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Thermal Effusivity Tester (TET)—A New Device to Determine Thermal Effusivity of Textiles

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Abstract: Thermal effusivity tester (TET) is a new device to measure the thermal conductivity and the thermal effusivity (heat dissipation) of textiles under a defined compression, developed at the R&D department of Lenzing AG (Austria). The device performance was tested by comparing its results with results from commercially available devices Alambeta, TCi Thermal Conductivity Analyzer and Kawabata KES-f thermal module. The fabrics tested were typical knit and weave constructions made of different fiber types, including cotton, wood-based cellulosics and polyester. For most of the fabrics, thermal effusivity results show wide agreement among TET, Alambeta and TCi, and strong positive correlation ($r > 0.82$) with heat flow (Q_{max}) as obtained from KES. Deviations were observed for some thicker and more resilient fabrics, most probably caused by the differences in the pressure applied by the devices on the fabric surface. The results show that TET offers a reliable and experimentally flexible approach to assessing thermal effusivity on textile structures and emphasizing the role of the dimensional change induced by the measurement conditions on the measured thermal effusivity and conductivity.

Keywords: thermal effusivity; thermal conductivity; compression; textile; haptics; measurement device

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1. Introduction

The perception of coolness and warmth by handfeel of textiles is an important aspect of evaluation and, in some cases, one of the selection factors at the point of sale. A textile surface that quickly dissipates heat will be perceived as cool, which is considered pleasant under normal conditions. Subjective fabric cool/warm perception can be assessed by consulting a group of human assessors in the form of a consumer inquiry or an expert panel. As a higher variation in subjective assessment is expected, an objective measurement as reference has significant advantages in terms of reproducibility and time and personnel resources [1].

In the Kawabata KES-f system for objective handfeel assessment, this transient thermal feeling is measured in the thermal module (Thermo Labo), which determines the maximal amount of heat transferred through the fabric (heat flow) in a short measurement time (100 s), expressed as Q_{max} (J·s/cm^2) [2].

Later, the Alambeta device was developed to assess the cool/warm feeling of fabrics, defined by the term "Thermal Absorptivity" [3–5], later called thermal effusivity [6], i.e., the ability of the material to exchange heat with its surroundings. It is defined by Equation (1), where λ is the thermal conductivity in W/mK, ρ the density in kg/m^3 and c_p the specific heat capacity in J/kgK.

$$e = \sqrt{\lambda * \rho * c_p} \tag{1}$$

The unit for thermal effusivity hence is W s$^{1/2}$/m^2 K. The higher this value, the cooler the surface feels. Textiles show effusivity values between 0 and 400, while this value goes up to 1300–1500 for moist textiles. Water, for example, has a thermal effusivity of 1600.

The works of Hes et al. showed that thermal effusivity is theoretically independent from the temperature difference between fabric and skin, as well as from the measurement time. However, it does depend on the contact pressure, as the compression of the fabric reduces the air voids and enhances the material density [7]. As textile fabrics show a degree of compressibility depending on the fabric construction, the applied contact pressure could influence the result.

Other developments took place to assess the thermal effusivity on solid surfaces like plastics and concrete. Jannot et al. developed a measurement technique to assess effusivity and conductivity on solid materials. The approach was based on the measurement of the electrical and thermal behavior of an internal metallic probe (hot wire) within the material over longer periods of time [8]. Other works took a thermographic approach to assess the effusivity of solid surfaces [9,10].

A recent development is the TCi device by C-Therm, which has the same theoretical approach as Alambeta to measuring the thermal effusivity. Unlike Alambeta, TCi offers a more flexible approach, as the measurement unit can be positioned in any direction on solid surfaces. The TCi version "Modified Transient Plane Source" (MTPS) considers the compressibility of textiles and is equipped with an accessory unit, which offers a manual control of the applied pressure on the textile surface [11].

To measure thermal effusivity on one fabric side, heat penetration beyond the sample must be avoided. Apparently oriented to TCi measurement setting, the test standard ASTM D7984-16 defines a minimal thickness of 1 mm [6]. As textile fabrics are usually thinner than 1 mm, a multi-layered measurement is suggested, where the number of layers is subject to pre-experimentation. Alambeta is able to measure a single layer, where the fabric backside is positioned on a metal plate with the same temperature [4].

