0 and 98 % relative humidity (RH). The desiccant inverted cup method allows moisture transfer to be measured without forcing it unlike frame tests. Methods are compared and this investigation clearly demonstrates that DVS and frame test can be used to assess quantitatively the hygroscopicity, and the moisture transfer rate between the microclimate and the surrounding environment. These parameters are related to the interactive forces between fibers and water molecules, and the ability to store water molecules within fibers by increasing the sample mass.

**Keywords:** Textile fabrics, Hydric transfers, Instrumented skin model, Dynamic vapor sorption, Microclimate

## Introduction

Thermal comfort refers to a state, which expresses satisfaction with the thermal environment and it is associated to changes in various physiological and environmental parameters, and it is closely related to clothing comfort or textile properties, such as fabric insulation, water vapor permeability, and affected by tactile or sensorial perception, and moisture and thermal interactions which influence the human perception [1]. The thermal insulation properties of a garment are mainly affected by fiber, yarn and fabric properties, but also by seams, fit closure and microclimate region. This region, which is located between clothing layer near to the skin and wearer's body, contributes to the heat and mass transfers from the wearer to the surrounding medium [2]. According to the Lu's study [3], the metabolic heat and sweat vapor generated on a wearer's skin transfer through the microclimate region towards the clothing by convection, conduction, radiation, evaporation, and/or moisture absorption/diffusion. Therefore, depending on the environmental conditions and the physical activity, the microclimate region may contain a lot of moisture, which leads to a state of discomfort.

In this context, various studies have been carried out to analyze the clothing variables contributing to the microclimate and perceived thermal comfort [4]. Thus, the fiber chemical nature, moisture regain and fabric design appear to affect some comfort-related properties of the clothing layer, since they influence also the microclimate over the skin surface and the thermoregulatory response at the skin [5]. The elements and properties of fabric structure, i.e., fabric and stitch densities, rib number, yarn properties, thickness, moisture regain, contribute to the moisture and thermal management in the microclimate related to thermal resistance, air permeability, water-vapor permeability, and liquid water permeability [6-9]. Therefore, the control of these parameters is critical to assess the heat and moisture exchanges and to evaluate the wearer's comfort perception [9-11]. There are different methods to simulate and determine the main aspects of the body exchange function and to perform textile measurements under well controlled energy exchange conditions in order to establish thermophysiological correlations. One of these methods is the upright cup method [12] which consists of placing a textile sample on a cup containing distilled water. The prepared assembly, which is placed in a climatic chamber, is weighed periodically in order to determine the rate of water vapour passing through the textile over a time period. An air gap of about 10 mm minimum is present between the surface of the water and the fabric. When distilled water is replaced with a desiccant, the water vapor transfers then take place from the external environment to the cup. Other methods such as inverted cup

*Corresponding author: adeline.marolleau@ensait.fr

method or dessicant inverted cup method [12] are based on the same principle but by positioning the cup directly in contact with the waterproof textile. The air gap does not exist between the textile and the water surface. The Turl Dish method [13] allows us to determine the rate of water vapour transmission through textiles by positioning several cups on a turntable in order to homogenize the air gap present on textile and water surfaces. For the moisture transmission test [14], a sample positioned in the middle of a closed cell whose upper part is dried by a desiccant and the lower part contains distilled water. A sensor recovers the data in the upper part of the cell. The presented methods are easy and inexpensive to implement however they give mainly static results with long measurements times. More complex devices are developed in order to eliminate these inconvenient for example Huang's device [15], guarded hot plate, sweating guarded hot plate (Skin Model) or thermal manikin [16, 17]. Huang's device measures the rate of water vapour transmission through a textile by means of a cylinder filled with distilled water and a measuring cell in which nitrogen circulates [15]. The Skin model used according to ISO 11092:2014 [18] allows the simulation of both water vapour and heat transfers through the textile without taking into consideration the microclimate. According to this norm, the method performs static tests by setting a temperature and humidity level throughout the test. Other studies based on the Skin model principle are developed to modify it for performing dynamic measurements [9,19-22]. The Skin model is an expensive device, less obvious to install than systems using cup but more representative for the conditions of use. As it is presented previously, the thermal manikin is the one of the complex devices which tests thermal and hydric transfers in an even more realistic way [23,24]. This device is very expensive and requires qualified people to handle it. However, most of these cited methods are realized under steady-state condition, and are not representative of the common use of the garment, since when the clothing is worn close to the skin, they can absorb quickly a high amount of sweating to maintain thermal comfort at long term during an activity.

The Skin model used according to ISO 11092:2014 standard does not make it possible to model the effects of the microclimate on hydric transfers. In addition, some studies modify this process to perform dynamic tests by opening a shutter to create a sweat pulse. In this case, the evaporation of a certain amount of previously inserted water is measured but during this process, the speed of evaporation of water is not controlled over time. In order to model the impact of the microclimate on hydric transfers under dynamic conditions, it is important to instrument the existing system, called Skin Model, and to modify the protocol by varying environmental conditions.

The purpose of this study is not only to collect experimental data about the moisture transfer through a selected group of underwear fabrics, but also to find a new method to analyze the mass transfer in the microclimate by using an instrumented Skin Model. The first part of the study evaluates the influence of the fabric physical and thermo-hydric parameters on the moisture transfer from 40 to 90 % RH at 35 $^{o}$C in a climatic chamber by integrating 4 resistive humidity sensors in the frame of the Skin Model. In the second part, Dynamic Vapour Sorption and desiccant inverted cup method are presented in order to explain the influence of the textile physical properties on the interaction which is present between water and selected fabrics. The moisture profiles, the hysteresis behavior as well as the water vapour permeability and fabrics breathability are studied, to determine the sorption behavior of various fabrics.

