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Thermal Effusivity Assessment of Sportswear Fabrics in the Dry State: Stacked and Air-Hoop Methods

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ABSTRACT

In recent years, thermal effusivity, a property that describes the warm or cool touch perception, has gained significant attention in the apparel industry as it contributes to human thermophysiological comfort. The current study aims to explore the thermal effusivity of 27 sportswear fabrics, including woven and knitted structures with various fiber contents, using the stacked method (according to ASTM D7984-21) and a modified air-hoop method. The results obtained revealed that the pressure range specified in ASTM D7984-21 (10 to 50 kPa) may cause fabric compression, resulting in the measurement of a material-based thermal effusivity rather than the fabric thermal effusivity. A pressure of 1 kPa was found to be more appropriate for obtaining accurate measurements of sportswear fabrics without altering their three-dimensional structure. Furthermore, a strong correlation was observed between the stacked and air-hoop methods for fabrics with thicknesses close to or greater than 0.4 mm. The air-hoop method simulates the configuration when the fabric is worn as part of a garment. The new knowledge provided by this research will enhance the accuracy of the thermal effusivity measurement of sportswear fabrics. It will contribute to the development of more comfortable fabrics considering realistic garment use scenarios.

Keywords

Thermal effusivity, Sportswear fabrics, Thermophysiological comfort, Fabric compressibility

Introduction

The measurement of thermal effusivity has recently gained substantial attention in the clothing, cosmetics, automotive, and medical industry as it influences human thermal comfort perception[1-5]. When touching an object at a certain temperature, the human body's thermoreceptors on the skin may sense a temperature drop due to heat absorption by the object[6]. The ability of a material at a lower temperature to absorb thermal energy from a warmer region (e.g., the human skin) is referred to as thermal effusivity (or absorptivity)[7]. Accordingly, it determines the thermal (i.e., warm or cool) touch perception of materials under specific ambient conditions[8]. For instance, a t-shirt made of cotton might provide a cooler touch perception than a

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t-shirt made of polyester with the same structural features under the same conditions due to the higher thermal effusivity of cotton fibers[9].

When wearing clothes, heat transfer occurs between the human body and the environment through the clothing ensemble[10]. The traditional way of measuring the heat transfer characteristics of fabrics is via the dry thermal resistance, which determines the clothing heat transfer property under steady-state conditions[11]. Steady-state heat transfer occurs when the temperature gradient is constant on both sides of the cloth, i.e., when the amount of heat entering the fabric from one side (e.g., the side touching the skin) and the amount of heat leaving from the other side (e.g., the side is exposed to air) are equal[12]. Transient heat transfer through the fabric is observed before reaching the steady state; the amount of heat entering and leaving the cloth are not equal. Heat transfer can take place during sports activities for instance. The human body generates metabolic heat and sweat, which undergoes condensation, absorption, evaporation, and wicking in the fabric. All these mechanisms contribute to heat flow through the fabric, which can be transient or steady state depending on the net result of the system. The thermal touch perception of fabric materials originates from the transient heat transfer at the skin-cloth interface and is described as the thermal effusivity of fabrics in literature[13].

The first attempt to determine the thermal energy transfer through textile fabrics was made in 1930 by Marsh[13]. They developed an instrument to measure the thermal absorption of fabrics, which consisted of a copper cylinder surrounded by a guard ring. During the experiment, the fabric specimen was mounted on the top of the copper cylinder. The cylinder was powered so that its temperature reached skin temperature. The fabric thermal absorption was estimated from the amount of electrical energy needed to maintain the temperature in the copper cylinder at a constant value. During the 1970s, Kawabata and Akagi did some groundbreaking work to determine the thermal touch perception of textiles[13, 15]. They developed an instrument that was capable of estimating the maximum heat flux (Q_{max}) through fabrics due to transient heat transfer. Further development led to an instrument named Thermolabo that could measure Q_{max} at 0.2 sec after establishing the contact between the fabric and the sensor[12]. Yoneda and Kawabata[16] showed that Q_{max} and the heat diffusion rate (λ) between the skin and the fabric (Equation 1) have a strong positive correlation. They associated λ with the cool touch property of the fabric.

$$\lambda = \sqrt{((\rho . Cp . K)/\alpha_0))} \quad \textbf{(1)}$$

Here K is the thermal conductivity, ρ the material density, and C_p the specific heat capacity. The authors defined α_0 as the heat content per unit contact area.

Obata modified Equation 1 to yield what is defined as the thermal effusivity E and is provided as Equation 2[17].

$$E = \sqrt{(\rho . Cp . K)} \quad \textbf{(2)}$$

A higher value of thermal effusivity implies a superior cool touch perception. The first thermal effusivity sensor was developed by Mathis in the late 1990s[13]. A modified version of this sensor called the MTPS (Modified Transient Plane Source) sensor was produced by Emanuel in 2001. The working principle of the MTPS thermal effusivity sensor is different from that of the

Q_{max} sensor. The MTPS measures the temperature change at the interface between the sensor and the fabric specimen, which corresponds to what skin thermoreceptors would perceive[18].

Several studies have assessed the thermal effusivity of fabrics as a part of their research program. For instance, Bedek et al.[1] characterized the thermal effusivity of knitted fabrics using Q_{max} measured under 1 gf/cm^2 pressure with a temperature difference of 10°C between the sensor and the cloth. Their study found that the thermal effusivity of knitted fabrics had a strong positive correlation with the thermal conductivity, while it had a strong negative correlation with the water vapor permeability index (as described in ISO 11092). Pavlović et al.[12] theoretically estimated the thermal effusivity of fabrics made of natural (i.e., cotton and hemp) and regenerated (i.e., viscose) fibers using Equation 1. The results revealed that a fabric made of a blend of cotton/hemp fibers exhibited a higher thermal effusivity than other blends as well as mono-fiber compositions. In contrast, the experimental work of Komárková, Glombíková, and Havelka[9] using the MTPS system showed that an increased proportion of cotton fibers in the blend led to superior thermal effusivity for socks made of various cotton/synthetic fiber blends. Abu-Rous[19] reported that the presence of regenerated cellulosic fiber in the fabric system increased thermal effusivity of blended fabrics due to the high moisture regain of fibers.

Marolleau et al.[20] measured the thermal comfort properties of 1x1 interlock knitted fabrics while varying the fabric thickness and mass per unit area (g/m^2). The study found that fabric thickness and air permeability were negatively correlated with thermal effusivity measured using a hot circular plate, while fabric mass and porosity did not show any association with it. Guru and Choudhary[21] investigated the effect of chemical finishes (i.e., moisture management, UV resistance, anti-microbial, and soil-release finishes) on the thermal effusivity of sportswear knit products. The fabrics with a moisture management finish displayed superior thermal effusivity. Siddique et al.[22] explored the thermal effusivity of compression socks at different states of elongation in the elastic range (from 0 to 70%) using the MTPS sensor. Some compression socks exhibited an increase, while others exhibited a decrease in thermal effusivity with elongation.

Sokolowski et al.[13] investigated the thermal effusivity of sportswear T-shirt fabrics made of knit structures. The thermal effusivity of fabrics was assessed using the MTPS sensor under a 50 kPa pressure and stacking layers of fabrics to reach a 1-mm thick assembly following the ASTM D7984-21 standard test method. They found that the t-shirt sportswear fabrics had significantly different thermal effusivity values if they placed the technical face or backside up. The study also showed that fabric mass per unit area was a significant predictor of thermal effusivity, whereas fabric thickness was not a significant predictor of it. Abu-Rous et al.[23] conducted a comparative study of the thermal effusivity of various woven and knit fabrics using four different types of apparatus: (i) the Thermal Effusivity Tester (TET) developed by Lenzing AG, (ii) Alambeta, (iii) TCi Thermal Conductivity Analyzer, and (iv) Kawabata KES-F instrument. For most fabrics except for the thickest ones, the study revealed a satisfactory agreement in terms of thermal effusivity result between these different techniques. The discrepancy observed for the thickest fabrics was attributed to variations in the pressure applied on the fabric specimens during the test.