This work presents the thermal effusivity tester (TET)—a new device developed by the Instrument Development team at Lenzing's R&D department to perform profound research in the field of thermal perception. The motivation to design and build an additional device for the measurement of thermal perception (with several instruments already available) was to have a system that allows easy measurement and offers the possibility to adjust the measurement parameters to special needs. Therefore, the system was designed to offer more flexibility in the measurement setup and variation in the selected parameters. Despite the targeted flexibility, the new device also should be comparable to the existing systems and thus allow a comparison of various measurements. Similar to Alambeta, TET offers a semi-automated measurement of thermal conductivity and effusivity on single-layered fabric. It differs from the devices described above by two main aspects: it addresses the fabric compression issue mentioned above by targeting a harmonized fabric compression rate instead of a harmonized weight application. Furthermore, temperature control at both fabric sides offers a more precise assessment of the transient heat transfer into the fabric, which allows the measuring of thin single layers. The adjustability of fabric compression, temperatures on both fabric sides and measurement time provide the possibility of simulating various fabric use conditions.

The reliability of the device and the measurement approach were tested by comparing the obtained results with available measurement results from Alambeta and TCi systems. Results were also correlated with available results from Kawabata Thermo Labo, as Q_{max} is also usually used in the textile market to describe cool perception of the fabric.

2. Experimental

Fabric thickness was measured at the pressure of 1kPa according to ISO 5084 [12]. For Alambeta test device, the thickness was measured automatically with a photoelectric sensor in the device at its working pressure of 200 Pa [13], where the resulting thickness is not necessarily identical with manual measurement. The fabrics were measured with TET as described below, and the results compared with existing data from previous measurements of the same fabrics using TCi, Alambeta and KES-f-Thermo Labo.

Alambeta measurements were performed by placing the fabric between the upper plate, which has a temperature of 32 °C, and the lower plate, which is at room temperature (20 °C). The upper plate is lowered until a pressure of 200 Pa on the surface is reached. The heat streams onto the fabric are measured and the measurement ends when a heat flux equilibrium is reached. Textile thickness, thermal conductivity and thermal effusivity are measured. The process is repeated at 18 different positions on the fabric and the average value is calculated.

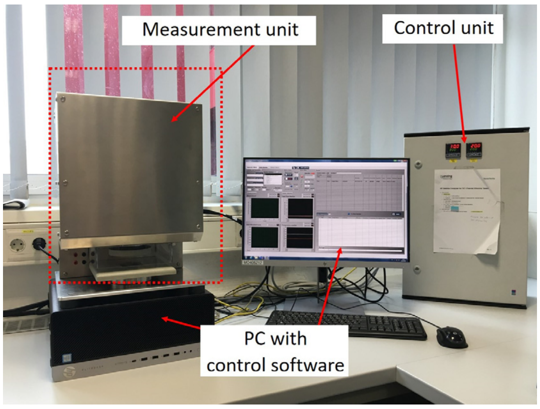
TCi measurements were performed at C-Therm Technologies using the TCi Thermal Conductivity Analyzer in the MTPS configuration along with a compression test accessory (CTA). The test procedure is described at the C-Therm website [11]. A 500 g weight was applied on the fabric surface. Considering the measurement head diameter of 18 mm, a pressure of 19 kpa is calculated. Pre-testing of heat penetration showed that multilayer sample positioning was required.

KES-f Thermo Labo measurements were performed by IFTH, France [14]. In this measurement, a square-shaped copper block is used as a skin probe. Its temperature is raised to 10 °C above the sample surface temperature and the peak heat dissipation Q_{max} is measured.

Thermal Effusivity Tester (TET)

The TET measurement unit comprises two plates, with the upper plate maintained at a temperature of 35 °C and the lower plate at 23 °C. The fabric sample is positioned on the stationary lower plate, while the upper plate is automatically lowered to establish contact with the fabric, applying a predefined compression rate based on the fabric thickness measurement. In this study, a fabric compression rate of 10% was used. The key measurement parameters include thermal conductivity, specific heat capacity and fabric density (previously determined by weight and thickness measurements).

Figures 1 and 2 show the TET device in more detail.



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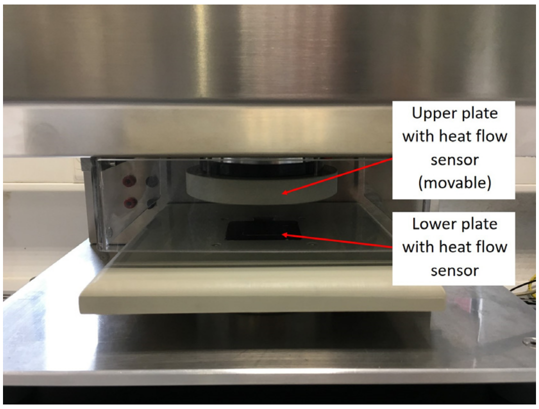