## Experimental

### Materials

In this study, eight commercially available underwears, obtained from Damart (France) are used (Tables 1 and 2). Two other fabrics (Samples (E) and (J)) which are not

**Table 1.** Description of test samples

| Sample code | Blend composition | Fabric design | Fabric weight ($g \cdot m^{-2}$) | Thickness at 0.1 kPa (mm) | Density ($g \cdot cm^{-3}$) | Porosity (%) | Air permeability at 100 Pa ($l \cdot m^{-2} \cdot s^{-1}$) | Moisture regain (%) |
|---|---|---|---|---|---|---|---|---|
| A | 50 % PES, 50 % polyacrylic fibers. | 1×1 interlock | 215±2 | 1.31±0.03 | 1.35 | 87.8±2.9 | 1059±73 | 1.1±0.2 |
| B | 68 % Polyacrylic, 25 % PES, 7 % polyacrylate. | 1×1 interlock | 157±2 | 1.09±0.06 | 1.26 | 88.5±6.1 | 1163±28 | 3.1±0.3 |
| C | 85 % Polyacrylic, 15 % polyacrylate. | 1×1 interlock | 156±4 | 1.22±0.08 | 1.23 | 89.4±8.5 | 1311±60 | 4.2±0.6 |
| D | 100 % Cotton. | 1×1 interlock | 177±3 | 1.03±0.05 | 1.54 | 88.5±6.1 | 861±45 | 7.5±0.5 |
| E | 95 % PES, 5 % elastane. | Single jersey | 160±2 | 0.64±0.06 | 1.37 | 81.7±9.2 | 418±21 | 1.3±0.2 |
| F | 87 % Polyacrylic, 7 % polyacrylate, 6 % elastane. | Single jersey | 145±4 | 0.82±0.04 | 1.21 | 85.4±7.3 | 779±18 | 2.8±0.1 |
| G | 66 % PES, 28 % cellulose based synthetic fibers, 6 % elastane. | Single jersey | 141±3 | 0.82±0.02 | 1.41 | 87.8±4.4 | 1213±70 | 4.1±0.1 |
| H | 80 % Polyacrylic, 14 % polyacrylate, 6 % elastane. | Single jersey | 158±2 | 1.02±0.02 | 1.23 | 87.4±3.2 | 785±46 | 4.4±0.1 |
| I | 66 % Polyacrylic, 28 % cellulose based synthetic fibers, 6 % elastane. | Single jersey | 138±5 | 0.71±0.02 | 1.29 | 85.0±5.6 | 1226±32 | 5.0±0.1 |
| J | 95 % Cotton, 5 % elastane. | Single jersey | 166±1 | 1.05±0.02 | 1.52 | 89.5±2.3 | 265±8 | 7.1±0.3 |

**Table 2.** Thermal and hydric properties of fabrics

| Sample code | $R_{ct}$ ($m^2 \cdot K \cdot W^{-1}$) | $R_{et}$ ($m^2 \cdot Pa \cdot W^{-1}$) | $I_{mt}$ | $W_d$ ($g \cdot m^{-2} \cdot h^{-1} \cdot Pa^{-1}$) | $WT_{Top}$ (s) | $R$ (%) |
|---|---|---|---|---|---|---|
| A | 0.0315 | 4.47 | 0.42 | 0.34 | 9.0±5.3 | 161.5±76.3 |
| B | 0.035 | 3.85 | 0.54 | 0.39 | 3.3±0.5 | 62.1±18.1 |
| C | 0.039 | 3.87 | 0.60 | 0.38 | 103.1±29.3 | 861.1±203.0 |
| D | 0.023 | 2.83 | 0.49 | 0.51 | 9.7±2.1 | -372.7±51.0 |
| E | - | - | - | - | 12.5±13.8 | 100.0±68.0 |
| F | 0.024 | 2.90 | 0.50 | 0.51 | 120.0±0.0 | 822.7±174.1 |
| G | 0.027 | 3.29 | 0.49 | 0.45 | 115.3±8.2 | 853.5±92.4 |
| H | 0.031 | 3.29 | 0.56 | 0.45 | 120.0±0.0 | 961.9±111.3 |
| I | 0.028 | 3.24 | 0.52 | 0.46 | 120.0±0.0 | 877.3±42.3 |
| J | - | - | - | - | 8.7±0.6 | 87.1±80.7 |

produced by this firm are added in the study as a common blend of fibers. Samples selected for the study represent a panel of common textiles with variable moisture regain.

Two fabric designs are studied: 1×1 interlock and jersey. Four 1×1 interlock samples which differ essentially in their composition are, i.e. (i) sample (A) is a blend of polyester (PES) (high quantity) and polyacrylic fibers; (ii) sample (B) is a blend of polyester (low quantity), polyacrylic and polyacrylate moisture sensible synthetic fibers; (iii) sample (C) is a blend of polyacrylic and polyacrylate; and (iv) sample (D) is made of cotton only. Sample (C) contains more polyacrylate than the sample (B). Other samples with a jersey structure are studied as: (i) sample (E) composed of PES and elastane fibers; (ii) sample (F) which is a blend of polyacrylic, polyacrylate moisture sensible fibers and elastane; (iii) sample (G) is a blend of PES fibers in high quantity, viscose and elastane; (iv) sample (H) has a similar blend than the sample (C) with an addition of elastane fibers; (v) sample (I) is composed of polyacrylic fibers in high quantity, viscose fibers in the same quantity than sample (G) and elastane; (vi) sample (J) is a blend of cotton (high quantity) and elastane fibers.

## Methods

### *Measurements with Frame*

*Sweating Guarded Hot Plate (Skin Model)*

The sweating guarded hotplate is commonly used to measure thermal and water vapour resistances of fabric in steady-state conditions according to ISO 11092:2014. The thermal resistance is representative of the fabric heat insulation. For this measurement, the sample is placed above the measuring unit of the sweating guarded hot plate. The hotplate (measuring unit) is a porous sintered stainless steel plate where an air ducted of 1±0.05 $m \cdot s^{-1}$ flows across and parallel to the upper surface of fabric. It is electrically heated at 35 °C to simulate the skin temperature during the whole test. For the determination of thermal resistance (equation (1)), the ambient conditions are settled to 20±0.1 °C and 65±3 %RH.

$$R_{ct} = \frac{(T_m - T_a) \times A}{H - \Delta H_c} - R_{ct0} \quad (1)$$

With $R_{ct}$ the thermal resistance ($m^2 \cdot K \cdot W^{-1}$), $T_m$ the temperature of the measuring unit (K), $T_a$ the air temperature in the test enclosure (K), $A$ the area of the measuring unit ($m^2$), $H$ the heating power supplied to the measuring unit (W), while $\Delta H_c$ is the correction term for heating power (W), and $R_{ct0}$ ($m^2 \cdot K \cdot W^{-1}$) is the apparatus constant determined as the « bare plate » value ($m^2 \cdot Pa \cdot W^{-1}$).

