Development of Experimental Setup for Measuring the Thermal Conductivity of Textiles

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Abstract

The thermophysical properties of textile materials are very important in helping to understand the thermal comfort of fabrics for clothing and technical textiles. An experimental setup for the measurement of the thermal conductivity of fabrics was developed based on the heat flow meter principle. The setup was considered highly accurate and reliable based on the low absolute error, high correlation coefficient, and the coefficient of determination between the results from the setup and commercially available devices. The setup is easy to use for testing any textile-based materials and their composites.

Keywords

effective thermal conductivity, comfort, material science, textile performance, thermal comfort, thermal insulation, textile clothing

The most important thermal property of fabric is insulation against the heat flow in a cold environment to keep the normal body temperature. Thermal-insulation properties of textile materials play a significant role in material engineering of protective clothing and it depends on the structural parameters of the fabric and the nature of fiber (Epps & Song, 1992; Starr, Cao, Peksoz, & Branson, 2015). Thermal-insulation properties are very important from the point of view of thermal comfort of a wearer as well as clothing protective efficiency against low or high temperature; it depends on the thermal conductivity and thermal resistance of the fabric (Matusiak & Kowalczyk, 2014). The overall or effective thermal conductivity ($K_{\text{eff}}$) of fabric can be calculated by Fourier’s law of conduction:

$$K_{\text{eff}} = \frac{Q \cdot h}{A \Delta T} \quad \text{(W/m.K)} \quad (1)$$

where $Q$ is the heat flow, $A$ is the surface area, $h$ is the thickness of fabric and $\Delta T$ is the temperature difference.

The thermal resistance indicates the ability of a fabric to provide the thermal barrier to the wearer (Huang, 2006). The insulation property of fabric is measured by thermal resistance. Thermal resistance ($R$) of fabric is defined as the ratio of temperature difference to the rate...
of heat flow per unit area. The thermal resistance of fabric can be expressed by electrical analogy according to the Ohm’s Law:

\[ R = \frac{\Delta T}{Q/A} \] (Thermal Resistance)  \[ R = \frac{\Delta V}{I} \] (Electrical Resistance)  
\[ (m^2 \cdot K/W) \]  \[ (V/Amp) \]  

where \( Q \) is the heat flow, \( A \) is the surface area, \( \Delta T \) is the temperature difference, \( \Delta V \) is the potential difference and \( I \) is the current flow.

Thermal resistance can also be calculated by the effective thermal conductivity of fabric:

\[ R = \frac{h}{K_{eff}} \]  
\[ (m^2 \cdot K/W) \]  

where \( h \) is the thickness of the fabric.

The overall thermal conductivity of fabric can be measured by three different methods (Ukponmwan, 1993):

1. two plate method, in which a fabric is placed between the two metallic plates where there is temperature gradient;
2. cooling method, in which a fabric is placed on hot surface and the other face of fabric is exposed to air; and
3. constant temperature method, in which a fabric is wrapped around the heating source.

There are several commercial instruments available which work on the principles of the above-mentioned methods.

Two Plate Method

In the two plate method, the fabric is placed between the two plates which have a temperature gradient, heat flows from hot plate to cold plate. In this method, thermal conductivity can be determined by the steady-state method or transient method. There are several devices available under the two plate category but they have different arrangements in the measurement of the thermal conductivity and thermal resistance of fabrics:
1. Hot plate with reference samples;
2. Hot plate with guarded heater; and
3. Hot plate with heat flow meter or transducer.

In order to determine the thermal conductivity and thermal resistance of fabric, it is necessary to know the heat flow rate per unit area (heat flux). It is difficult to measure the heat flux in a specific direction even with the use of heater with which power supply is known because it dissipates heat in all directions. There are two different ways to measure the heat flow through the fabric: one is to use reference sample of known thermal resistance to compare with the testing sample and the other is to eliminate the heat loss which does not pass through the fabric to be tested (Saville, 2002).

The Togmeter (manufactured by The Shirley Institute) is the device which works on the principle of using a reference sample. The testing arrangement of the apparatus is that all the conductors (fabrics) are placed in series with respect to the direction of heat flow and with fixed pressure to avoid the convection heat loss.

The thermal resistance of the fabric is equal to the ratio of the temperature difference across the two conductors next to the two faces of tested fabric. It is equivalent to the ratio of their thermal resistance which is analogous to the electrical circuit when two conductors are connected in series. The sketch of Togmeter with two plates is shown in Figure 1.
During the testing, the sample (330 mm in diameter) is placed on the reference fabric (with known thermal resistance) which is heated by a temperature controlled hot plate. The top plate (insulated) needs to be closed gently to avoid compression of the sample. The details about the testing method can be found in BS 4745:2005 (BSI, 2005). The following three temperatures are obtained at steady-state conditions:

1. $T_1$: the temperature at hot plate;
2. $T_2$: the temperature between the upper surface of reference fabric and lower surface of tested specimen; and
3. $T_3$: the temperature in between the upper surface of the test specimen and top plate.