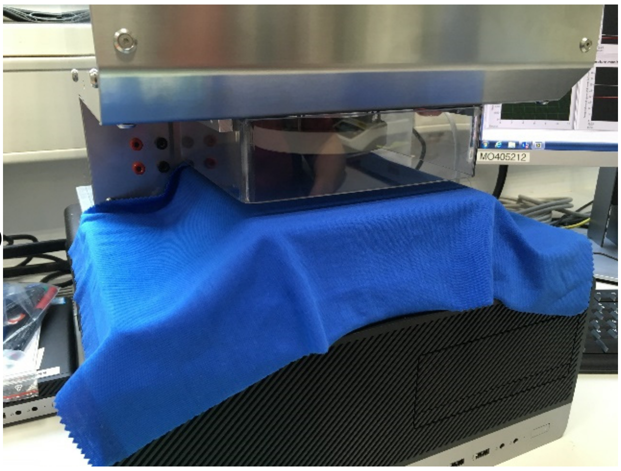
(**b**)

Figure 1. (**a**) Thermal effusivity tester (TET); (**b**) detail view of measurement unit.

When the fabric is placed on the lower sensor plate, a heat flux takes place through the fabric due to the temperature difference. Once thermal equilibrium between the fabric and the lower sensor plate is reached (i.e., the fabric has reached the same temperature as the lower plate), the warmer upper plate is gradually lowered at a defined speed, pressing the specimen between the two plates.

During the movement of the upper plate, the heat flow through both sensors is recorded for a specified duration (Figure 3). The temporal behavior of both heat flows is utilized to determine the thermal conductivity and the heat capacity of the test specimen.

(**a**)



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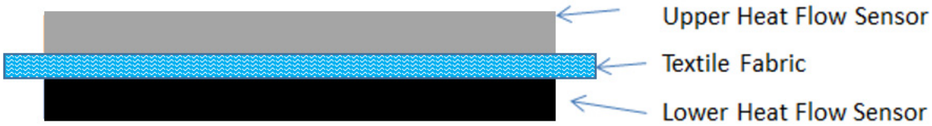
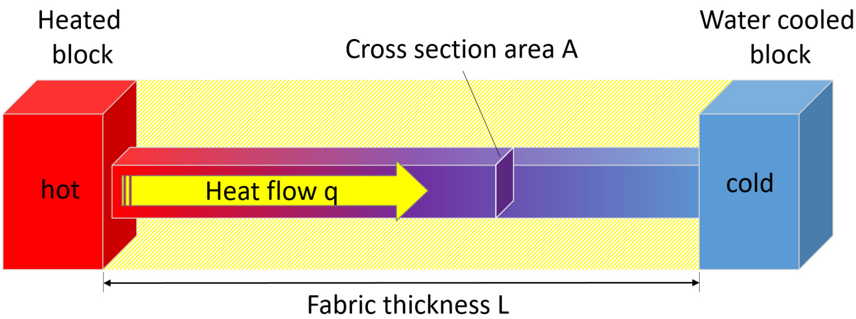


Figure 2. Sample placed on the measurement unit; (**a**) photo, (**b**) schematic drawing.

(**a**)



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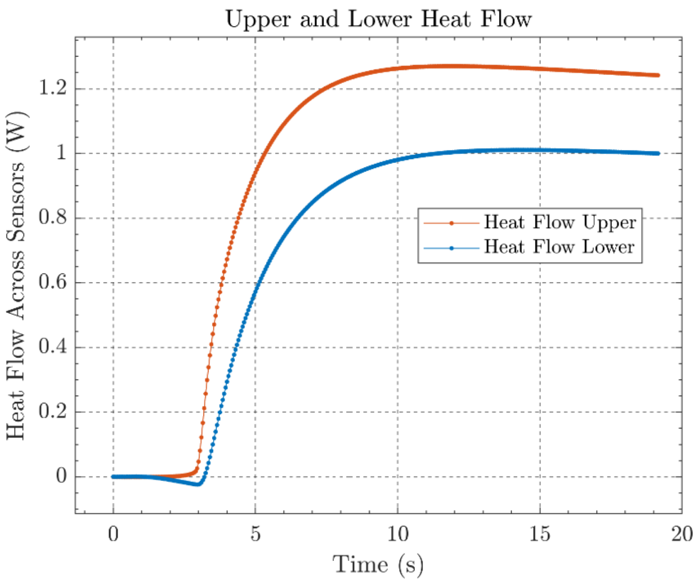

Figure 3. (**a**) Measurement principle of TET device; (**b**) heat flow at the upper (red line) and the lower (white line) plate.

