

Experimental Evaluation of Thermal Effusivity and Air Permeability of Locally Produced Cotton Fabrics from Burkina Faso

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Abstract

The objective of this paper is to provide additional data of thermal effusivity and air permeability of locally produced cotton fabrics, two key properties relevant for the assessment of thermal comfort. Selected cotton fabrics from Burkina Faso of knit and weave constructions were used in this study. The measurement of the thermal effusivity is obtained with TCi thermal conductivity analyzer, while the air permeability is obtained with an air permeability tester from Testex. Results suggest that the measured thermal effusivity is collectively affected by weave type, yarn ply, thickness and density. Moreover, the volumetric density rather than the thickness seems to drive the thermal conductivity and the thermal effusivity of the fabric.

Keywords

Cotton Fabrics, Thermal Effusivity, Air Permeability, Thermal Conductivity, Thermal Comfort

1. Introduction

Burkina Faso is one of the biggest producers of cotton in Africa. Currently, the country has a very low value addition in cotton processing. Most of the produced cotton is exported after ginning. A relatively small portion is industrially transformed by local companies. Recently, the country has undertaken some initiatives in order to increase the amount of locally transformed cotton, including the creation of new processing companies in order to industrialize the garment produc-

tion. Historically, the country is also known for its “Faso Dan Fani”, meaning “woven cloth of the homeland”, which was promoted during the 1980s and is now backed by official government labelling standards to preserve authenticity. Other initiatives include the development of washable sanitary towels.

Besides these developments, it appears necessary to have an insight on the quality of the produced garments, in order to provide the required thermal comfort to the wearer. Moreover, Burkina Faso as a Sahelian country faces higher temperatures. Despite these severe meteorological conditions, the clothing should provide the required comfort. Clothing comfort is a relatively complex function of construction design of fabrics as well as of the physiological state of the wearer. It is worth noting that clothing comfort can be assessed based on subjective or objective responses [1] [2].

It is not uncommon to use our tactile sense when choosing between different fabrics. This simple subjective technique is used oftentimes by consumers, but also in the apparel industry in order to have an insight of consumers preferences. Though the end user preference cannot be replaced by technology, alternative approaches using objective responses can be used to eliminate unlikely candidate fabrics and reduce the expenditure of resources required by the former method [2]. The perceived warmth or coolness through initial contact with a textile fabric is an indicator of comfort, influencing consumer preference and the functional performance of clothing and technical fabrics.

Though intuitively, one might think that the thermal conductivity of the fibers plays a critical role in such a scenario, the perceived warmth is due to the transient heat transfer and is actually related to the thermal effusivity [1].

Thermal effusivity, also described as thermal inertia, describes a material's ability to exchange heat with its surroundings or other materials with which it is in contact. A material with high thermal effusivity, such as a steel, will draw heat away from the skin rapidly, creating a sensation of coolness. On the other hand, a material with low effusivity, like wood, impedes this initial heat flow, resulting in a sensation of warmth. Hence, by measuring the thermal effusivity of textiles, the rate at which fabrics absorb heat when it comes in contact with skin can be inferred. This fact is exploited in the industry of sport in order to design clothing suited to a particular environment [3] [4]. Warm touch is typically suited to cold environments, and cool touch for hot environments. Thermal effusivity of textiles is not intrinsic to the fiber alone but is a complex function of the fiber type, yarn structure, fabric porosity, surface morphology, and moisture content [1]. Cotton fabrics are widely used and are very prized for their softness and comfort. For that reason, a number of studies on thermal conductivity of cotton fabrics have been reported in the literature, while thermal effusivity appears less explored [2] [5]-[15]. Furthermore, the wide variety of cotton fabric constructions results in a broad spectrum of effusivity values, the quantification of which is essential for optimizing fabric design for specific end-uses, such as next-to-skin summer wear or lined winter garments.

Therefore, this study aims to provide additional data by measuring and analyz-

ing the thermal effusivity of some locally made cotton fabrics with varying structural characteristics. The TCi device by C-Therm, which is based on the Modified Transient Plane Source (MTPS) technique, and was recently adopted as test standard ASTM D7984-16 for the measurement of the thermal effusivity of textiles, is used herein [16]. Moreover, fabric parameters like mass per unit area, thickness, thermal conductivity, and air permeability are measured, as we seek to investigate their relation with the resulting thermal effusivities.