Despite all the above, some concerns remain regarding the standard test method and how it can quantify fabrics' thermal effusivity in a manner that is relevant to garments in use. First, as fabrics are highly compressible, it is critical to ensure that the pressure applied on the fabric specimen during the test - 10 kPa to 50 kPa according to the standard[8] - does not affect its 3D structure, including its porosity. However, the effect of pressure on the thermal effusivity has not been discussed in previous studies. Most studies have conducted the thermal effusivity experiment using the pressure range specified by the standard (ASTM D7984-21). Second, since several layers of fabric generally have to be stacked to reach the minimum of 1 mm thickness specified for the test to be conducted, it is important to verify that the heat transfer at the interface between the layers does not affect the thermal effusivity measurement. Third, in the configuration used in the standard test method, the fabric stack is sandwiched between the sensor and a solid presser foot. However, when clothes are worn, one side is in contact with the skin while the other side is exposed to the ambient air.

With the aim of addressing these research gaps, the current study investigated the effect of pressure and number of stacked layers on the thermal effusivity results measured using the stacked method for a series of sportswear fabrics, revealing issues with the test conditions mentioned in the corresponding standard test method. We also explored a novel thermal effusivity measurement technique, the air-hoop method, that allows characterizing the thermal effusivity of sportswear fabrics in a configuration that is closer to the scenario when fabrics are worn as part of the single-layer garment.

Materials and Methods

MATERIALS

A total of 27 commercial sportswear fabrics, including both woven and knit structures, were obtained. These fabrics are used for single-layer sports garments, specifically for yoga, running, exercising, and training. The information related to the fiber composition, fabric structural feature, fabric count, mass per unit area, thickness, and porosity are listed in Table 1.

TABLE 1. Fabric characteristics

Fabric Code	Fiber content	Structure	Fabric count (yarn/cm)		Mass per unit area (g/m^2)	Thickness (mm)	Porosity (%)
			Warp/ wale	Weft/ course			
F1	86% Polyester, 14% Elastane	Plain (woven)	50	40	127 ± 3	0.349 ± 0.004	72
F2	51% Nylon, 38% Polyester, 8% Elastane, 3% X-static®	Single jersey (weft knit)	16	38	134 ± 2	0.45 ± 0.01	76
F3	71% Pima cotton, 24% Lyocell regenerated cellulose, 5% Elastane	Single jersey (weft knit)	18	26	180 ± 4	0.67 + 0.01	82
F4	82% Nylon, 18% Elastane	Single jersey (weft knit)	15	26	326 ± 3	0.90 + 0.01	70
F5	91% Nylon, 9% Elastane	Single jersey (weft knit)	14	26	238 ± 5	0.81 ± 0.01	75
F6	60% Recycled polyester, 33% Nylon, 2% X-static®, 5% Elastane	Single jersey (weft knit)	13	25	175 ± 2	0.66 ± 0.01	80

F7	81% Nylon, 19% Elastane	Interlock (weft knit)	23	34	234 ± 3	0.80 ± 0.01	75
F8	77% Nylon, 23% Elastane	Single jersey (weft knit)	19	38	250 ± 2	0.66 ± 0.00	68
F9	56% Polyester, 33% Coolmax®, 11% Elastane	Single jersey (weft knit)	16	22	141 ± 2	0.50 ± 0.01	79
F10	82% Nylon, 18% Elastane	Interlock (weft knit)	22	32	240 ± 4	0.90 ± 0.01	78
F11	69% Nylon, 31% Elastane	Interlock (weft knit)	17	34	223 ± 7	0.65 ± 0.01	72
F12	40% Pima cotton, 37% Nylon, 13% Lyocell regenerated cellulose, 10% Elastane	Single jersey (weft knit)	17	26	166 ± 2	0.45 ± 0.01	73
F13	92% Pima cotton, 8% Elastane	Single jersey (weft knit)	15	26	131 ± 3	0.54 ± 0.01	84
F14	87% Nylon, 13% Elastane	Single jersey (weft knit)	24	34	199 ± 3	0.58 ± 0.01	71
F15	82% Polyester, 18% Elastane	Tricot (warp knit)	16	18	126 ± 3	0.46 ± 0.01	80

F16	100% Recycled polyester	Plain (woven)	72	60	61 ± 1	0.083 ± 0.003	47
F17	84% Nylon, 16% Elastane	Interlock (weft knit)	31	38	212 ± 2	0.61 ± 0.01	71
F18	83% Nylon, 17% Elastane	Interlock (weft knit)	32	36	202 ± 4	0.64 ± 0.01	73
F19	54% Nylon, 40% Recycled polyester, 3% Elastane, 3% X-static®	Single jersey (weft knit)	16	27	161 ± 2	0.68 ± 0.01	81
F20	49% Nylon, 43% Recycled polyester, 4% Elastane, 4% X-static®	Single jersey (weft knit)	15	25	143 ± 3	0.66 ± 0.01	83
F21	60% Nylon, 38% Wool, 2% Elastane	Jacquard (weft knit)	11	18	674 ± 9	2.19 ± 0.02	75
F22	77% Nylon, 23% Elastane	Interlock (weft knit)	24	47	251 ± 3	0.72 ± 0.01	71
F23	91% Polyester, 9% Elastane	Jacquard (woven)	58	32	216 ± 2	0.60 ± 0.01	74
F24	100% Polyester	Single jersey (weft knit)	23	34	108 ± 1	0.40 ± 0.01	81

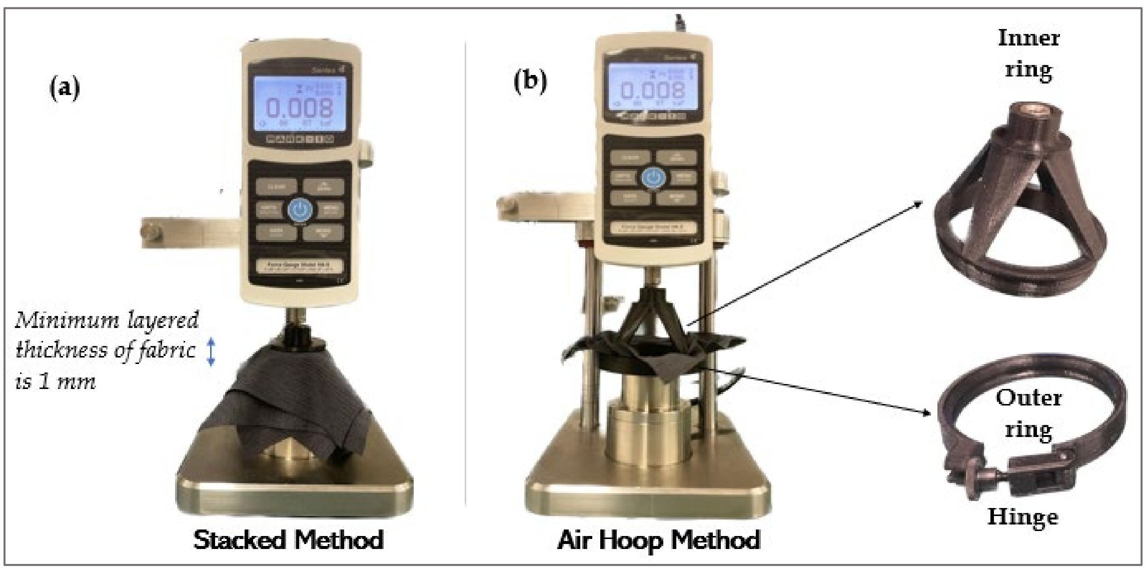
F25	53% Elastomultiester polyester, 47% Recycled polyester	Interlock (weft knit)	13	22	229 ± 3	0.513 ± 0.004	67
F26	53% Elastomultiester polyester, 47% Recycled polyester	Interlock (weft knit)	13	22	225 ± 3	0.50 ± 0.01	67
F27	70% Cotton, 30% Polyester	Single jersey (weft knit)	9	13	322 ± 4	1.63 ± 0.02	86

TEST METHOD

Thermal effusivity

The thermal effusivity of fabrics was evaluated using a modified transient Plane Source (MTPS) instrument (TCi-3-A, C-Therm, Canada) following ASTM D7984-21[8]. This standard specifies the use of the stacked method for the measurement. After being conditioned at 20°C and 65% RH, several layers of the same fabric are mounted over the MTPS sensor to make the stack height at least 1 mm (Figure 1a), which corresponds to the size of the heat pulse released from the sensor toward the fabric specimen. The presser foot of the pressure gauge is lowered to apply a certain pressure on the specimen stack. The standard specifies that this pressure should be between 10 and 50 kPa. In this study, we also explored the use of lower values of the pressure applied on the specimen stack, down to 0.5 kPa. Then, the thermal effusivity measurement is performed. The MTPS equipment also provides a measurement of the thermal conductivity of the fabrics.