When the upper plate makes contact with the specimen, the longitudinal surface area of the fabric is much larger as compared to the transverse area; hence, the difference in heat flux between the sensors can be used to quantify the heat absorbed by the material. Once the heat flows have reached an equilibrium (curve flattening in Figure 3), it can be assumed that there exists a uniform temperature gradient across the fabric, from which the average temperature rise in the fabric can be calculated. As the mass of the specimen is known, the mean specific heat capacity (c_p) can be calculated using Equation (2).

$$c_p = \frac{\Delta Q}{m \cdot \Delta T_{AVG}} \quad (2)$$

Here, ΔQ represents the amount of heat energy absorbed by the material in Joules (J), m is the mass of the specimen in kilograms (kg) and ΔT_{AVG} is the average temperature rise in Kelvin (K).

The energy absorbed by the material can be determined by subtracting the lower heat flow from the upper heat flow and integrating this difference for a defined time period.

Once the heat flow equilibrium within the specimen is reached, the thermal conductivity is determined using the steady-state heat flow and the temperature difference, following the Fourier conduction equation (Equation (3)).

$$q = \lambda \cdot \frac{A}{L} \cdot \Delta T \quad (3)$$

In this equation, q represents the heat flow into the fabric in Watts (W), λ is the thermal conductivity in Watts per meter-Kelvin (W/m·K), A is the cross-sectional area in square meters (m^2), L is the fabric thickness in meters (m) and ΔT is the temperature difference. Rearranging the equation leads to Equation (4).

$$\lambda = q \cdot \frac{L}{A} \cdot \frac{1}{\Delta T} \quad (4)$$

According to the current protocol, each measurement is repeated at five different positions on the fabric, whereas five measurements are performed fully automated at each position and the average is calculated. Different measurement repetitions took place on different days to test reproducibility.

The LABVIEW v.2016 software is employed for measurement automation, result processing and the user interface (UI). This software allows operation under preset device mechanics and temperature conditions, as well as variations in research conditions. The obtained data is exported as an Excel file for further analysis.

3. Materials & Results

All fabric samples were provided by Lenzing AG and represent common fabric types used for textile applications.

In the first comparison, fabrics with different common constructions and fiber contents were tested. Thermal conductivity and thermal effusivity were measured by TET and compared with available data from TCi (4 samples) and Alambeta (all). Fabric characteristics can be found in Table 1. Results for thermal conductivity and effusivity are presented in Tables 2 and 3.

Table 1. Composition and construction properties of the textiles tested on Alambeta, TCi and TET.

Sample No.	Composition	Construction	Weight (g/m^2)	Thickness (µm)	
				ISO	Alambeta
1	100% Cotton	Interlock (knit)	170	780	750
2	65% Polyester/35% Cotton	Plain weave (woven)	231	440	440

Table 1. *Cont.*

Sample No.	Composition	Construction	Weight (g/m^2)	Thickness (μm)	
				ISO	Alambeta
3	65% Polyester/35% Cotton	Plain weave (woven)	202	420	450
4	100% Polyester	Jaquard weave (woven)	270	490	280
5	100% Cotton	Plain weave (woven)	157	450	440
6	100% Lyocell	Plain weave (woven)	157	400	360
7	100% Cotton	Single jersey (knit)	143	720	550
8	95% Modal/ 5% Elastane	Single jersey (knit)	225	970	740
9	57% Lyocell/ 43% Polyester	Interlock (knit)	143	560	500

Table 2. Results for thermal conductivity measured by Alambeta, TCi and TET.

Sample No.	Composition	Construction	Alambeta		TCi		TET	
			Thermal Conductivity (W/m*K)	CV (%)	Thermal Conductivity (W/m*K)	CV (%)	Thermal Conductivity (W/m*K)	CV (%)
1	100% Cotton	Interlock (knit)	0.036	2.8	0.073	1.8	0.045	4.3
2	65% Polyester/35% Cotton	Plain weave (woven)	0.057	6.7	0.090	0.8	0.051	2.1
3	65% Polyester/35% Cotton	Plain weave (woven)	0.051	7.4	0.088	0.6	0.048	1.1
4	100% Polyester	Jaquard weave (woven)	0.053	1.7	0.067	0.7	0.040	1.1
5	100% Cotton	Plain weave (woven)	0.048	3.1	-	-	0.041	0.9
6	100% Lyocell	Plain weave (woven)	0.050	6.3	-	-	0.039	1.7
7	100% Cotton	Single jersey (knit)	0.049	4.1	-	-	0.045	1.2
8	95% Modal/ 5% Elastane	Single jersey (knit)	0.054	2.8	-	-	0.048	1.4
9	57% Lyocell/ 43% Polyester	Interlock (knit)	0.053	3.2	-	-	0.047	1.3

Table 3. Results for thermal effusivity measured by Alambeta, TCi and TET.