The water vapour resistance is the capacity of the fabric to allow water vapour to pass through the material. The measuring unit is covered by a water vapour permeable and liquid-water impermeable membrane. Water is supplied by channels beneath the hotplate. Then the water evaporates through pores of the plate like sweat at the surface of the skin. Standard conditions for the measurement of this parameter (equation (2)) are 35±0.1 °C and 40±3 %RH.

$$R_{et} = \frac{(P_m - P_a) \times A}{H - \Delta H_e} - R_{et0} \quad (2)$$

With, $R_{et}$ the water vapour resistance ($m^2 \cdot Pa \cdot W^{-1}$), $P_m$ the water vapour partial pressure (Pa) at the surface of the measuring unit at temperature $T_m$, $P_a$ the saturation water vapour pressure (Pa) of the air in the test enclosure at temperature $T_a$, $A$ the area of the measuring unit ($m^2$), $H$ the heating power supplied to the measuring unit (W), while $\Delta H_e$ is the correction term for heating power (W), and $R_{et0}$ ($m^2 \cdot Pa \cdot W^{-1}$) is the apparatus constant determined as the « bare plate » value ($m^2 \cdot Pa \cdot W^{-1}$).

The water vapour permeability index ($I_{mt}$) presents the ability of a material to transmit water vapour by giving information about the breathability of fabrics. This parameter is calculated from thermal and water vapor resistances by equation (3). It varies between 0 (impermeable fabric) and 1 (permeable fabric).

$$I_{mt} = 60 \times \frac{R_{ct}}{R_{et}} \quad (3)$$

With $I_{mt}$ the water vapour permeability index (dimensionless), $R_{ct}$ the thermal resistance ($m^2 \cdot K \cdot W^{-1}$), and $R_{et}$ the water vapour resistance ($m^2 \cdot Pa \cdot W^{-1}$).

In our study, an additional module is added to the Skin model in order to represent the microclimate which is present between the skin and the textile. The frame is positioned between the guarded hot plate and the textile. It allows us to measure water vapour flows through the textile with sensors. Its conception, instrumentation and implemented tests are described below.

*Frame Design*

The frame with a size of 322×322 $mm^2$ is positioned on the guarded hot plate and designed according to Figure 1.

It is made of aluminium to allow the homogenisation of heat flows within its structure. It is composed of 3 parts. The first part consists of a solid plate attached to the frame body by screws. As the test is performed isothermally, this plate prevents hydric leaks from below. At the top of the central plate hollow in its center, a polyethylene mesh with openings of 20×20 $mm^2$ is placed in order to maintain the textile flat by avoiding the belly effect. The height of the central plate (10 mm) represents the thickness of the air gap between the textile and the guarded hot plate by creating a microclimate for hydric exchanges. Humidity sensors are positioned inside the central plate. The composite supports, which are made of vegetable fibers and waterproof polymer, are placed on the surface of the solid plate and hold sensors HR1, HR2, HR3 and HR4 in position (Figure 2). A passage for connecting sensors is created at the right end of the central plate. Once the textile is laid on the mesh, a cover is positioned over it to limit the passage of hydric flows on the sides. In order to ensure a total water tightness of the system, rubber insulation joints are glued to the upper surface of the central plate and under the cover. Screws hold the cover in position and tightening them ensures contact between seals. Moreover, in order to avoid the passage of moisture through the screws, their heads are covered by a tape. An air flow of 1 $m \cdot s^{-1}$ passes horizontally over the surface of the entire system.

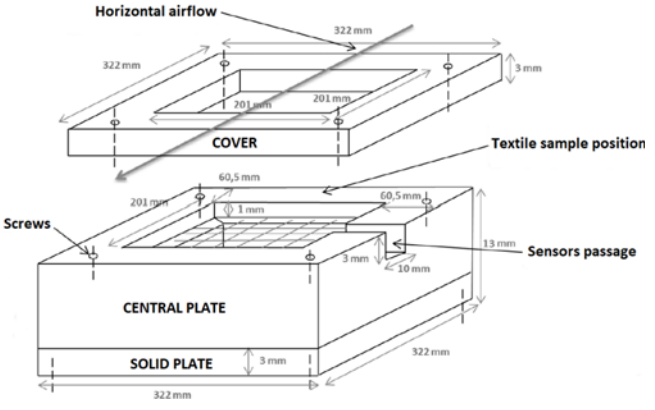


**Figure 1.** Frame design.

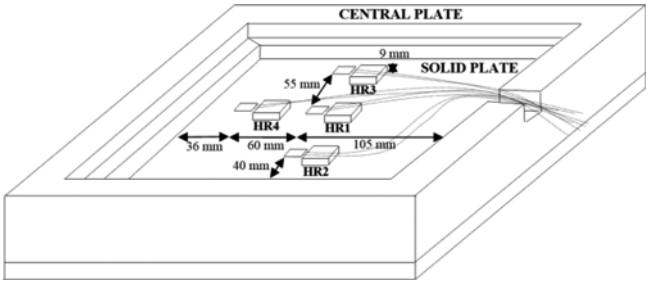


**Figure 2.** Sensors positioning within the frame.

*Frame Instrumentation*

The frame is instrumented with four resistive humidity sensors EFS-10 from Conrad®. It consists of a ceramic substrate coated with a metal electrode and a hygroscopic polymer. When the sensor absorbs moisture, ionic groups dissociate and increase its electrical conductivity. The impedance of the sensor varies between 1.5 kΩ and 3 MΩ. This variation is measured by placing the sensor in an electrical circuit, shown in Figure 3, powered by a low frequency generator set at 1 kHz. Other resistors have a fixed impedance of 100 kΩ and the alternating current signal (AC) is recovered by a Keithley acquisition device. The measuring range of these sensors is between 20 % and 90 %RH with a response time of 12 seconds. They have also a good long-term stability and an average accuracy of 5 %RH.