The objective of this work is to obtain reliable thermal effusivity and air permeability values of selected cotton fabrics, and to have an insight of how fabric structure influences the initial “coolness” or “warmth” perception. The results are expected to guide textile engineers, product developers, and thermal physiologists seeking to engineer fabrics with targeted properties.

2. Materials and Methods

2.1. Fabric Samples and Ancillary Measurements

Four (4) commercially available 100% cotton fabrics were selected to represent a range of structural parameters commonly found in the market. The sample set included a plain weave voile made from a single white yarn for warp; a bleached plain weave voile made from double-ply yarn for warp and weft; a hand-loomed twill weave fabric; and a bleached single jersey knitted fabric made from organic cotton. The different fabrics are presented in **Figure 1** and their structural parameters are given in **Table 1**. From now on, the different fabrics will be referred to as Sample 1, Sample 2, Sample 3 and Sample 4, respectively, following the order above.

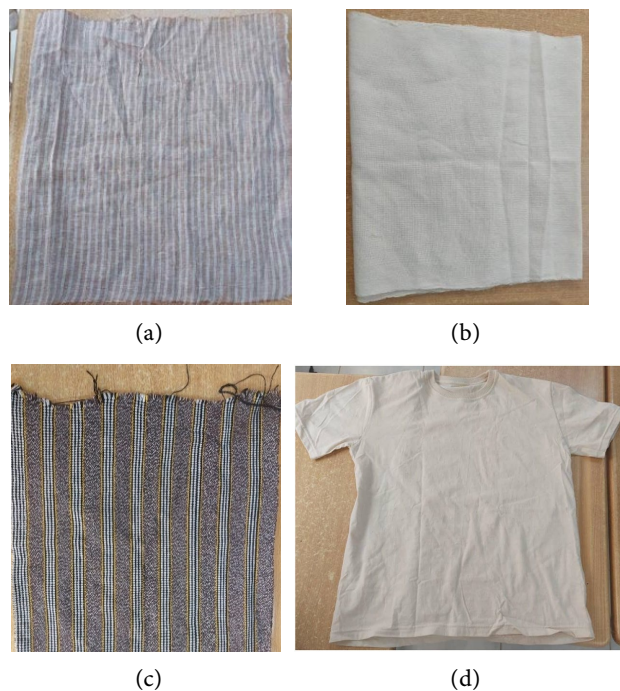


Figure 1. Samples of the cotton fabrics: (a) Plain weave single white yarn; (b) Plain weave double ply yarn; (c) Hand-loomed twill weave; (d) Single jersey knitted fabric.

Table 1. Samples of the cotton fabrics with associated structural parameters.

Sample	Construction	Key structural features
Sample 1	1/1 plain weave	Single white warp; patterned weft (3 grey/2 white repeat)
Sample 2	1/1 plain weave	Bleached; 2-ply yarn for both warp and weft
Sample 3	2/1 twill	Multi-coloured 2-ply and 3-ply weft yarns
Sample 4	Knit (stockinette/rib)	Ecru; stockinette body with 1 × 1 rib collar

It is well known from literature that some physical properties, like fabric thickness (mm), mass per unit area (g/m^2), and wetness, are related to the thermal effusivity of fabrics. Moreover, fabric air permeability (mm/s), also referred to as breathability, is strongly related to thermal comfort, hence is systematically measured. Herein, the fabrics are in a conditioned state, so the wetness is not considered. The thickness and the weights of the different fabrics were measured with a micrometer (Wilmart) and a precision balance (Sartorius Lab), respectively. The computation of both areal density and volumetric density is easily obtained from these measurements.

Prior to testing, all samples were kept in an ambient for 24 hours in an atmosphere of $68\% \pm 2\%$ relative humidity and $21^\circ\text{C} \pm 1^\circ\text{C}$.

2.2. Measurement of the Air Permeability



(a)



(b)



(c)

Figure 2. (a) Air permeability tester; (b) Test head; (c) Orifice plate.