Sample No.	Composition	Construction	Alambeta		TCi		TET	
			Effusivity (Ws$^{1/2}$/m^2 K)	CV (%)	Effusivity (Ws$^{1/2}$/m^2 K)	CV (%)	Effusivity (Ws$^{1/2}$/m^2 K)	CV (%)
1	100% Cotton	Interlock (knit)	107	7.2	191	1.9	161	6.0
2	65% Polyester/35% Cotton	Plain weave (woven)	233	2.9	233	0.7	232	4.5

Table 3. *Cont.*

Sample No.	Composition	Construction	Alambeta		TCi		TET	
			Effusivity ($Ws^{1/2}/m^2$ K)	CV (%)	Effusivity ($Ws^{1/2}/m^2$ K)	CV (%)	Effusivity ($Ws^{1/2}/m^2$ K)	CV (%)
3	65% Polyester/35% Cotton	Plain weave (woven)	210	2.8	228	0.4	228	4.6
4	100% Polyester	Jaquard weave (woven)	165	3.0	176	0.7	174	2.9
5	100% Cotton	Plain weave (woven)	184	1.9	-	-	181	3.1
6	100% Lyocell	Plain weave (woven)	192	5.0	-	-	195	4.7
7	100% Cotton	Single jersey (knit)	141	6.2	-	-	136	4.6
8	95% Modal/ 5% Elastane	Single jersey (knit)	164	11.7	-	-	187	3.0
9	57% Lyocell/ 43% Polyester	Interlock (knit)	158	2.9	-	-	148	4.8

In a second comparison, a set of woven and knitted fabrics made of different cellulosic fibers was measured using TET, and the results were compared with Q_{max} values as obtained by Kawabata KES-f Thermo Labo. Fabric characteristics. The results are shown in Table 4.

Table 4. Composition and construction properties of the tested textiles and results of thermal effusivity and Q_{max} as measured with TET and KES-f.

Sample No.	Composition	Construction	Weight (g/m^2)	Thickness (μm)	TET		KES-f	
					Effusivity ($Ws^{1/2}/m^2$ K)	CV (%)	Q Max [$J.s/cm^2$]	CV (%)
W1	100% Cotton	Plain weave (woven)	131	320	186	5.0	0.157	n.a.
W2	100% Modal (1.0 dtex)	Twill weave (woven)	135	260	252	4.4	0.201	n.a.
W3	100% Lyocell (1,3 dtex)	Twill weave (woven)	130	260	200	6.9	0.190	n.a.
W4	100% Lyocell (1,0 dtex)	Twill weave (woven)	135	260	202	10.9	0.182	n.a.
W5	100% Modal (1,3 dtex)	Twill weave (woven)	138	260	220	5.4	0.191	n.a.
K1	100% Cotton	Single jersey (knit)	163	650	168	3.7	0.107	n.a.
K2	50% Cotton/ 50% Lyocell	Single jersey (knit)	155	620	166	4.9	0.102	n.a.
K3	100% Modal (1,0 dtex)	Single jersey (knit)	149	550	165	4.8	0.113	n.a.
K4	100% Modal (1,3 dtex)	Single jersey (knit)	132	510	165	3.7	0.119	n.a.
K5	95% Modal (1.0 dtex)/ 5% Elastane	Single jersey (knit)	142	510	183	3.2	0.147	n.a.

4. Discussion

The results shown in Table 3 reflect the calculated means of various single measurements grouped in several temporally independent measurement batches. Robustness of the TET's effusivity measurement (temporal stability, respectively batch-to-batch variation due to uncontrolled factors) was evaluated by calculating batch standard deviations between each of the nine different samples by means of single factor ANOVA.

The results of the ANOVA calculations, summarized in Table 5, illustrate that there is no significant batch-to-batch variation, except for samples 1 and 6. In case of sample 1, where the most repetitions were made, an erroneous data set was discovered and consequently left out of account, leading to a slight change in the main value (sample 1a). For sample 6, no explanation could be found, but irregularities in the fabric surface could be the reason. As for all other samples, there was hardly any batch-to-batch variation detected; as such, effusivity measurement with TET can be regarded as robust and very stable.

Table 5. Summarized ANOVA results. Bold indicates significant variations.