The sensors must be calibrated before tests. This step is performed by using a capacitive humidity probe, Testo 435 from Conrad®, as reference. Its measuring accuracy is 3 %RH. Within a climatic chamber, the sensor is positioned as close as possible to the probe and they are subjected to different humidity levels from 40 % to 90 %RH with a step of 10 %. From data recovered by the exceLINX (humidity sensors) and Testo Comfort X35 software, a specific

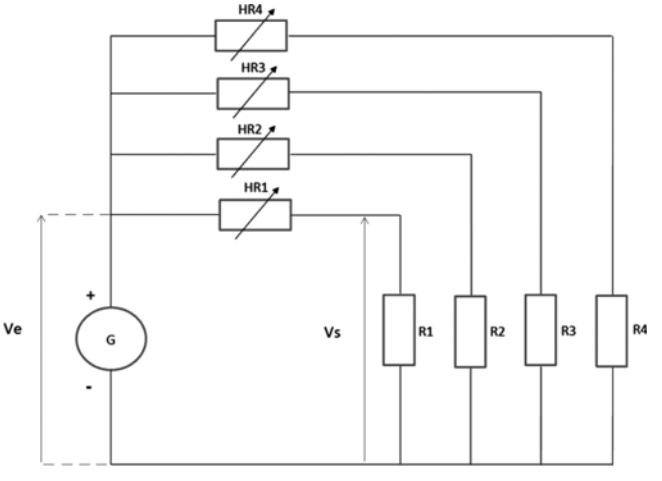


**Figure 3.** Electrical circuit with resistive humidity sensors.

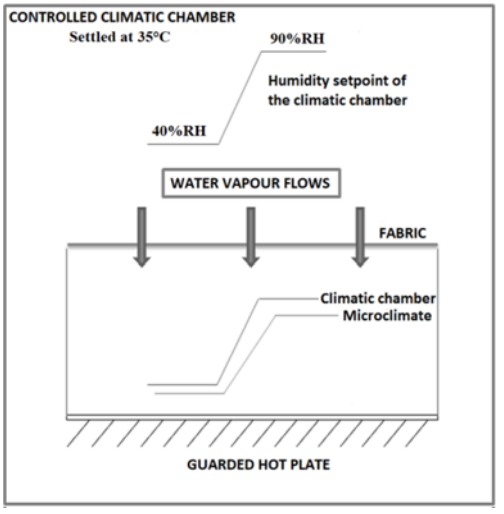


**Figure 4.** Schematization of the protocol put in place.

calibration equation is defined for each sensor. This polynomial equation of degree four links the measured voltage within the electrical circuit with the surrounding humidity of the controlled climatic chamber.

*Test Protocol*

The test is carried out in isotherm to measure only the water vapour flows passing through the textile. The temperature is set at 35 °C and represents the temperature at the skin's surface. Using a climatic chamber, a textile sample is subjected to a humidity ramp from 40 % to 90 %RH with a speed of 10 %HR·min$^{-1}$ in order to simulate a sudden sweating. At the beginning and at the end of this ramp, the samples are treated at 40 % RH and 90 % RH during one hour, respectively. This protocol is used to test the dynamic barrier effect of textiles on the passage of water vapour flows according to Figure 4. If a textile lets the hydric flow pass through it, the humidity ramp obtained in the microclimate will follow the one set in the climatic chamber. In this case, the textile has little influence on the transfer of water vapour molecules. Otherwise, the humidity within the microclimate will be lower than that of the climatic chamber and water vapour molecules take longer time to pass through the textile. Three tests per sample are carried out.

***Desiccant Inverted Cup Method***

The water vapour permeability of fabrics ($W_d$) is measured with a desiccant inverted cup method according to ISO 15496:2004. A temperature of 23 °C is settled for this test. A saturated potassium acetate solution, which is previously subjected to a temperature of 23 °C for 12 hours, generates 23 %HR into the cup covered by a vapour permeable PTFE membrane. The textile is positioned between this PTFE membrane and another one. The system (cup, PTFE membranes, and fabric) is immersed in a water bath maintained at a constant temperature of 23±0.1 °C. During the test, the measuring cup is turned over, weighed and then reinstalled in its initial position for others measurements. These steps are carried out at the beginning and after 15 minutes. The water vapour permeability of fabrics is calculated according to equation (4).

$$W_d = \frac{a_1 - a_0}{S} \quad (4)$$

With $W_d$ the water vapour permeability (g·m$^{-2}$·h$^{-1}$·Pa$^{-1}$), $a_0$ and $a_1$ are the mass of inverted cup before and after 15 min (g), respectively, S the fabric area (m$^2$).

***Moisture Management Properties***

The determination of moisture management properties of fabrics is determined by a Moisture Management Tester (MMT) (Atlas, UK) according to AATC 195-2009. The transport of liquid water in dynamic is measured, i.e. (i) spreading outward on the top surface (inner) of the fabric; (ii) transferring through the textile from the top surface to the bottom (outer) one; (iii) spreading outward on the bottom surface of the fabric. The textile (8.0×8.0±0.1 cm$^2$) is placed between two concentric sensors after a conditioning at 65±4 % RH and 20±2 °C. The liquid solution, composed of sodium chloride, simulates the sweat. A quantity of 0.21×0.01 g is introduced at the top plate during the first 20 seconds of the test. The MMT device measures several indices like the wetting time ($WT_{Top}$) at the inner surface and the one-way transport index (R).

***Dynamic Vapor Sorption Test (DVS)***

The dynamic vapor sorption apparatus (DVS) measures the textile's ability to sorb and desorb moisture in the form of water vapour by measuring mass change from an electrical balance (SMS Ultrabalance$^{TM}$) with an accuracy of ±0.1 µg. Test temperature is set to 35±0.1 °C to simulate skin surface temperature. The controlled chamber with mass flow controllers (200 m*l*·min$^{-1}$) provides an humidity at ±1 %RH. Samples are initially dried for 600 minutes and then the humidity is modified by step of 10 % RH between 0 and 90 % RH, with a step of 5 % RH between 90 and 95 % RH and finally with a step of 3 % RH between 95 and 98 % RH. During desorption, the same protocol is used. The sample is maintained at a constant RH step until the rate change in mass is less than 0.005 % per minute. When the mass change rate falls below this threshold, the humidity level changes to the next programmed one. Data are acquired every 20 seconds and two tests are carried out by samples in order to ensure the reproducibility of the measures. An hysteresis appears between sorption and desorption cycles. It is calculated as the difference between $M_{Desorption}$ and $M_{sorption}$ at each RH step according to equation (5).

$$Hysteresis_{RH_i}(\%) = M_{Desorption,\%RH_i} - M_{Sorption,\%RH_i} \quad (5)$$

With $M_{Sorption,\%RH_i}$ the quantity of water sorbs at each step i of humidity (%), $M_{Desorption,\%RH_i}$, the quantity of water

desorbs at each step i of humidity (%).