FIGURE 1. Thermal effusivity measurement setup for (a) stacked and (b) air-hoop method.



Tests were also conducted using the air-hoop (Figure 1b), which only requires one layer of fabric for the measurement of thermal effusivity. The side of the specimen not in contact with the MTPS sensor is exposed to ambient air. While securing the specimen in the air-hoop frame, great care was taken to avoid applying any stretch to the fabric. Different values of pressure between 0.5 and 2 kPa were applied for the measurement using the air-hoop. The specimens were positioned so that the technical back of the fabric was in contact with the MTPS sensor. For the measurement, the instrument was located in a room at 20°C and 65% RH.

Fabric structure and count

Fabric structure and count were assessed using a stereomicroscope (Stemi 508, Zeiss, Germany). The fabric specimen was placed on a transparent platform and observed in reflection and transmission light mode. Each fabric was observed at five different locations.

Fabric mass per unit area

The fabric mass per unit area was determined in accordance with ASTM D3776–20[24]. Fabric specimens were cut in 10cm × 10cm dimensions, and no two replicates were from the same set of warp/wale and weft/course. The specimens were conditioned at 20°C and 65% RH for a minimum of 24 hours and then weighed using a high-precision balance scale (PM2500 DeltaRange®, Mettler Toledo, Switzerland). Five replicates were measured for each fabric.

Fabric thickness

Fabric thickness was measured using a thickness tester (CS-55, Custom Scientific Instruments Inc, USA) under a 1 kPa pressure following the CAN/CGSB-4.2 No. 37 standard test method[25]. The thickness values were obtained in inches and converted into mm. Five replicates were measured for each fabric.

Compressive strain

Fabric compressive strain was measured using a thermomechanical analyzer (TMA Q400, TA Instrument, USA) at 25°C with a 2.80-mm diameter probe. The measurement was performed by increasing the pressure applied on the fabric specimen up to 50 kPa at a rate of 0.0001 kPa.min^{-1}. The compressive strain was calculated using Equation 3. Three replicates were measured for each fabric.

$$Compressive\ strain = \frac{Intial\ thickness - Thickness\ at\ load}{Initial\ thickness} \quad \textbf{(3)}$$

Fabric porosity

The volumetric porosity (ε_p) of the fabrics was estimated using Equation 4[26]. The term volumetric porosity refers to the volume of void space in the fabric structure divided by the total volume of the fabric. This void space includes the void spaces in fibers, yarns, and fabric. The range of fabric porosity is $0 < \varepsilon_p < 1$. ε_p close to zero represents an almost non-porous fabric structure, while ε_p close to 1 indicates a highly porous fabric structure. In Equation 4, ρ_{Fabric} represents the fabric density, which was estimated from the fabric mass per unit area divided by the thickness. The fiber density (ρ_{Fiber}) was estimated from the weighted average of the density of the different fibers present in fabrics using the fiber content values in Table 1.

$$\varepsilon_p = 1 - \frac{\rho_{Fabric}}{\rho_{Fiber}} \quad \textbf{(4)}$$

Statistical analysis

Different statistical analyses were conducted, such as ANOVA, correlation analysis, linear regression, and moderation analysis[27], to support the discussion. A significant level of .05 was used. ANOVA was conducted to explore whether there was a significant difference in thermal effusivity results among various groups. For the reliable interpretation of results, the underlying conditions of ANOVA (such as normal distribution of data and homogeneity of variance) were confirmed. The one-tailed Pearson's correlational analysis was carried out to study the relationship between thermal effusivity and fabrics' physical properties. This analysis reveals the type of relationship between variables (positive or negative), the strength of that relationship (from Pearson's correlation coefficient, r), and the significance level of the correlation. It was verified that the four requirements of Pearson's correlational analysis were satisfied: (a) interval or ratio data types, (b) linear relationship between variables, (c) absence of outliers, and (d) normally distributed data.

Linear regressions were performed to find the best-fit trendline between the stack and air-hoop methods. It was verified that the linear regression analysis assumptions (such as independence of error, normal distribution of residual errors, homoscedasticity, multicollinearity, linearity, and non-zero variance) were satisfied[27]. Lastly, moderation analysis was conducted to explore the effect of a third variable (i.e., fabric thickness) on the relationship between the two other variables (i.e., stack and air-hoop methods). The assumptions of the moderation analysis were also validated before running the analysis. The moderation analysis is a type of linear regression, so it has the same underlying assumptions as linear regression.

Results

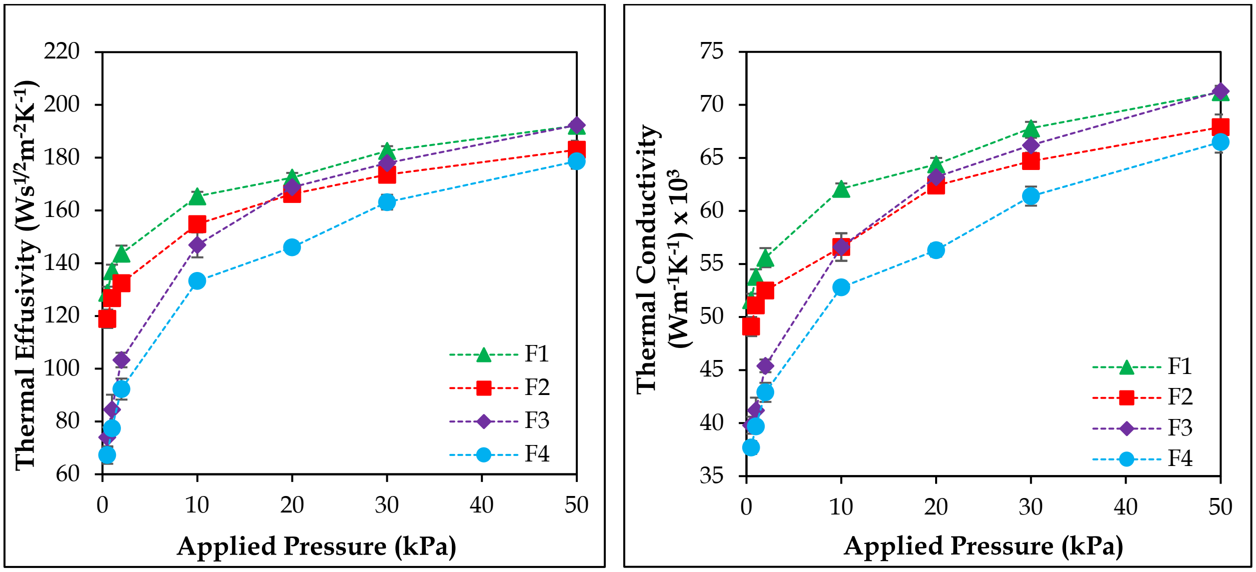
THERMAL EFFUSIVITY OF SPORTSWEAR FABRICS BY THE STACKED METHOD

Effect of applied pressure

Four fabrics (F1, F2, F3, and F4) corresponding to two types of fabric structures (woven and knitted) and a wide range of masses per unit area (127 to 326 g/m^2) were selected to study the effect of the pressure applied by the presser foot on the fabric stack on the effusivity results. The values of applied pressure used covered the 10 to 50 kPa range specified in the ASTM D7984-21 standard test method[8]. Pressures lower than 10 kPa were also included in the test matrix.

Figure 2a shows the variation of the thermal effusivity results of these four fabrics (F1, F2, F3, and F4) as a function of the pressure. Because these fabrics had different thicknesses, the number of layers in the stack varied depending on the fabric: three layers were used for Fabric F1 and F2, and two layers were used for Fabric F3 and F4. The results indicate that the thermal effusivity of these four fabrics increased with the pressure applied. The same trend was observed for the thermal conductivity to which thermal effusivity is related, as described in Equation 2 (Figure 2b). This trend in the variation of thermal conductivity with applied pressure can be attributed to the fact that fabrics are compressible[28]. The compressibility of fabrics (such as woven, knit, spacer, nonwoven, and sponge fabrics) generally ranges between 16 and 88%[29]. When the applied pressure increases, the density of the fabric increases due to the decrease in the fabric thickness. As a result, the size of the air-containing pores in the fabric is reduced. Air has a lower thermal conductivity compared to fiber materials[30]. This could explain why the thermal conductivity measured on the four fabrics at low applied pressure is lower compared to the thermal conductivity under higher applied pressure.