Sample No.	1	1-a	2	3	4	5	6	7	8	9
Batches (N)	5	4	4	3	4	2	2	2	2	2
Single measurements (n)	32	25	24	18	24	12	12	12	12	12
mean	161	164	232	216	174	181	195	136	187	148
$RSD_{within\ batch}$	4.6	4.9	4.6	4.8	3.1	3.5	4.0	4.5	3.1	5.1
$RSD_{batch\text{-}to\text{-}batch}$	**4.2**	1.8	0.9	0.0	0.0	0.0	**4.0**	2.1	0.9	0.0
$RSD_{measurement}$	6.2	5.2	4.6	4.8	3.1	3.5	5.6	5.0	3.2	5.1

Figure 4 shows a comparison of thermal effusivity as measured on nine fabric samples. For the first four samples, a comparison of Alambeta, TCi and TET is given. For all the samples, a comparison of Alambeta and TET is given.

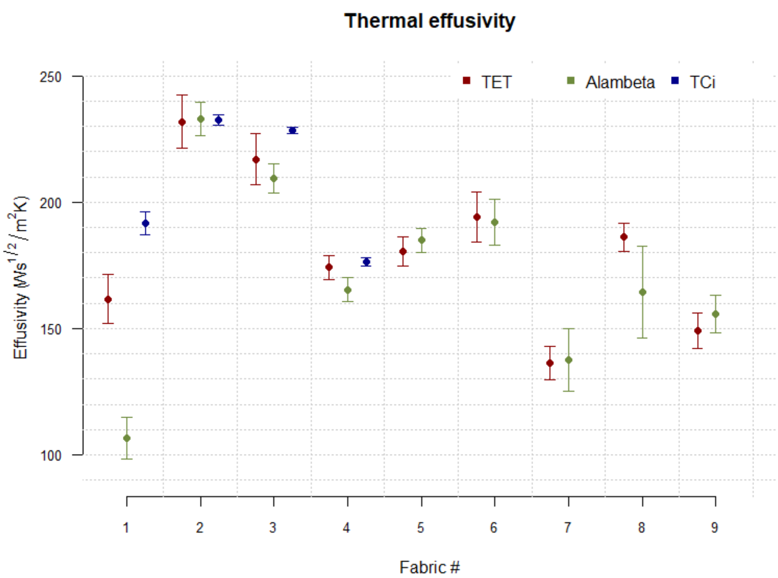

Figure 4. Thermal effusivity as measured with Alambeta, TCi and TET; mean values ± standard deviation.

Except for fabric 1, wide agreement was observed among the three devices, and the correlation factor among the three methods was between 0.86 and 0.92 (see Table 6).

Table 6. Pearson correlation of results of TET with results from Alambeta, TCi and Kawabata, and the correlation of thermal effusivity and conductivity between Alambeta and TCi.

	Correlation Factors	
	Effusivity	**Conductivity**
TET/Alambeta	0.86	0.24
TET/TCi	0.92	0.92
TET/Kawabata	0.92	-
TCi/Alambeta	0.81	0.44

A closer look was taken at the correlation of Alambeta's and TET's effusivity results. *t*-tests were applied to check whether the respective means are comparable. Prior to the *t*-tests, F-tests were performed to check for comparability of variances, and the pooled standard deviations for the respective data sets were calculated. The *t*-tests revealed differences for five samples at the 5% significance level; however, at the 1% significance level, only three samples turned out to give different effusivity results (samples 1,4 and 8 in Table 7 and Figure 5).

Table 7. *t*-test statistics for comparison of Alambeta's and TET's effusivity results.

Sample No.	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**	
t-Test	26.5		0.5		2.3		5.4		1.7		0.6		0.3		3.9		2.1	
$t_{n1+n2-2}$ (p = 0.05)	2.00	x	2.02	√	2.03	x	2.02	x	2.09	√	2.09	√	2.09	√	2.09	x	2.09	x
$t_{n1+n2-2}$ (p = 0.01)	2.66	x	2.70	√	2.73	√	2.70	x	2.86	√	2.86	√	2.86	√	2.86	x	2.86	√