This test is performed on seven fabrics: samples A to C, and samples G to J. They are chosen in order to represent different fabric blends with natural or synthetic fibers. The hysteresis area is measured with the OriginPro 9.0 software. Between 40 and 90 %RH, the difference in textile mass is calculated. These values are compared with the frame moisture rate transfer, $I_{mt}$ index representing the breathability of fabrics and $W_d$ assessing the ease of water molecules to pass through it.

## Results and Discussion

### Frame Results

***Reproducibility***

The reproducibility is the ability to repeat an experiment. For its calculation, tests are repeated three times and the coefficient of variation (CV%) is calculated in order to prove the reproducibility of obtained measures. A value of CV% less than 10 % is considered as correct.

According to Table 3, all moisture transfer rates, which are measured with frame protocol, have a CV% less than 10 %. It means that results obtained are reproducible and the protocol put in place is validated.

***Statistical Tests***

Statistical analyses are performed with the R software 3.4.1. The t-test for paired samples is applied to data obtained from sensors for all tested textile samples. It is used to determine whether differences in sensor responses depend on their location. Before performing this test, the symmetry of the data is checked for each sensor by using a histogram, the calculation of the mean and the median. Then, the normal Q-Q plot, Shapiro and Kolmogorov-Smirnov tests are performed on sensors responses to check if they follow a normal distribution ($H_0$ hypothesis). If they do not follow a normal distribution, the Friedman test is applied. It is used to determine if the distribution of at least one sensor is different from others (alternative hypothesis).

According to Table 4, the means and median of each sensor, calculated with the R software, are equivalent, the distribution is symmetrical. However, according to the histogram and normal Q-Q plot, distributions do not seem to follow a normal distribution. For Shapiro and Kolmogorov-Smirnov tests, the $H_0$ hypothesis indicates that data follow a normal distribution and the alternative hypothesis means the opposite. When the p-values are less than 0.05 then the alternative hypothesis is accepted, otherwise the hypothesis $H_0$ is followed. The p-value of Shapiro test is greater than 0.05 only for the HR4 sensor which indicates that the distribution follows a normal distribution ($H_0$ hypothesis). However, for all sensors, distributions do not follow a normal one with the Kolmogorov-Smirnov test. The Shapiro

**Table 3.** Moisture transfer rate results from the frame test obtained with TableCurve software

| Sample code | Fabric design | | Moisture transfer rate (%RH·min$^{-1}$) | | | | Mean sensors |
|---|---|---|---|---|---|---|---|
| | | | HR1 | HR2 | HR3 | HR4 | |
| A | 1×1 interlock | Mean | 10.3±0.1 | 10.3±0.1 | 10.3±0.2 | 10.7±0.2 | 10.4±0.2 |
| | | CV% | 1.5 | 1.5 | 1.6 | 1.9 | 2.1 |
| B | 1×1 interlock | Mean | 10.0±0.3 | 9.8±0.3 | 10.1±0.2 | 10.3±0.2 | 10.1±0.3 |
| | | CV% | 2.7 | 3.1 | 1.8 | 2.2 | 2.7 |
| C | 1×1 interlock | Mean | 9.3±0.5 | 9.1±0.5 | 9.5±0.4 | 9.7±0.3 | 9.4±0.4 |
| | | CV% | 5.1 | 5.8 | 4.8 | 3.6 | 4.8 |
| D | 1×1 interlock | Mean | 7.9±0.3 | 7.4±0.3 | 8.6±0.3 | 8.7±0.3 | 8.1±0.6 |
| | | CV% | 3.9 | 4.6 | 3.9 | 4.0 | 7.4 |
| E | Single jersey | Mean | 10.3±0.1 | 10.5±0.1 | 10.4±0.1 | 10.7±0.1 | 10.5±0.1 |
| | | CV% | 0.4 | 0.4 | 0.4 | 0.6 | 1.4 |
| F | Single jersey | Mean | 9.2±0.1 | 9.3±0.1 | 9.7±0.2 | 9.8±0.1 | 9.5±0.3 |
| | | CV% | 1.6 | 1.0 | 2.0 | 1.6 | 3.2 |
| G | Single jersey | Mean | 8.3±0.2 | 8.2±0.2 | 9.0±0.2 | 8.9±0.1 | 8.6±0.4 |
| | | CV% | 2.1 | 2.4 | 2.2 | 1.5 | 4.5 |
| H | Single jersey | Mean | 9.3±0.1 | 9.0±0.3 | 9.8±0.1 | 9.6±0.2 | 9.4±0.3 |
| | | CV% | 1.4 | 3.0 | 1.6 | 1.7 | 3.5 |
| I | Single jersey | Mean | 8.7±0.1 | 8.4±0.1 | 9.4±0.2 | 9.3±0.1 | 9.0±0.4 |
| | | CV% | 1.7 | 1.3 | 1.9 | 0.5 | 4.9 |
| J | Single jersey | Mean | 7.9±0.1 | 7.6±0.1 | 8.8±0.1 | 8.5±0.3 | 8.2±0.5 |
| | | CV% | 0.1 | 0.1 | 0.1 | 0.3 | 0.5 |

**Table 4.** Results of statistical tests with the R software

| Sensors | HR1 | HR2 | HR3 | HR4 |
|---|---|---|---|---|
| Mean (%RH·min$^{-1}$) | 8.943 | 8.621 | 9.580 | 9.438 |
| Median (%RH·min$^{-1}$) | 9.001 | 8.545 | 9.655 | 9.388 |
| Shapiro test | p-value=0.005 | p-value=0.023 | p-value=0.002 | p-value=0.087 |
| Kolmogorov-Smirnov test | p-value=$9.118\times10^{-10}$ | p-value=$1.201\times10^{-11}$ | p-value=$8.515\times10^{-14}$ | p-value=$8.773\times10^{-13}$ |
| Friedman test | p-value < $2.200\times10^{-16}$ | | | |

test is sensitive to sample size. When the number of samples is low, this test is less significant and the $H_0$ hypothesis is considered. Otherwise, for a large number of textile samples (<50) $H_0$ will be more easily rejected. Thus, coupling this test with another one is needed to confirm obtained results. In this work, the sample size is small which explains why $H_0$ is retained for HR4 sensor unlike with the Kolmogorov-Smirnov test. The results from two tests indicate that there is a difference for HR4 sensor so; in general, data do not follow a normal distribution. In this case, the Friedman test is applied. The p-value obtained for this one is less than 0.05 and the $H_0$ hypothesis is rejected (distributions are equivalent). Thus, at least one sensor has a different distribution than other sensors. This means that the placement of sensors within the microclimate would have an impact on the measurement of hydric flows. The boxplot in Figure 5 shows obtained distributions. The accuracy of sensors is ±5 %RH and the difference observed graphically is less than this value. Thus, average moisture rate transfer measured by all sensors and for each textile sample can be used. The effect of the sensors positioning on measurements obtained is considered negligible taking into account their sensitivity.