The thermal resistance of the test specimen is calculated by:

$$\frac{R_f + R_c}{R_s} = \frac{T_2 - T_3}{T_1 - T_2}$$

where $R_f$, $R_c$ and $R_s$ are the thermal resistance of the specimen, contact and standard respectively.

KES-F7 Thermo-Lab-II (manufactured by Katotech Ltd.) works on the two plate method with guarded heater to ensure that heat only passes through the tested fabric. The testing arrangement is that fabric sample (5 x 5 cm) is placed on a cold plate which is attached to a

**Figure 1**: Togmeter: two plate method
water box at room temperature. The temperature controlled hot plate (B.T- Box) with the accuracy of ±0.1°C is placed over the fabric sample as shown in Figure 2 (a). When steady-state condition achieved the heat loss from the B.T- Box will be displayed on the panel. The heat loss is calculated on the principle of the electric power supplied to the heater by using a multiplier as illustrated in Figure 2 (b). The detailed information about the testing method can be found in KES-F7 Thermo-Lab-II B (KES-F7, 1983). The effective thermal conductivity ($K_{eff}$) of fabric sample can be calculated by:

$$K_{eff} = \frac{W \cdot h}{A \Delta T} \quad (W/cm. ^\circ C) \quad (5)$$

where $W$ is the heat loss (mW or W), $h$ is the thickness of sample (cm), $A$ is the area of B.T-heat plate (cm²) and $\Delta T$ is the temperature difference across the sample (°C).

Figure 2: (a) Thermo-Lab-II for thermal conductivity measurement and (b) circuit-diagram of B. T. Box ("KES-F7 Thermo-Lab-II B, precise and fast Thermal-property measuring instrument,"
DTC-25 (manufactured by TA Instruments) works on the principle of heat flow meter method in which a heat flux sensor is attached to a heat sink cooled by liquid. The testing arrangement is that the sample (50 mm in diameter) is placed between the two plates under a compressive load and uses thermal interface pastes to avoid the contact thermal resistance as shown in Figure 3 (a). An axial temperature difference is achieved between the two plates, heat flows from heat source (the hot plate) to the cold plate, presented in Figure 3 (b). When steady-state condition reaches the temperature difference across the sample is measured by the temperature sensor installed on the surface of plates. Heat flux is measured by the heat flux sensor. The detailed information about the testing method can be found in ASTM E1530 (ASTM, 2006). The effective thermal conductivity ($K_{\text{eff}}$) of the sample can be calculated by:

$$K_{\text{eff}} = \frac{Q}{A \Delta T/h}$$

(6)

where $Q$ is the heat flow, $A$ is the cross-sectional area, $\Delta T$ is the axial temperature difference and $h$ is the thickness of sample.

**Figure 3:** (a) Test Section Schematic and (b) Heat flow mechanism ("DTC-25. Thermal conductivity meter ", 2014)
The Alambeta developed at the Technical University of Liberec (Czech Republic) has been used to simulate the first moment of the contact of human skin with fabric (warm-cool-feelings) by using the term thermal absorptivity, shown in Figure 4(a).

Heat flows from the skin to fabric which has a lower temperature than skin. The Alambeta is used to measure transient and steady-state thermo-physical properties of the fabric. The arrangement of the device is that sample (5) is placed on a plate located at the instrument base (6) and top plate with a heat flow sensor (7) connected to a copper block (2) which has temperature controller maintaining the constant temperature difference from the sample.

During the testing, the sample is placed between the two measuring heads both have heat flow sensors as shown in Figure 4 (b). When the top measuring head comes down and touches the sample, the sudden transient heat flow is measured by the Alambeta and different parameters are obtained such as thermal conductivity, thermal absorptivity, the ratio of maximum heat flow density to stationary heat flow density \( \frac{q_{\text{max}}}{q_{\text{st}}} \), thermal diffusion, thermal resistance, and thickness of sample by photoelectric sensor. The detailed information about the testing method can be found in SENSORA 1990 (SENSORA, 1990).

**Cooling Method**

The guarded hot plate method has also been used to evaluate the thermal transmittance of textile fabrics. It works on the principle that the fabric is placed over the heated plate maintained at a constant temperature in the range of human skin comfort temperature (33-36°C) and the upper surface of the fabric is exposed to the air. The arrangement of the apparatus is that the heater is sandwiched between two aluminum plates and test plates are surrounded by a guard ring to ensure that all heat passes through the fabric without any heat loss, illustrated in Figure 5. A test apparatus placed inside the chamber for maintaining nearly still air conditions has a temperature range between 4.5 and 21.1°C (40 to 70°F).