FIGURE 2. Effect of applied pressure on (a) thermal effusivity and (b) thermal conductivity of Fabric F1, F2, F3, and F4 using the stacked method



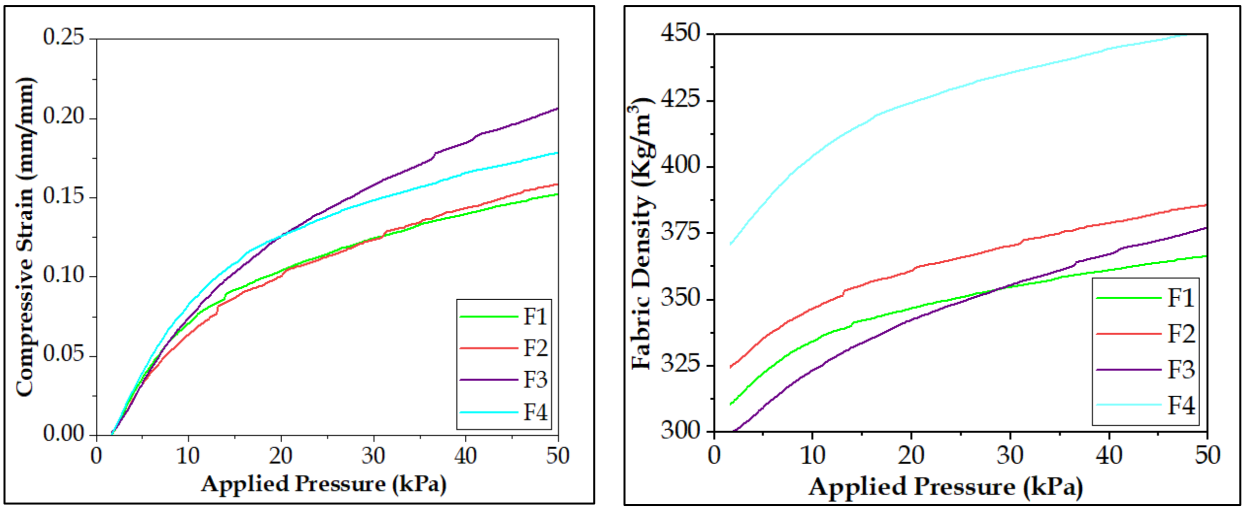
(a) (b)

Another observation when looking at the data in Figure 2 is that there is a change in the fabric ranking between the low and high applied pressure regimes. More specifically, Fabric F3 has the second lowest values of thermal effusivity and conductivity below 10 kPa, while it has the highest value at 50 kPa. On the other hand, the other fabrics kept the same ranking over the range of applied pressures used: F4 was the lowest and F1 was the highest between F1, F2, and F4.

In order to determine the reason for this change in the ranking of the four fabrics' thermal effusivity at the different applied pressures, compressibility tests were conducted using TMA. Figure 3a shows the results in terms of compressive strain for the four fabrics between 0 and 50 kPa. It is observed that F3 had the highest compressive strain above 20 kPa. This suggests that F3 is more compressible than the other three fabrics. As a result, the air is more readily expelled from Fabric F3 when high pressure is applied on the fabric stack by the presser foot. This can also be observed from the increase in the fabric density, computed from the TMA data, as a function of applied pressure (Figure 3b). As a result, Fabric F3's thermal effusivity and conductivity experience a larger increase with increased applied pressure than the three other fabrics.

Fabric F3 had the highest thermal effusivity and conductivity values at 50 kPa applied pressure. This result can be related to the difference in fiber content between the four fabrics. Fabric F3 includes 71% cotton fibers, while the three other fabrics are made of a combination of synthetic and regenerated cellulose fibers, such as polyester, nylon, elastane, lyocell, and X-static®. Previous studies have reported that cotton fibers exhibit high thermal conductivity and effusivity compared to synthetic and regenerated cellulose fibers due to the high crystallinity of cotton fibers[9, 31-32]. The highest thermal effusivity and conductivity values exhibited by Fabric F3 at 50 kPa pressure can thus be attributed to the higher thermal effusivity and conductivity of cotton fibers. This shows that, as air trapped in the fabric's structure is expelled at high applied pressure, the thermal effusivity experiment provides a measurement of the material-based thermal effusivity rather than the fabric's thermal effusivity.

FIGURE 3. (a) Compressive strain and (b) calculated change in density of Fabric F1, F2, F3, and F4 under 0 to 50 kPa applied pressures.



(a) (b)

However, the amount of applied pressure used to conduct the thermal effusivity experiment should mimic the pressure level of textiles during use. For instance, an applied pressure of 13.8 kPa was used to simulate the compression experienced by firefighters' protective clothing while in operation[33]. Mirjalili et al. reported that the contact pressure between the human body and the cloth layer usually varies between 1 to 2 kPa[34]. Clothing pressure up to 1.5 kPa was identified as comfortable[35].

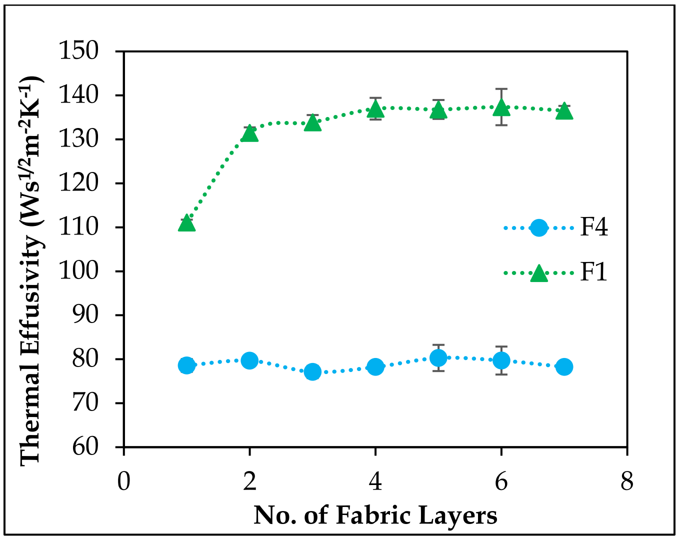
In the case of sportswear fabrics, they mostly drape over the body with a minimum level of stress[36-37]. The lowest value of applied pressure tested here for the thermal effusivity measurement was 0.5 kPa. However, at this value of applied pressure, the presser foot was not able to create proper contact between the fabric specimen and the MTPS sensor. The lowest applied pressure providing consistent thermal effusivity measurements was 1 kPa. This is the same pressure recommended for fabric thickness measurement in the CAN/CGSB-4.2, No. 37 standard test method[25]. As this applied pressure of 1 kPa represents the best compromise between the need to have good contact between the fabric and the MTPS sensor and the preservation of the fabric's 3D structure, we have used this value for the thermal effusivity measurements using the stacked method presented in the next sections of this article.

Effect of the number of layers in the stack

Measurements were conducted to determine the effect of the number of layers of Fabric F1 and F4 in the specimen stack on the thermal effusivity results under 1 kPa applied pressure. These two fabrics were selected as they correspond to two extreme fabric thicknesses among the four fabrics, with Fabric F1 being 0.349 mm thick and Fabric F4 being 0.90 mm thick. Figure 4 shows the thermal effusivity results when the number of layers varied between one and seven.

In the case of Fabric F4, the thermal effusivity values were not affected by the number of layers in the stack (ANOVA: $p = .158$). This can be attributed to the fact that the fabric thickness is very close to the penetration depth of the pulse released from the MTPS sensor, which is approximately 1 mm (ASTM D7984, 2021). On the other hand, the thermal effusivity of Fabric F1 strongly increased between one and two layers and then appeared to reach a plateau for stacks of three layers and more (ANOVA: $p = .237$). This indicates that at least three layers of Fabric F1 are needed to match the penetration of depth of the heat pulse released from the MTPS sensor.