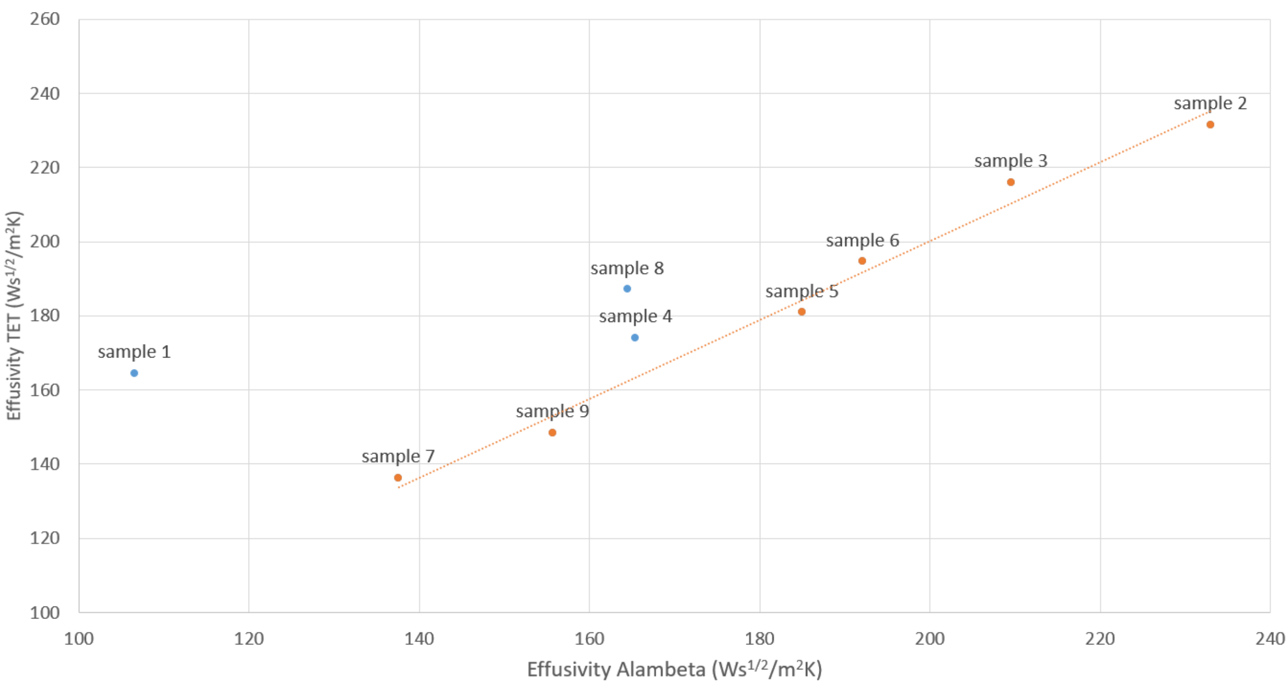

Figure 5. Effusivity correlation between Alambeta and TET.

The different results obtained on fabric 1 (cotton interlock knit) and the smaller differences between TET and Alambeta on other fabrics (Table 7) can be explained by the differences in the applied pressure on the compressible fabrics, as these fabrics show some 3D (vertical) structure with a resilient character. The effect of applied pressure on thermal effusivity has already been emphasized in earlier studies [7]. While the Alambeta device works with a pressure of 200 Pa, the TET device adapts its pressure on the fabric to compress the fabric to 10% of the pre-measured thickness. TCi, on the other hand, applies a fixed weight of 0.5 kg on a multilayered sample. This results in different compression forces on the sample, of which the logical consequence is thinner fabric, higher density and higher conductivity. Cotton fiber has a higher crimp and hence more volume and resilience in the fabric. A comparable effect can be expected in fabrics with elastane. This makes the measurement more sensitive to the pressure force applied by the device than the measurement on flatter fabrics.

Woven fabrics show higher thermal effusivity due to their smooth surface, which provides more contact points with the device surface than the knitted fabrics.

In total, the result shows that the thermal and mechanical setting of TET provide results close, or at least comparable to, such provided by other commercially available devices.

Figure 6 shows the results for thermal conductivity. A fair agreement between Alambeta and TET results can be seen, while TCi measures much higher conductivities on the four tested fabrics.