The air permeability tester TM2101-T7 from Testex was used to measure the air permeability of the different samples. Air permeability measures the fabric's ability to allow airflow, which is crucial for convective heat loss and moisture vapor transport. **Figure 2** shows the permeability tester, which consists of a frame, a sample clamping mechanism, a flow control system, a display panel, and other components. The instrument uses a fan to draw air through a test head, which can be fitted with a circular aperture. The appropriate test head must be installed on the instrument depending on the specific test standard. Herein, we made use of the ISO 9237 test standard, so the pressure is set to 100 Pa and a test head of 20 cm² is selected, while different orifice plates are used. The clamping ring is then used to secure the sample and the orifice plate over the test head aperture. After that, the instrument is then ready for testing. The preset test pressure is automatically maintained, and the sample's breathability index is displayed directly in digital format and can also be printed. The measurements were performed with one specimen per sample, and for each specimen the test was repeated 05 times. The average is then reported as the measured air permeability and the uncertainties are computed by assuming a 99% confidence interval.

2.3. Measurement of the Thermal Effusivity

The thermal effusivity of the fabric samples was measured using a C-Therm TCI Thermal Conductivity Instrument [17]. This measurement device is based on the Modified Transient Plane Source (MTPS) method, and consists of a sensor, a power control unit, and a computer software (see **Figure 3**).

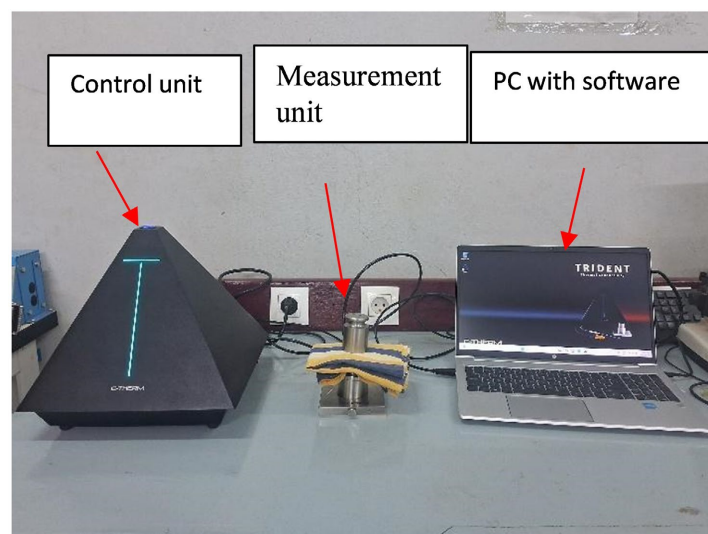


Figure 3. Trident TCI-thermal conductivity instrument.

The method makes use of a one-sided interfacial sensor which consists of two parts: a coiled heat source and a guard ring around the coil. The sample fabric is placed on the surface of the sensor, which applies a short-duration heat flux to the sample, typically 1 - 3 seconds. Hence generating a small amount of heat by Joule

effect, that penetrates the sample material in contact with the sensor.

The guard ring surrounding the coil heat source ensures that the heat transfer to the sample is approximately one-dimensional. The applied current to the coil results in a temperature increase at the interface between the sensor and the sample, which induces variation in the voltage drop of the sensor and is used to determine the thermophysical properties of the sample. The rate of this temperature rise is directly and uniquely related to the material's ability to absorb heat.

The instrument's software analyses the transient temperature profile based on a solution to the heat diffusion equation for a semi-infinite solid. The voltage $\Delta V(t)$ required to maintain the constant heat flux is monitored, and the thermal effusivity e of the sample is retrieved from the following relationship [17]:

$$\Delta V(t) = m\sqrt{t}$$

where m is a function of both sample and sensor thermal effusivities, as well as the applied heat flux and other related variables. By fitting the theoretical curve to the measured data, the system directly outputs the thermal effusivity value in $\text{W}\cdot\text{s}/\text{m}^2\cdot\text{K}^{-1}$. By exploiting the same data set used for the measurement of the sample's effusivity, a measurement of the thermal conductivity is also provided simultaneously.