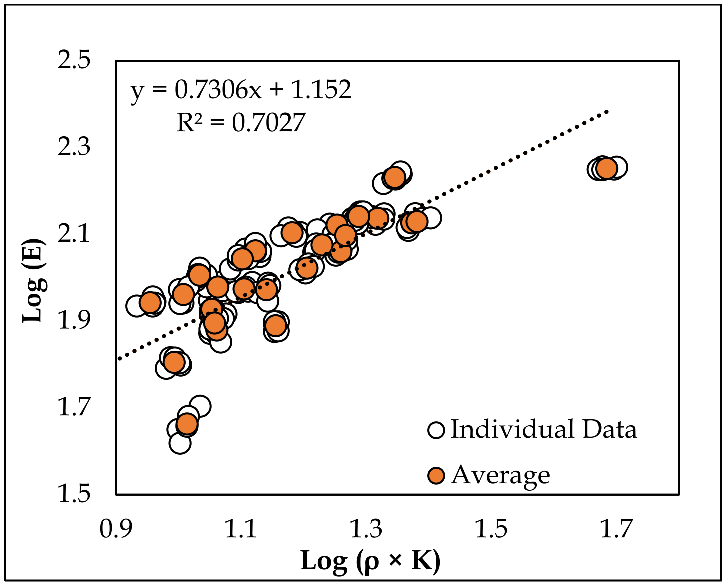
FIGURE 4. Effect of the number of fabric layers stacked on the thermal effusivity results



Effect of fabric density

The thermal effusivity of the 27 fabrics listed in Table 1 was measured using the stacked method under an applied pressure of 1 kPa. Figure 5 displays the variation of the log of the thermal effusivity of these 27 fabrics as a function of the log of the product of the fabric density and thermal conductivity based on Equation 2. In this equation, the thermal effusivity is related to the square root of the product of the fabric density, thermal conductivity, and heat capacity. The value of thermal conductivity was provided by the MTPS instrument. The density of these 27 fabrics was calculated from the mass per unit area divided by the fabric thickness. The data in Figure 5 can be described relatively well by a linear fit. The slope of the linear fit has a value close to 0.7, which differs from the value of 0.5 expected from Equation 2. This deviation can possibly be attributed to the fact that the heat capacity of the different fabrics has not been taken into account in the data plotted in Figure 5. As the heat capacity of fabrics is mainly controlled by their fiber content and fabric structure[32, 38], variations are expected between the 27 fabrics. However, the fact that the coefficient of determination for the fitting curve is equal to 70% indicates that 70% of the thermal effusivity value can be attributed to the product of the fabric density and thermal conductivity. The remaining 30% variation can be ascribed to the fabric heat capacity, which is controlled by the fabric textile properties, such as fiber content, type of yarn and geometry, and fabric structure [32, 38-39].

FIGURE 5. Variation of the log of the thermal effusivity (log (E)) as a function of the log of the product of the fabric density by the thermal conductivity (log (ρ × K)) for 27 fabrics measured under 1 kPa applied pressure using the stacked method.

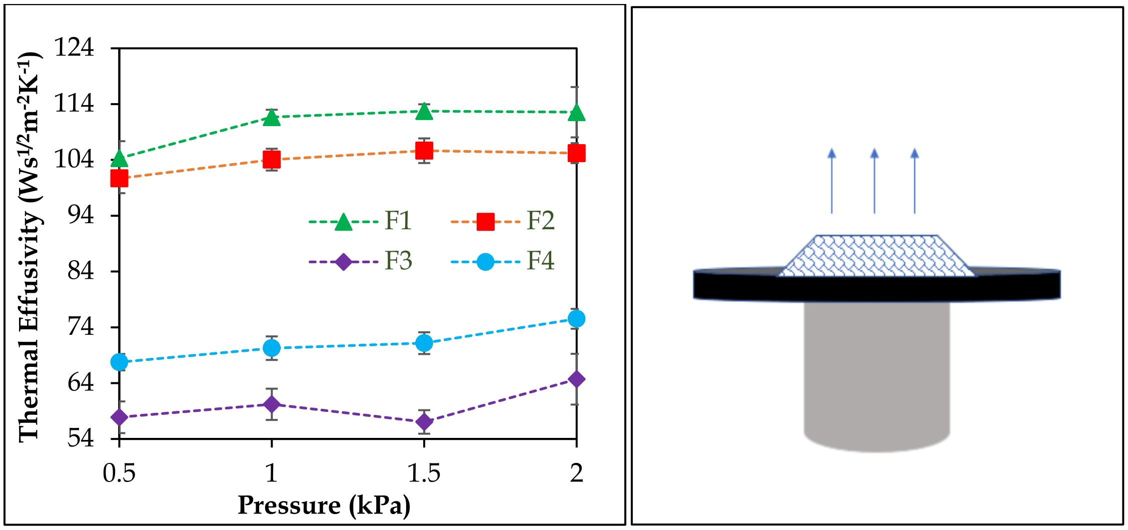


THERMAL EFFUSIVITY OF SPORTSWEAR FABRICS BY THE AIR-HOOP METHOD

Effect of applied pressure

The effect of the applied pressure was also studied with Fabric F1, F2, F3, and F4 using the air-hoop method. Four values of applied pressure between the fabric specimen secured in the air-hoop and the MTPS sensor were used: 2 kPa, 1.5 kPa, 1 kPa, and 0.5 kPa. The results are shown in Figure 6a. The highest contact pressure to measure the thermal effusivity using the air-hoop method was 2 kPa, as higher pressures caused some fabrics to stretch (Figure 6b). This stretching would affect the fabric's porosity[40-41] and thermal effusivity. In fact, even at 2 kPa, Fabric F3 and F4 showed an increase in thermal effusivity, which can potentially be caused by some level of fabric stretching. These two fabrics were observed to be stretchier compared to Fabric F1 and F2.

FIGURE 6. (a) Variation of the thermal effusivity of Fabric F1, F2, F3, and F4 using the air-hoop method as a function of the applied pressure, and (b) schematic representation of a fabric being stretched by the MTPS sensor in the air-hoop under high applied pressure.



(a) (b)

On the other side of the pressure range, it was observed that an applied pressure of 0.5 kPa did not allow the fabric to create proper contact with the MTPS sensor. In all instances, a decrease in thermal effusivity was recorded, which would be caused by the inefficient heat transfer between the sensor and the fabric.

Similar to what was proposed for the stacked method, a pressure of 1 kPa thus appears as the optimal value for conducting thermal effusivity measurements of fabrics using the air-hoop method, as this pressure offers the best compromise between the need to have good contact between the fabric and the MTPS sensor and the importance of avoiding stretching the fabric.

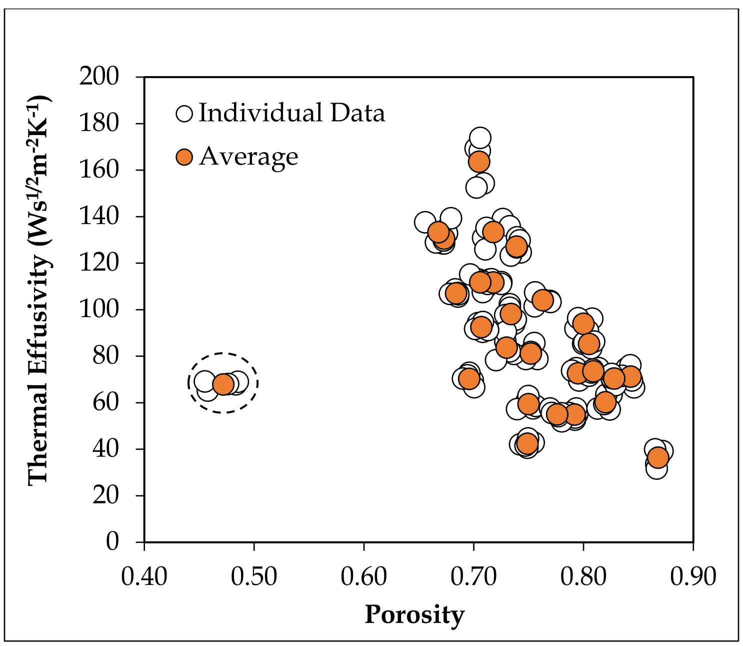
Effect of fabric porosity

As fabric porosity can play an important role in thermal effusivity[42], the thermal effusivity values measured using the air-hoop method for the 27 fabrics listed in Table 1 were expressed as a function of the fabric porosity (Figure 7). The porosity of these 27 fabrics was calculated from the fabrics' density using Equation 4.