***Multiple Linear Regression***

Multiple linear regression are applied to analyze moisture rate transfer variations according to physical and thermo-hydric textile parameters. The ability of a fabric to let water molecules through is reflected in a high transfer rate value and a low transfer time; which depends on the chemical nature of the fibers. Thus, the presence of very hygroscopic fibers in the textiles leads to a low value, such as samples D and J (Tables 1 and 3). Fabrics act as a barrier layer against moisture since they absorb water molecules before transferring them to the outside environment. On the other hand, water sorption is low for samples made of fibers with low hygroscopy, and the transfer rate is higher because the moisture passes quickly through the fabric layer, such as samples A and E.

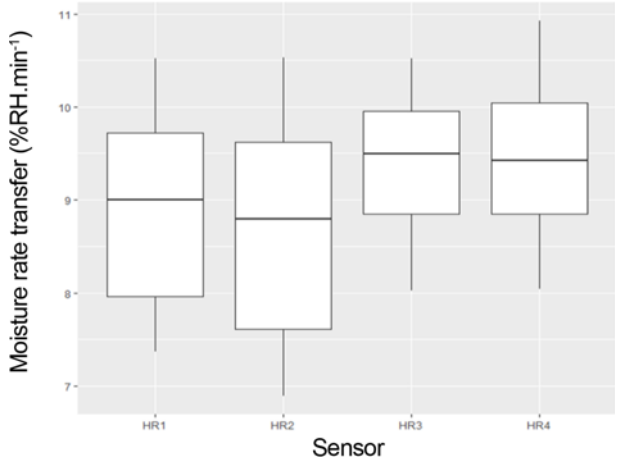


**Figure 5.** Boxplot of moisture rate transfer for each sensor.

The first linear regression (model 1), which studies the impact of physical properties of textiles, is defined according to equation (6) and the calculated coefficients are given in Table 5. The fabric design is encoded in R as a factor in which it is assigned two levels jersey and interlock.

$$Y_{Moisture\ rate\ transfer} = \beta_0 + \beta_1 \times X_{Fabric\ weight} + \beta_2 \times X_{Thickness} + \beta_3 \times X_{Moisture\ regain} + \beta_4 \times X_{Jersey\ fabric\ design} \quad (6)$$

With $\beta_0$ is the intercept, $\beta_i$ are coefficients given with the *R* software, $X_i$ are explanatory variables of the model.

The histogram, normal Q-Q plot (symmetric distribution) (Figure 6) and Shapiro tests (p-values>0.05) show that residuals follow a normal distribution which validates the application of the model 1. For a p-value greater than 0.05, observed differences are not statistically significant; between 0.20 and 0.10 the effect of parameters is low; and below 0.05 parameters are the major factor leading to moisture rate transfer variations. The moisture regain value is the only parameter to have a significant negative impact on the moisture rate transfer measurement. Thus, for a high measured value, the moisture regain value is low. For hydrophobic materials as samples containing PES fibers, fabrics have a weak affinity with water vapour molecules; they mainly pass through the material without being caught on fibers. Thus, the rate of water vapour molecules transferred from the microclimate to the external environment is faster for hydrophobic textiles than hydrophilic ones. Therefore, the measured moisture transfer rate for hydrophilic samples is lower compared to hydrophobic ones. For interlock based samples, the rate of moisture transfer value is 0.42 units higher. The influence of the fabric design (jersey or 1×1 interlock) on frame values is assessed with the function "drop1". This parameter has a low influence on the measured moisture transfer rate since the p-values are about 0.137. The model 1 is a predictive model for the data obtained from the frame by knowing the physical characteristics of fabrics.

**Table 5.** Multiple linear regression with the R software Model 1

| Model 1 | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $r^2$ | Adjusted-$r^2$ | Residual standard error | Shapiro test p-value |
|---|---|---|---|---|---|---|---|---|---|
| Coefficients | 11.4410 | -0.0004 | -0.3013 | -0.3925 | -0.4149 | 0.9112 | 0.8667 | 0.2863 | 0.1959 |
| p-values | $3.960\times10^{-6}$ | 0.952 | 0.685 | $2.920\times10^{-5}$ | 0.137 | | | | |

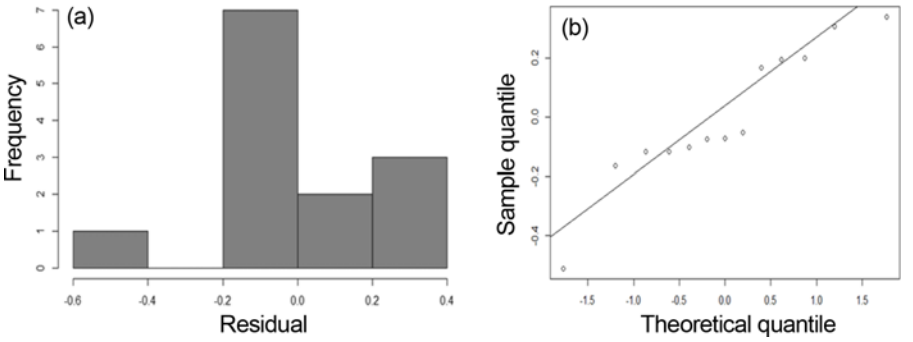


**Figure 6.** Checking of residuals normal distribution for model 1; (a) histogram of residuals and (b) normal Q-Q plot of residuals.

The model 2, which studies the influence of thermo-hydric properties on moisture transfer rate, is described according to equation (7).

$$Y_{Moisture.rate.transfer} = \beta_0' + \beta_1' \times X_{Air\ permeability} + \beta_2' \times X_{WT_{Top}} + \beta_3' \times X_R + \beta_4' \times X_{R_{ct}} + \beta_5' \times X_{W_d} \quad (7)$$

Coefficients $\beta_0, \beta_i'$ calculated are given in Table 6.

The normality of residuals is checked again by plotting the histogram and the normal Q-Q plot (Figure 7). With the Shapiro test, the p-value is higher than 0.05 which confirms that residuals follow a normal law.