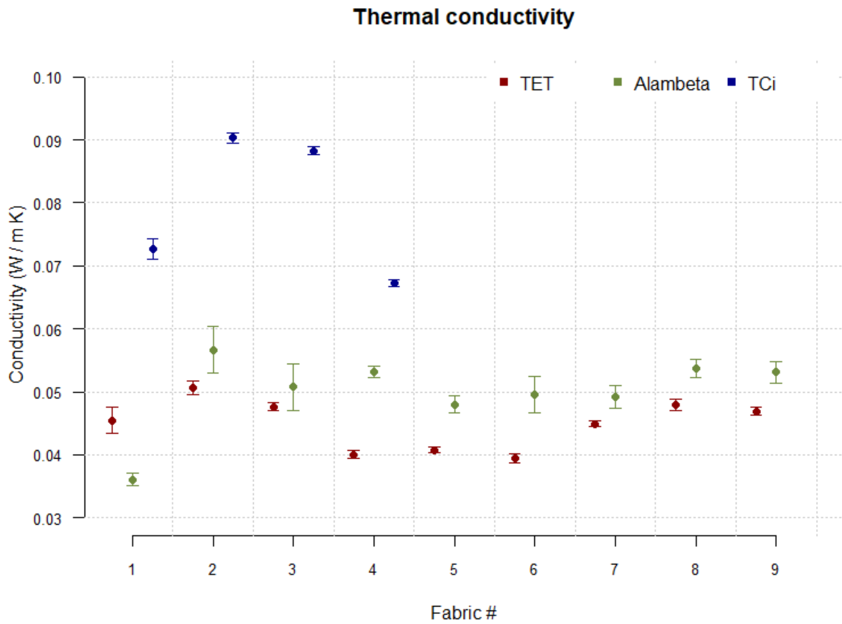

Figure 6. Thermal conductivity measured with Alambeta, TCi and TET; in mean values ± standard deviation.

Also, here, the applied pressure seems to play a decisive role in the obtained result. The higher the applied pressure, the thinner the fabric and hence the higher the measured conductivity. Due to the higher pressure applied in TCi, a significantly higher thermal conductivity was measured. Fabrics 1 and 4 show large differences among the three devices, most probably due to their resilient character. In textile apparel and home application, thermal insulation/conductivity is usually measured with other means, such as the compression-free "Sweating Guarded Hot Plate" test according to ISO 11092 [15].

Figure 7 shows a comparison of TET results with KES-f Thermo Labo (Q_{max}) results for 10 knitted and woven fabrics. Having different units in this case, the fabrics are compared in the trends or the ranking according to the value measured. Similar trends are obtained for most samples. The Pearson correlation factor between the two methods was 0.9.

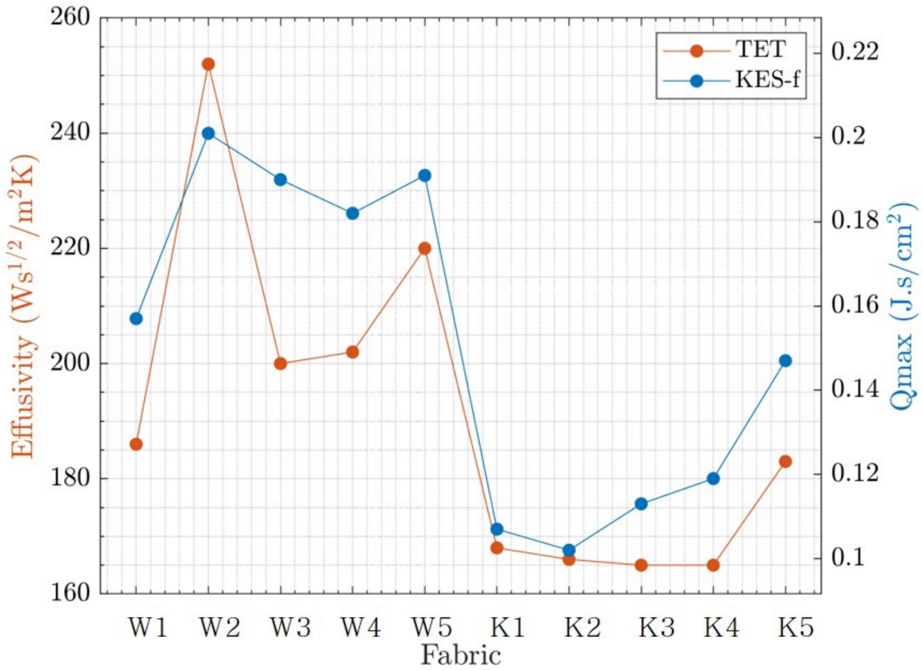

Figure 7. TET and Kawabata KES-f thermal effusivity results on woven (W) and knitted (K) fabrics.

5. Conclusions

Thermal effusivity measurements with TET were performed on different textile fabrics and the results show accordance with other commercially available measurement devices. A good correlation was achieved with Q_{max} from KES-f Thermo Labo. TET can therefore be considered reliable for assessing the thermal effusivity of textile fabrics and offers a flexible measurement approach that considers textile structure. Differences among the three devices occurred on rather fluffy constructions, which are more sensitive to the applied pressure in terms of compression behavior, which leads to different fabric densities C_p. The results obtained by TET and Alambeta devices on single-layered samples show that the minimal sample thickness indicated by ASTM D7948 should not be mandatory if heat break-through can be avoided. Less accordance among the test devices was observed in the thermal conductivity, where especially higher conductivity was measured with TCi due to the higher applied weight. The effect of fabric compression in fluffy/resilient fabric constructions and under different compressions relevant to wear situations is to be a subject of a more detailed study.

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