Figure 7 shows that the porosity and thermal effusivity of 26 out of these 27 fabrics have a strong negative correlation ($r = -0.667$; $p < .001$) irrespective of their fiber content, type of yarn, fabric structure, nature of finish, etc. Despite the fact that fabric porosity originates from micro, meso, and other macro-level properties, such as fiber type, yarn density, fabric structure, etc.[5,43], it is a macro-level textile property that appears as an overarching parameter that controls thermal effusivity. In terms of the negative correlation between the fabric porosity and thermal effusivity, it can be attributed to the fact that fabrics with low porosity contain less air[44] and thus have higher thermal conductivity, to which thermal effusivity is correlated through Equation 2. In addition, since one side of the fabric is in contact with the ambient air in the air-hoop method, another phenomenon may play a role. If low porosity is associated with small pore size, air movement by convection through the fabric may be restricted, which limits the thermal energy exchange between the human skin symbolized by the MTPS sensor and the fabric[45-46]. Previous researchers reported an absence of the effect of fabric porosity on thermal effusivity[1, 20]. However, the experimental techniques, specimen boundary conditions, and applied pressures were different, which may explain this apparent discrepancy in the findings.

One fabric, F16, stands out as an outlier (black dotted circle in **Fig. 7).** This fabric has a very low thickness (0.083 mm) compared to the other fabrics (thicknesses between 0.349 and 2.19 mm). When the fabric thickness is much lower than the penetration depth of the MTPS sensor pulse, which is approximately 1 mm[8], only a small proportion of the heat pulse is absorbed by the fabric; the rest of the heat pulse ends up being absorbed by the air layer on the other side of the fabric. Therefore, the fact that the thermal effusivity result for Fabric F16 does not follow the same trend as the other fabrics is possibly due to its very low thickness.

FIGURE 7. Effect of the fabric porosity on the thermal effusivity measured using the air-hoop method



CORRELATION BETWEEN THE STACKED AND AIR-HOOP METHODS

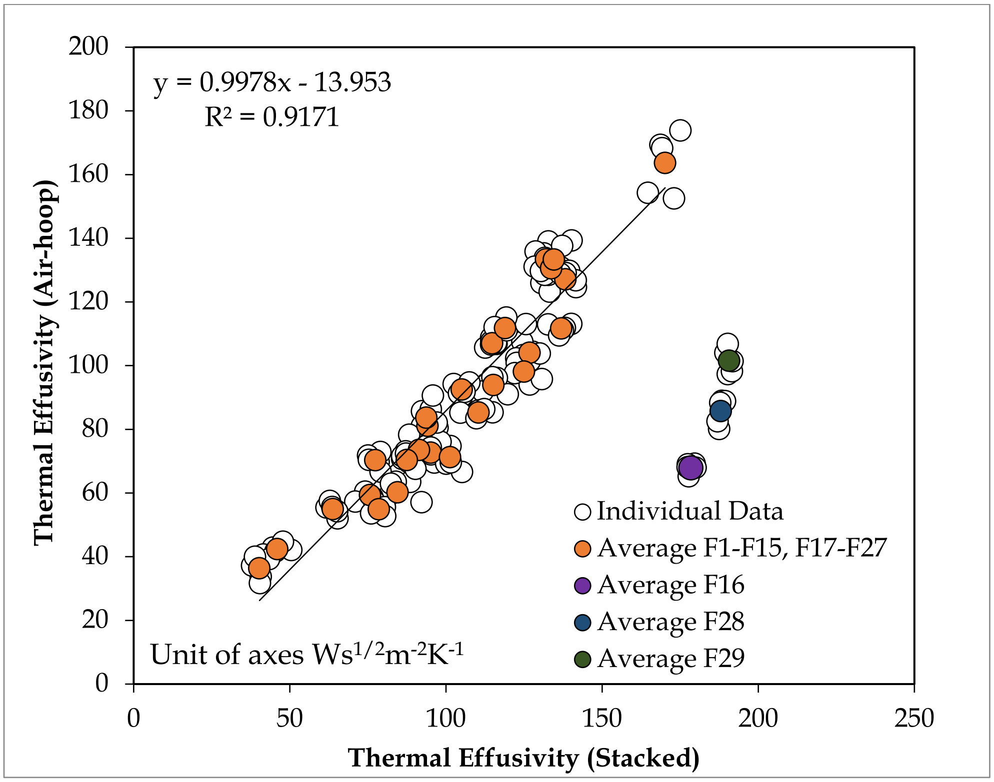
Figure 8 shows the correlation between the thermal effusivity results for the 27 fabrics measured under a 1 kPa applied pressure using the stacked and air-hoop methods. The data follow a strong positive linear relationship ($R^2 = 0.92$) for all the fabrics except Fabric F16. Similar to what has been discussed regarding the correlation between the thermal effusivity measured with the air-hoop and the fabric porosity, this discrepancy observed for Fabric F16 can possibly be associated with its very low thickness (0.083 mm) compared to the heat pulse penetration depth.

To validate this hypothesis, thermal effusivity measurements were conducted with two other very thin fabrics (shown as F28 and F29 in Figure 8). Information regarding the fiber composition, fabric structure, fabric count, mass per unit area, and thickness of Fabric F28 and F29 is provided in Table 2. F28 was 0.101 mm thick, and F29 was 0.127 mm thick. As Figure 8 shows, the results for these two other very thin fabrics are also located outside of the linear trend observed between the thermal effusivity values measured by the stacked and air hood methods for the 26 fabrics with a thickness of 0.349 mm and above. This confirms the hypothesis that there is a fabric thickness effect on the measurement of thermal effusivity using the air-hoop method.

TABLE 2. Fabric characteristics

Fabric Code	**Fiber content**	**Structure**	**Fabric count (yarn/cm)**		**Mass per unit area (g/m^2)**	**Thickness (mm)**
			Warp/ wale	**Weft/ course**		
F28	100% Polyester	Plain (woven)	88	50	51 ± 1	0.101 ± 0.002
F29	100% Polyester	Plain (woven)	94	50	76 ± 2	0.127 ± 0.03

FIGURE 8. Effect of fabric thickness on the correlation between the dry thermal effusivity results measured using stacked and air-hoop methods under 1 kPa applied pressure for the 27 fabrics of the study plus two additional very thin fabrics (F28 and F29). The linear fit shown with a dotted line includes all the fabric data except Fabric F16, F28, and F29.



A moderation analysis was conducted with all the fabrics, including Fabric F28 and F29. The moderation analysis revealed that the fabric thickness has a significant effect on the correlation between the stacked and air-hoop methods (p < .001). The analysis provided three regression models for the correlation between the stacked and air-hoop methods based on the fabric thickness. The first regression model corresponds to negative fabric thickness values, which is not relevant in this case. The second regression model corresponds to fabric thicknesses close to 0 mm. This model would apply to Fabric F16, F28, and F29. The last regression model relates to fabric thicknesses close to 0.40 mm or higher. This model would apply to all the tested fabrics excluding F16, F28, and F29. The effect size was 1.243 for the second regression model (thickness close to 0 mm) and 1.752 for the third regression model (fabric thickness close to 0.40 mm or higher).

For all the fabrics tested, the thermal effusivity values measured with the stacked method were systematically higher than those measured with the air-hoop method. This difference in the absolute value of the thermal effusivity can be attributed to the effect of the air layer on the side of the fabric specimen opposite to the MTPS sensor when they are tested using the air-hoop method. The use of the air-hoop method to measure thermal effusivity is thus providing a closer representation of how a person would feel the thermal touch of the fabric when it is worn as a part of a single layer garment.

Conclusions

The study explored the thermal effusivity of 27 sportswear fabrics using the stacked method (ASTM D7984-21) and a novel air-hoop method that more closely matches the real-life scenario of wearing the single-layer fabric, where one side of the fabric touches the skin and other side is exposed to the environment. The effect of experimental parameters (such as pressure between the fabric specimen and the sensor) and fabric characteristics (such as density and porosity) on the thermal effusivity were also investigated.