The $WT_{Top}$ and R parameters of the MMT results have a low impact on the moisture rate transfer measurements. A fast desorption rate of water molecules through the textile implies a low time required to wet the surface directed towards the environment of the climatic chamber. In this case, the parameter R, characterizing the difference in liquid accumulated between the two fabric sides is important. The moisture contained in the knit fabric is easily desorbed.

**DVS Test**

The equilibrium moisture content (EMC) represents the ability of the textile fabric to store water vapor within its

**Table 6.** Multiple linear regression with the R software Model 2

| Model 2 | $\beta'_0$ | $\beta'_1$ | $\beta'_2$ | $\beta'_3$ | $\beta'_4$ | $\beta'_5$ | $r^2$ | Adjusted-$r^2$ | Residual standard error | Shapiro test p-value |
|---|---|---|---|---|---|---|---|---|---|---|
| Coefficients | 8.5480 | -0.0006 | -0.0631 | 0.0067 | -11.4464 | 6.5499 | 0.9009 | 0.6532 | 0.4715 | 0.5586 |
| p-values | 0.287 | 0.677 | 0.170 | 0.161 | 0.873 | 0.619 | | | | |

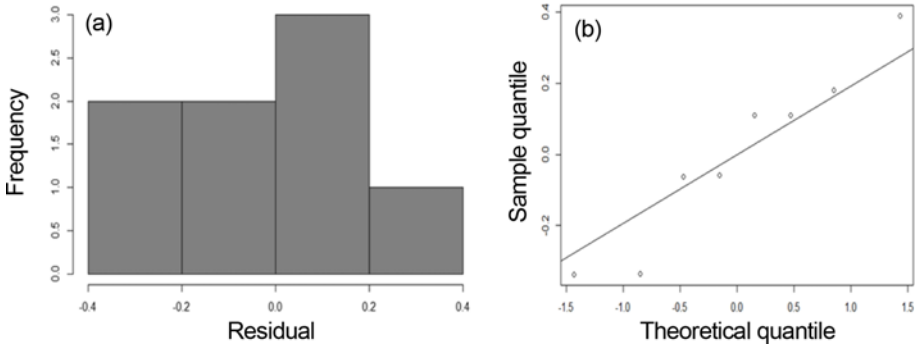


**Figure 7.** Checking of residuals normal distribution for model 2; (a) histogram of residuals and (b) normal Q-Q plot of residuals.

structure (Figure 8) during the DVS test between 0 and 98 %RH. EMC is calculated by summing the maximum amount of water taken by the textile on each humidity level. When this quantity is important it means that the fabric can sorb a relatively important amount of water molecules. Water molecules are sorbed either at the surface or inside the fabric structure in monolayer or polylayer [25]. The hysteresis area is the difference of the measured values during sorption and desorption processes; the results are presented in Table 7. Hysteresis is generally related to different phenomena such as the fibrous structure deformation or swelling, and the "ink bottle" shape of pores that can delay the release of water molecules [26]. The sample J is the one that has the most significant quantity of water vapour (EMC) and the sample A the least. Other fabrics (B, C, G, H and I) have intermediate behavior. According to Table 7, between 40 and 90 %RH, mass change and hysteresis area measured with the DVS apparatus are greater when the fabric contains hygroscopic fibers as sample J. The ability of the cotton fibers to swell at high humidity level slows down the release of water molecules during the desorption process, and lead to the calculation of a high hysteresis area. On the other hand, fabrics having a low moisture regain value (Table 1) and a high quantity of PET, have a low mass

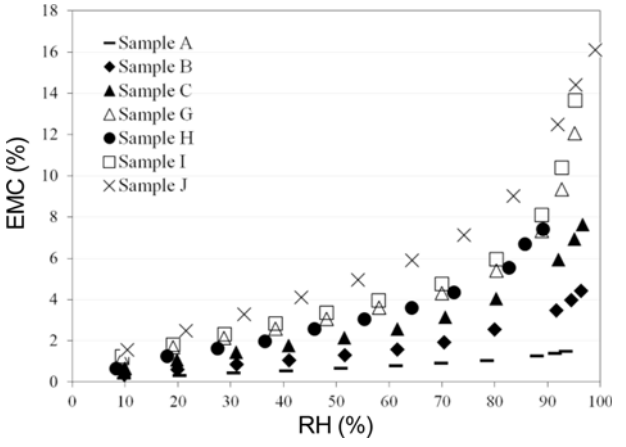


**Figure 8.** DVS results.

**Table 7.** DVS results compared to those of frame test from Table 3

| Sample code | ΔEMC (%) between 40-90 %RH | Hysteresis area | Moisture transfer rate (%RH·min$^{-1}$) |
|---|---|---|---|
| A | 0.8±0.03 | 11.2 | 10.4±0.2 |
| B | 2.4±0.2 | 45.5 | 10.1±0.3 |
| C | 4.1±0.1 | 69.3 | 9.4±0.4 |
| G | 4.7±0.1 | 44.9 | 8.6±0.4 |
| H | 4.7±0.3 | 75.3 | 9.4±0.3 |
| I | 5.3±0.2 | 63.2 | 9.0±0.4 |
| J | 8.3±0.2 | 116.1 | 8.2±0.5 |

variation (ΔEMC) and hysteresis area values, such as the sample A. This sample holds few water vapor molecules in its fibers, and the water molecules desorb quickly from the fibrous structure slightly deformed. The others samples have intermediate values in correlation with their moisture regain and depending on the nature of fibers used to make the fabric.

## Comparison between Results of Frame, DVS, $I_{mt}$, and $W_d$

### *Frame and DVS Results*

The trends of the results obtained from the frame moisture rate transfer and DVS are reversed for all the textiles samples (Table 7). For sample A, moisture rate transfer measured with the frame is significant when the mass variation and hysteresis area from the DVS test are the lowest. The moisture rate transfer from the outside environment to microclimate is fast for a textile fabric sorbing a few amounts of water vapor molecules and creates few hydrogen bonds. In this case, the available sites forming hydrogen bonds with the water molecules are quickly saturated. The hysteresis, representing the difference in water uptake between the sorption and desorption process, is low and few water molecules are held within the fibrous structure. Water molecules diffuse through the textile layer in a short period of time to be released to the surrounding. On the other hand, the moisture rate transfer measured with the frame is small while the mass variation and hysteresis area values are high with the DVS test, for samples having a strong affinity with water as fabric J. Sample's mass increases considerably because of its strong affinity with water molecules and the created numerous hydrogen bonds. Water molecules are sorbed and maintained within fibers as long as all sorption sites are not filled. Few of them pass directly through the pores of textile. Once all the sites are filled, the presence of the humidity gradient, between microclimate and the external environment, induces moisture transfer through the textile layer. Samples B, C, G, H and I exhibit an intermediate behavior.