A key advantage of this method for textile testing is that it is one-sided and non-destructive, requiring no special sample preparation and accommodating the compressible nature of fabrics.

For each experiment, a 500 g weight was placed on top of the sample in order to ensure a good contact pressure between the sample and the sensor. Given the measuring head diameter of 18 mm, the calculated pressure is 19 kPa. In order to ensure the semi-infinite assumption underlying the MTPS technique, a multilayer configuration was adopted. That is, different layers of the fabrics were formed by constituting different plies (see the sample in **Figure 3**).

For each sample, five consecutive measurements were performed using the insulation calibration without contact agent. The results of the different measurements were then averaged and the uncertainties were computed by assuming a 99% confidence interval.

3. Results and Discussions

Table 2 presents some additional features of the selected cotton fabrics under study. Both thickness and areal density were obtained through measurements as previously mentioned. A close look to **Table 2** enables us to describe Sample 1 as the thinnest and lightest and Sample 3 as the thickest and heaviest. Both Samples 2 and 4 can be defined as moderately thick in comparison with Samples 1 and 3. Although the volumetric density is not measured, an estimate can be obtained by simply dividing the areal density by the thickness. These estimates are also given in **Table 2**. The uncertainties reported in **Table 2** were computed from manufacturer specifications and uncertainty propagation.

Table 2. Measured thickness and areal density of the selected cotton fabrics.

	Sample 1	Sample 2	Sample 3	Sample 4
Thickness (mm)	0.23 ± 0.01	0.98 ± 0.01	1.26 ± 0.01	0.92 ± 0.01
Areal density (g/m²)	133 ± 5	206 ± 5	339 ± 5	223 ± 5
Volumetric density (g/cm³)	0.578 ± 0.033	0.210 ± 0.006	0.269 ± 0.006	0.242 ± 0.006

We recall that thermal effusivity governs the transient heat exchange during the first fraction of a second when skin contacts the fabric. It is the objective measure of the warm-cool feeling of a fabric. **Table 3** presents the measured thermal effusivities for the different samples, as well as the thermal conductivity and the air permeability.

By examining the reported results, one can notice that Sample 1 has the highest thermal effusivity, followed by Sample 4, and then by Samples 2 and 3, respectively. Otherwise stated, Sample 1 exhibits the strongest cool touch sensation, making it more convenient for hot environment or active wear, while Sample 3 displays the warmest initial feel, hence is suitable for cold weather applications. Overall, the wide range of thermal effusivities ($139.1 - 241.6 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\cdot\text{K}$) demonstrates that structural modifications can substantially alter the tactile thermal experience, consistent with literature reporting cotton fabrics' effusivity values ranging from 0 to $400 \text{ (W}\cdot\text{s}^{1/2}/\text{m}^2\cdot\text{K})$ [18]-[20]. Besides, recent studies based on Finite Element Modelling (FEM) have established quantitative relationships between woven fabric structure and thermal properties [21]. These models show that increasing fabric density directly leads to higher thermal conductivity and higher thermal effusivity [21]. It can be noticed that these findings are consistent with the measured thermal properties of Sample 1 and Sample 2. The rationale behind this is that the increasing of fabric density reduces the amount of trapped air in its pores. Given that air has insulating thermal properties, its reduction has a positive effect on the fabric thermal properties. It should be noted, however, that while the relative trend between Sample 1 and Sample 2 holds true, the thermal properties in **Table 3** reflect a multi-layer stacked state under a 500 g contact mass. This localized compression and the presence of interfacial contact resistance alter the exact in-test structural dimensions relative to the uncompressed single-layer densities in **Table 2**. Nonetheless, the underlying structural differences between the samples remain the dominant driver of the observed thermal behavior.

Table 3. Measured thermal properties and air permeability of the selected cotton fabrics.