The results showed that the 10 to 50 kPa range of applied pressure between the MTPS sensor and the fabric specimen mentioned in the ASTM D7984-21 standard for conducting thermal effusivity measurements using the stacked method affected the result of the thermal effusivity measurement. These values of applied pressure expelled air from the fabric structures and led to a measurement of the material-based thermal effusivity (based on the fiber content) rather than the fabric thermal effusivity. In the case of the air-hoop method, an applied pressure of 2 kPa created an excessive amount of stretch in the fabric and affected the thermal effusivity results, while 0.5 kPa was not sufficient to ensure proper contact between the fabric and the MTPS sensor. For both the stacked and air-hoop methods, a value of applied pressure of 1 kPa was identified as the best condition. This finding is breakthrough information that will allow reporting more accurate thermal effusivity values for compressible fabrics, which includes sportswear fabrics as well as many others. For the stacked method, the results obtained also confirmed the importance of maintaining a minimum of 1 mm for the fabric stack.

In terms of the effect of the fabric characteristics on the thermal effusivity results, a negative correlation was observed between the thermal effusivity measured using the air-hoop method and the porosity for all 27 tested sportswear fabrics except the thinnest one. This correlation observed with the fabric porosity was associated with the lower amount of air in the fabric structure and reduced air convection for the lower porosity fabrics. It shows porosity as an overarching parameter controlling thermal effusivity, irrespective of the fabric structure, fiber content, type of yarn, nature of finish, etc. The discrepancy observed for the thinnest fabric was attributed to the fact that the penetration depth of the MTPS heat pulse was much higher than the fabric thickness.

Finally, the results showed an excellent correlation between the thermal effusivity results measured with the stacked and air-hoop methods under a 1 kPa applied pressure for all the tested fabrics except the thinnest one. However, for all the fabrics tested, the thermal effusivity values measured with the stacked method were systematically higher than those measured with the air-hoop method due to the effect of the air layer on the other side of the fabric specimen with the air-hoop method. The use of the air-hoop method to measure thermal effusivity is thus providing a closer representation of how a person would feel the thermal touch of the fabric when it is worn as a part of a single layer garment. The findings of the study shed new light on thermal effusivity and will contribute to the development of more comfortable fabrics considering realistic use scenarios when worn as a garment.

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References

1. G. Bedek, F. Salaün, Z. Martinkovska, E. Devaux, and D. Dupont, "Evaluation of Thermal and Moisture Management Properties on Knitted Fabrics and Comparison with a Physiological Model in Warm Conditions," *Applied Ergonomics* 42, no. 6 (November 2011): 792–800, http://web.archive.org/web/20231004164900/https://www.sciencedirect.com/science/article/abs/pii/S0003687011000020?via%3Dihub
2. A. Sikorska, and B. B. Linde, "Manifestation of Hydration Effects in Dioxane–Water Solutions by Concentration-Dependent Changes of Thermal and Elastic Properties," *Chemical Physics* 354, no. 1–3 (December 2008): 148–154, http://web.archive.org/web/20231004165149/https://www.sciencedirect.com/science/article/abs/pii/S0301010408004448?via%3Dihub
3. E. B. Ratts, "Thermal Performance of Ventilated Passenger Seats," *Heat Transfer* 4 (January 2005): 1013–1016, http://web.archive.org/web/20231004165352/https://asmedigitalcollection.asme.org/HT/proceedings-abstract/HT2005/47349/1013/314056
4. E. Choi, O. Sul, J. Gong, H. Sun, M. Kwon, and S. Lee, "Portable Heat Transfer Measurement System Mimicking Human Thermal Sensation" *Sensors and Actuators A: Physical* 349 (January 2023): 1–10. https://web.archive.org/web/20231116025156/https://www.sciencedirect.com/science/article/abs/pii/S0924424722006549?via%3Dihub.
5. M. R. Islam, K. Golovin, and P. I. Dolez. "Clothing Thermophysiological Comfort: A Textile Science Perspective," *Textiles* 3, no. 4 (September 2023): 353–409. https://web.archive.org/web/20231116025827/https://www.mdpi.com/2673-7248/3/4/24.
6. L. Van Der Tempel, "The Effective Temperature at Which Fingertips Sense Thermal Effusivity and the Bias of Measurements at Room Temperature," *Measurement* 135 (March 2019): 747–752, http://web.archive.org/web/20231004165719/https://www.sciencedirect.com/science/article/abs/pii/S0263224118311072?via%3Dihub

7. N. P. Loredan, D. Lipovac, S. Jordan, M. D. Burnard, and N. Šarabon, "Thermal Effusivity of Different Tabletop Materials in Relation to Users' Perception," *Applied Ergonomics* 100 (April 2022): 1–10, http://web.archive.org/web/20231004165930/https://www.sciencedirect.com/science/article/pii/S0003687021003112?via%3Dihub
8. *Standard test method for measurement of thermal effusivity of fabrics using a modified transient plane source (MTPS) instrument*, ASTM D7984 (2021) (West Conshohocken, PA: ASTM International, approved July 29, 2022).
9. P. Komárková, V. Glombikova, and A. Havelka, "Heat and Moisture Transport of Socks," *IOP Conference Series* 254, no. 18 (October 2017), http://web.archive.org/web/20231004170040/https://iopscience.iop.org/article/10.1088/1757-899X/254/18/182004
10. A. Joshi, F. Wang, Z. Kang, B. Yang, and D. Zhao, "A Three-Dimensional Thermoregulatory Model for Predicting Human Thermophysiological Responses in Various Thermal Environments," *Building and Environment* 207 (January 2022): 1–14, http://web.archive.org/web/20231004170148/https://www.sciencedirect.com/science/article/pii/S036013232100901X?via%3Dihub
11. *Textiles — Physiological effects — Measurement of Thermal and Water Vapour Resistance under Steady-State Conditions (Sweating Guarded Hotplate Test),* ISO 11092 (2014) (Geneva, Switzerland: International Organization for Standardization, approved September 1, 2014).
12. S. Pavlović, S. Stankovic, D. Popović, and G. B. Poparić, "Transient Thermal Response of Textile Fabrics Made of Natural and Regenerated Cellulose Fibers," *Polymer Testing* 34 (April 2014): 97–102, http://web.archive.org/web/20231004170334/https://www.sciencedirect.com/science/article/abs/pii/S0142941813002523?via%3Dihub
13. S. L. Sokolowski, E. Karolidis, A. Hakimian, and S. L. G. Ackermann, "Measuring Cool Touch of Key Sports Performance Apparel T-Shirt Materials Using a Modified Transient Plane Source (MTPS) Sensor to Inform Future Technology Development," in *TMS 2022 151st Annual Meeting & Exhibition Supplemental Proceedings. The Minerals, Metals & Materials Series* (Cham, Switzerland: Springer, 2022), 1327–1337, http://web.archive.org/web/20231004170652/https://link.springer.com/chapter/10.1007/978-3-030-92381-5_126
14. M. Marsh, "The Thermal Insulating Properties of Fabrics," *Proceedings of the Physical Society* 42, no. 5 (August 1930): 570–588, http://web.archive.org/web/20231004171513/https://iopscience.iop.org/article/10.1088/0959-5309/42/5/326/pdf
15. S. Kawabata and Y. Akagi, "Relation Between Thermal Feeling and Thermal Absorption Property of Clothing Fabric," *Journal of the Textile Machinery Society of Japan* 30, no. 1 (January 1977): T13–T22,

http://web.archive.org/web/20231004171659/https://www.jstage.jst.go.jp/article/transjtmsj1972/30/1/30_1_T13/_article/-char/ja/