Moisture regains (Table 1), representing the fabric affinity to water molecules, are positively correlated with DVS mass variation and hysteresis area. For a strong affinity, the mass change and hysteresis area are important and the quantity of water stored within fibers is consequent. In this case the moisture rate transfer from frame has weakest values because hydric transfer is slowed down. For samples C and H, frame values are similar but a difference is obtained for DVS results, the quantity of water vapour taken into fabric is not the same. The sensitivity of sensors from frame is lower than The DVS ones, which may explain that the humidity transfer speed does not seem to be affected by the mass variation, which is certainly not the case in the reality.

### *Impact of Fabric Design on Moisture Rate Transfer, $I_{mt}$ and $W_d$ Results*

Interlock fabrics A, B, C have a lower $W_d$ than those with

single jersey (G, H and I). Water vapour molecules are more easily trapped within the fibrous structure or sorbed to fibers surface when they pass through interlock structured fabric. In the case of a single jersey, interfibers and interfils spaces are wider, and water molecules pass easily through fabric pores without creating hydrogen bonds with the fibrous material. According to Yoon and Bucklet [27], the influence of the geometry of the textile is predominant in water vapor resistance compared to the physical properties of fibers. For a low $W_d$ value, the $I_{mt}$ index is lower for sample A. This index, measured from the skin model under stationary conditions, represents the breathability of a fabric. This characteristic describes a fabric with high thermal insulation and low resistance to the passage of water vapour. Fabric is less breathable in the case of 1×1 interlock due to the shape of its structure. Differences in $I_{mt}$ values between fabrics are small and do not allow easy discrimination between them. The frame moisture transfer rate is measured by creating a humidity gradient imposed by the climate-controlled chamber between two different environments. The delays measured when this moisture passes through the textile allow determining a transfer rate. In the case of the inverted desiccant method, moisture transfer takes place without being forced between two environments with different relative humidity rate. Measured moisture rate transfers are greater in the case of interlock fabric while $W_d$ values are lower. This parameter measured with the frame is correlated to the ability of fibers to create hydrogen bonds with water molecules rather than to the fabric design as demonsrated by the multiple linear regression. By forcing the passage of moisture through the textile, hydrophilic fibers come into contact easily with water molecules and delay their transfers to the external environment while in the case of an unforced transfer, these molecules move with limited inter-connection between them through empty spaces of fabric.

***Comparison between Methods to Discriminate Textile Behavior***

The fabrics' hydric behavior measured with DVS does not take into account the fabric design because textiles are cut into small pieces before being positioned on a precision scale. Nature of fibers will considerably influence the amount of water sorbed and desorbed during this test. In the case of the frame method, moisture rate transfer is statistically influenced by hydrophilic or hydrophobic fibers. Moisture transfer is forced and does not allow studying the impact of the fabric design. For this reason, measurements obtained with the frame are inverted correlated to DVS results. DVS and frame tests make it possible to discriminate hydric behavior of fabric according to the type of fibers composing the blend. The frame test is the most realistic one approaching wearer's conditions because it allows modeling the effect of microclimate on hydric exchanges and tests are performed dynamically. The water vapour permeability determined from desiccant inverted cup method studies hydric transfer through the textile when it is subjected to a moisture gradient. Depending on the fabric design, the $W_d$ value is different while between samples of the same structure, observed differences are minimal. When this parameter increases, the fabric capacity to store water within its fibers also rises. When the geometric structure of the textile (single jersey) allows water vapour to pass easily through it, water molecules can access to more sorption sites and increase the fabric's ability to create hydrogen bonds with them. This test can be used mainly to determine the fabric design impact on textiles hydric behavior. Samples are differentiated principally by the construction of their fibrous structure. With regard to $I_{mt}$ values obtained with the Skin model, differences observed between fabrics do not seem to depend on hydrophobic/hydrophilic fibers or on fabric design. However, this parameter increases with the area of the hysteresis. The textile's ability to let water vapour to pass through it depends on the deformation capacity of its polymer chains. This structure evolution allows molecules to penetrate easily or not within the fabric. In our case, this test provides information on the ability of textiles to deform their structure as water molecules pass through them which results in a difference in the quantity of water stored between sorption and desorption processes.

## Conclusion

The existing Skin model is instrumented in order to model the microclimate and to study the moisture transfer through the textile subjected to a dynamic humidity pulse. Moisture rate transfers, representing transfer rate of water molecules through textiles, are measured for different fabrics. By the application of a multiple linear regression on data, it is demonstrated that the fabric design, wetting time and the one way transport index have a low influence on the transfer of water vapour. Only the moisture regain has a negative statistically significant impact on this parameter. Thus, for textiles with a low value of moisture regain, measured moisture rate transfer is related to a high capacity of the textile to transmit moisture towards the outside environment. The opposite phenomenon is observed for textiles with high moisture regain. Results obtained with the frame are compared with those of DVS, desiccant inverted cup method, and $I_{mt}$ index measured with the Skin model. For DVS and frame tests, measured values depend mainly on the nature of fibers composing the textile blend. The rate of moisture transfer from the microclimate to the outside environment slows down when the textile has the capacity to store a significant quantity of water within its fibers (high $\Delta MC$). In the opposite case, moisture transfer is faster when the textile has a low affinity with water molecules which is expressed by a small variation in mass when the surrounding humidity increases. Contrary to the frame test where the transfer of humidity is forced by the climatic chamber, the

passage of water vapour molecules through fabrics for the desiccant inverted cup method relies on the fabric design. Single jersey fabrics facilitate the passage of water vapour molecules through the textile and the more compact 1×1 interlock structure reduces this capacity. The Skin Model's $I_{mt}$ parameter makes it possible to differentiate the ability of textiles to modify polymer chains arrangement as water molecules pass through them. When this deformation is significant, the breathability of the textile increases with a low resistance to moisture transfer. Thus, values obtained from the frame test make it possible to differentiate the hydric behavior of fabrics by approaching the conditions of wearer.

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