	Sample 1	Sample 2	Sample 3	Sample 4
Thermal Effusivity (W·s^{1/2}/m²·K)	241.6 ± 0.5522	171.3 ± 1.2241	139.1 ± 1.5193	196.1 ± 0.8952
Thermal conductivity (W/m·K)	0.0863 ± 0.0003	0.0574 ± 0.0003	0.0494 ± 0.0003	0.0653 ± 0.0003
Air permeability (mm/s)	1139.5 ± 57.91	899.7 ± 46.74	430.2 ± 26.92	674.6 ± 11.38

Also reported in **Table 3**, are the thermal conductivities of the different fabrics' samples obtained simultaneously with the C-Therm TCi thermal conductivity Analyzer. Differently from thermal effusivity, thermal conductivity determines how efficiently heat flows through the fabric under steady-state conditions. It is worth noting that the ranking of the measured thermal conductivities mirrors that of effusivity, showing that both transient and steady-state thermal behaviours are probably governed by the same structural factors.

The relatively high thermal conductivity (0.0863 W/m·K) of Sample 1 reflects its dense (the highest volumetric density in **Table 2**), compact plain weave with minimal trapped air. On the other hand, the low thermal conductivity (0.0494 W/m·K) of Sample 3 results from its thick (1.26 mm) twill structure and plied yarns, which introduce substantial dead-air spaces.

On the other hand, although both Sample 1 and Sample 2 have 1/1 plain weave construction, Sample 1 is the thinnest and has the lowest areal density, yielding a volumetric density nearly three times higher than Sample 2. As a consequence, this high fiber packing density reduces trapped air, increasing both thermal conductivity and effusivity.

The measured air permeability of the different samples is also presented in **Table 3** above. As can be noticed, the measured air permeabilities show an exploratory strong positive linear trend with the thermal conductivities and effusivities within this specific sample set. Indeed, the computed correlations are 0.8515 and 0.8430, respectively for thermal effusivity and thermal conductivity. However, the computed p-values are 0.1485 and 0.1570, respectively, due to the limited sample size. Sample 1 has the highest air permeability (1139.5 mm/s), and is approximately three times that of Sample 3, revealing its open, thin plain weave construction. On the other side, the low air permeability (430.2 mm/s) of Sample 3 is consistent with its dense twill structure and heavy yarns, which restrict airflow.

From the foregoing analysis, the following conclusions can be drawn: 1) Thermal effusivity is highly sensitive to how densely the cotton fibers are packed into the fabric's thickness. In fact, by packing more solid cotton per unit volume, Sample 1 achieves the highest volumetric density. From the definition of thermal effusivity, one can notice that it is proportional to the volumetric density. As a consequence, Sample 1's higher volumetric density yields the highest thermal effusivity (241.6 W·s^{1/2}/m²·K), so the strongest cool-touch. 2) On the other side, the lower value of the thermal effusivity of Sample 3 can be attributed to its 2/1 twill weave construction with heavy 2-ply and 3-ply yarns, which creates room for dead-air. Given that air is a poor heat conductor, the fabric's effective thermal conductivity is lowered; hence, the thermal effusivity; thus, making it feel warm to the touch.

4. Conclusions

The obtained results suggest that fabric construction parameters, weave type, yarn ply, thickness and density collectively affect the measured thermal effusivity.

Within the scope of the present study, plain weave with single white yarn for warp

and patterned weft (Sample 1) offers maximum cooling, breathability, and heat dissipation; hence, ideal for summer. However, the handwoven twill fabric with plied yarns (Sample 3) provides maximum warmth and insulation; thus, it is suitable for cold-weather applications.

The experimental results corroborate theoretical models and previous experimental studies on the relationship between fabric structure and thermal properties.

Although the present study allowed us to have an insight on the impact of some construction parameters on the measured properties, it has considered a limited number of samples. Future studies will consider a larger sample size and build specific batches in order to isolate the effects of areal mass, thickness, density, weave, yarn count and twist; hence, which will strengthen our understanding of the sought relationships.

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Author Contributions

B. Lamien and I. Tougri have performed the experimental measurements. I. Pezaco has prepared the fabric samples. E.M. Ouedraogo has prepared the experimental protocol of the air permeability tester. B. Lamien prepared the results and drafted the manuscript. B. Lamien, I. Tougri, H. Sorgho and M. Beidari made critical revisions to the manuscript. All authors revised and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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