16. S. Kawabata and M. Yoneda, "Analysis of Transient Heat Conduction and Its Applications: Part 2: A Theoretical Analysis of the Relationship between Warm/Cool Feeling and Transient Heat Conduction in Skin," *Journal of the Textile Machinery Society of Japan* 31, no. 4 (1985): 79–85, http://web.archive.org/web/20231004171656/https://www.jstage.jst.go.jp/article/jte1955/31/4/31_4_79/_article
17. M. Tian, S. Zhu, and N. Pan, "Skin Thermal Stimulation on Touching Cool Fabric from the Transient Stage to Steady-State Stage," *International Journal of Thermal Sciences* 53 (March 2012): 80–88, http://web.archive.org/web/20231004171851/https://www.sciencedirect.com/science/article/pii/S1290072911003061?via%3Dihub
18. C-Therm, *TRIDENT: Thermal Conductivity Instrument User Manual Version 4.1* (New Brunswick: Canada: C-Therm, 2020).
19. M. Abu-Rous, "The Influence of Cellulosic Content on Heat Dissipation in Knits," *10th European Conference on Protective Clothing* (Arnhem, Netherlands: ESPC, 2023), 164–165
20. A. Marolleau, F. Salaün, D. Dupont, H. Gidik, and S. Ducept. "Influence of Textile Properties on Thermal Comfort." *IOP Conference Series* 254, no. 18 (October 2017), http://web.archive.org/web/20231004172428/https://iopscience.iop.org/article/10.1088/1757-899X/254/18/182007
21. R. Guru and A. K. Choudhary, "Study of the Effect of Functional Finishes on Thermal Properties Sportswear Knit Garments," *Journal of Textile and Apparel Technology and Management 4*, *no.* 11 (2020): 1–20.
22. H. F. Siddique, A. A. Mazari, A. Havelka, and R. Laurinová, "Analysis of thermal properties affected by different extension levels of compression socks," *Fibres and Textiles* 2, (2019), 64–68, http://web.archive.org/web/20231003040219/http://vat.ft.tul.cz/2019/2/VaT_2019_2_11.pdf
23. M. Abu-Rous , S. Schürz-Peschka, R. K. Sobhee, J. Innerlohinger, J. Lughofer, and W. Milacher, "Thermal Effusivity Tester (TET)—a New Device to Determine Thermal Effusivity of Textiles," *Applied Sciences* 13, no. 15 (July 2023): 1–12. https://web.archive.org/web/20231116034816/https://www.mdpi.com/2076-3417/13/15/8749.
24. *Standard test methods for mass per unit area (weight) of fabric*, ASTM D3776/D3776M (2020) (West Conshohocken, PA: ASTM International, August 23, 2021).
25. *Textile Test Methods: Fabric Thickness,* CAN/CGSB-4.2 No. 37 (2002) (Ottawa, Ontario: Standards Council of Canada).
26. F. Gholamreza, Y. Shao-Horn, R. Li, A. V. Nadaraja, R. Gathercole, R. Li, and P. I. Dolez, "Modeling and Prediction of Thermophysiological Comfort Properties of a Single Layer

Fabric System Using Single Sector Sweating Torso." *Materials* 15, no. 16 (August 2022): 1–16, http://web.archive.org/web/20231004172643/https://www.mdpi.com/1996-1944/15/16/5786

27. A. P. Field, *Discovering Statistics Using IBM SPSS Statistics* (Thousand Oaks, California: Sage Publications, 2018).

28. S. Kara, Ü. H. Erdoğan, and N. Erdem, "Effect of Polypropylene Fiber Cross Sectional Shapes on Some Structural/Mechanical Fiber Properties and Compressibility Behaviour of Plain Knitted Fabrics," *Fibers and Polymers* 13, no. 6 (July 2012): 790–794, http://web.archive.org/web/20231004173059/https://link.springer.com/article/10.1007/s12221-012-0790-8

29. R. Chauhan and S. Ghosh, "Effect of Different Parameters on Stitch Shape and Thread Consumption," *Indian Journal of Fibre & Textile Research* 45, no. 4 (December 2020): 411–418, https://web.archive.org/web/20231116043022/http://14.139.47.23/index.php/IJFTR/article/view/28573

30. S. Baxter, "The Thermal Conductivity of Textiles," *Proceedings of the Physical Society* 58, no. 1 (January 1946): 105–118, http://web.archive.org/web/20231004173215/https://iopscience.iop.org/article/10.1088/0959-5309/58/1/310

31. C. Zhang and F. Wang, "Comfort Management of Fibrous Materials," in *Handbook of Fibrous Materials* (Hoboken, NJ: Wiley, 2020), 857–887, http://web.archive.org/web/20231004173237/https://onlinelibrary.wiley.com/doi/10.1002/9783527342587.ch31

32. W. E. Morton and J. W. S. Hearle, *Physical Properties of Textile Fibres* (London, UK: Woodhead Publishing Limited, 2008), http://web.archive.org/web/20231004173448/https://www.sciencedirect.com/book/9781845692209/physical-properties-of-textile-fibres

33. F. Gholamreza, "Performance of Thermal Protective Clothing upon Exposure to Hot Liquid Splash" (PhD Dissertation, University of Alberta, 2018).

34. S. A. Mirjalili, M. Rafeeyan, and Z. Soltanzadeh, "The Analytical Study of Garment Pressure on the Human Body Using Finite Elements," *Fiber & Textiles in Eastern Europe 16,* no. 3 (September 2008): 69–73, https://web.archive.org/web/20231116043022/http://14.139.47.23/index.php/IJFTR/article/view/28573

35. H. Makabe, H. Momota, T. Mitsuno, and K. Ueda, "Effect of Covered Area at the Waist on Clothing Pressure," *Sen'i Gakkaishi* 49, no. 10 (January 1993): 513–521, https://web.archive.org/web/20231116170839/https://www.jstage.jst.go.jp/article/fiber1944/49/10/49_10_513/_article/-char/ja/

36. A. Joshi, "Comprehensive Model for Heat and Mass Transfer in Human Skin-Clothing-Environment System" (PhD Dissertation, Université de Haute-Alsace, 2019).

37. E. Mert, A. Psikuta, M-A. Bueno, and R. M. Rossi, "Effect of Heterogenous and Homogenous Air Gaps on Dry Heat Loss through the Garment," *International Journal of Biometeorology* 59, no. 11 (March 2015): 1701–1710, http://web.archive.org/web/20231004173547/https://link.springer.com/article/10.1007/s00484-015-0978-x

38. Y. A. Çengel and A. J. Ghajar, *Heat and Mass Transfer: Fundamentals & Applications* (New York, USA: McGraw-Hill Higher Education, 2015).

39. G. Song, S. Mandal, and R. M. Rossi. *Thermal protective clothing for firefighters* (Amsterdam, Netherlands: Elsevier/Woodhead Publishing, 2017).

40. V. Kumar, V. R. Sampath, and C. Prakash, "Investigation of Stretch on Air Permeability of Knitted Fabrics Part II: Effect of Fabric Structure," *Journal of the Textile Institute* 107, no. 10 (October 2015): 1213–1222.

41. R. Oğulata, R. Tuğrul, and S. Mavruz, "Investigation of Porosity and Air Permeability Values of Plain Knitted Fabrics," *Fibres & Textiles in Eastern Europe* 18, no. 5 (January 2010): 71–75, http://web.archive.org/web/20231003060205/http://fibtex.lodz.pl/pliki/Fibtex_%28qpcosra6jb5c7emy%29.pdf

42. M. K. Öztürk, M. Venkataraman, and R. Mishra, "Influence of Structural Parameters on Thermal Performance of Polypropylene Nonwovens," *Polymers for Advanced Technologies* 29, no. 12 (September 2018): 3027–3034, http://web.archive.org/web/20231004173804/https://onlinelibrary.wiley.com/doi/10.1002/pat.4423

43. T. Olfatbakhsh and A. S. Milani, "A Highly Interpretable Materials Informatics Approach for Predicting Microstructure-Property Relationship in Fabric Composites," *Composites Science and Technology* 217 (October 2022): 1–9, https://doi.org/10.1016/j.compscitech.2021.109080

44. G. Song, and S. Mandal, "Testing and Evaluating the Thermal Comfort of Clothing Ensembles," in *Performance Testing of Textiles* (Cambridge, UK: Woodhead Publishing Limited, 2016), 39–64, http://web.archive.org/web/20231004173833/https://www.sciencedirect.com/science/article/abs/pii/B9780081005705000049?via%3Dihub

45. G. Zhu, K. Dana, Y. Wang, J. Militky, and R. Mishra, "Study on Air Permeability and Thermal Resistance of Textiles under Heat Convection," *Textile Research Journal* 85, no. 16 (February 2015): 1681–1690, http://web.archive.org/web/20231004174022/https://journals.sagepub.com/doi/10.1177/0040517515573407

46. N. Ghaddar and K. Ghali, “Modeling of Heat and Moisture Transfer in Porous Textile Medium Subject to External Wind: Improving Clothing Design,” in *Handbook of Thermal Science and Engineering* (Cham, Switzerland: Springer, 2018), 885–916, http://web.archive.org/web/20231004174041/https://link.springer.com/referenceworkentry/10.1007/978-3-319-26695-4_40