During testing when the equilibrium or steady-state condition is reached, the temperature of the hot plate and air above 500 mm from test plate inside the chamber is measured. The detailed information about the testing method can be found in ASTM D 1518-85 (ASTM,
The heat flux value determined by the power supplied to the heater to maintain the temperature and the overall thermal transmittance of fabric with air can be calculated by:

\[
U_i = \frac{P}{A \times (T_p - T_a)} \quad \text{(W/m}^2\text{K)} \quad (7)
\]

where \( P \) is the power loss from test plate (W), \( A \) is the area of test plate (m\(^2\)), \( T_p \) is the test plate temperature (°C) and \( T_a \) is the air temperature (°C).

**Figure 5**: Guarded hot plate instrument: (a) top view and (b) side view.
The thermal transmittance of fabric alone can be calculated by subtracting the thermal transmittance of the bare plate ($U_{bp}$):

$$U_2 = \frac{U_1 U_{bp}}{U_{bp} - U_1} \quad \text{(W/m}^2\text{.K)} \quad (8)$$

The intrinsic thermal conductivity or effective thermal conductivity ($K_{eff}$) of the fabric alone can be calculated by the following equation.

$$K_{eff} = \frac{U_2 \times h}{1000} \quad \text{(W/m.K)} \quad (9)$$

where $h$ is the thickness of sample (mm).

**Constant Temperature Method**

The basic concept of the constant temperature method is that fabric sample is to wrap around the hot body and the amount of energy required in maintaining the constant temperature difference between the fabric and coolant normally being the air. The general arrangement of apparatus consists of cylinder heater on which fabric sample is wrapped, the end of the cylinder properly insulated and the chamber. The cylinder is heated electrically and at steady-state conditions, the thermal conductivity of fabric can be calculated by measuring the amount of energy required to maintain the temperature difference between the cylinder surface and the air in the chamber (Ukponmwan, 1993).

**Rationale**

The knowledge of thermo-physical properties of textile materials is important to understand the thermal comfort of the fabric. Accurate and highly efficient thermal measurement of material is the key for the development of products that have thermal transport applications such as thermo-regulation, thermal comfort, thermal protection, thermal insulation and more.

Thermal property evaluation technique should be reliable and accurate. The thermal conductivity is one of the thermal properties influencing the heat transfer behavior of fabrics.
For this purpose, an experimental setup was designed and developed which is capable of testing thermal conductivity by using one plate and two plate methods.

The developed experimental setup is different from commercially available instruments mentioned above. A Proportional-Integral-Derivative (PID) controller and highly sensitive heat flux sensor were used to control the temperature of the heater, and it is designed with the consideration of small sample size, fast testing, high accuracy and reproducibility of testing results.

In this research, an in-house experimental setup was developed to measure the thermal conductivity of fabric by using two plates heat flow meter method. The heat flow meter method has a high accuracy and reliable method in determining the thermal conductivity of anisotropic fabric material when heat flows in one direction as compared to the other methods explained above.

**Design and Development of Experimental Setup**

The 3D model of the experimental setup is illustrated in Figure 6. Based on the motivation discussed above, the experimental setup was developed in three steps:

1. Hot plate development;
2. Cold plate development; and
3. Heat flow data acquisition.
Figure 6: 3D model of experimental setup (Siddiqui & Sun, 2016)

Hot Plate Development

A halogen-free thermoplastic box was used to enclose the controller; it provides the base of the hot plate. A fiberglass insulation plate is fastened in the center of the box to avoid the effect of excessive heat build-up during the heating process especially in steady-state analysis with one plate as shown in Figure 7(a).

An OMEGALUX® Kapton® insulated flexible heater shown in Figure 7(b) is used to heat the aluminum plate (50 × 50 mm) acted as a hot plate. The construction of flexible heater is that the etched foil element which is encapsulated between the layers of Kapton® and Teflon® adhesives. The selection criteria are: Kapton® is polyamide film produced by Dupont® which can withstand at high temperature and the operating temperature range of flexible heater is -200 °C to 200 °C.

The heater was mounted on top of the fiberglass plate and an aluminum plate was placed and fixed over the heater. A slight groove was made on the aluminum plate to fix the K-Type
thermocouple which was connected to the controller to maintain the temperature of the hot plate.

A CN7800 controller manufactured by Omega was used to control the temperature of the heater as shown in Figure 7 (b). It works with a wide variety of thermocouples (B, E, J, K, L, R, S, T, U and W) with temperature range covering from -212 °C to 1820 °C. K-type thermocouples have been used to measure the temperature of hot and cold plates. The selection criteria are: (1) the available control options of the controller are: on/off, PID (Proportional-Integral-Derivative), auto-tune and manual-tune; and (2) the measuring error of the controller is below ±0.25% and the temperature fluctuation of the heater is within ±0.1°C.

The controller controls the heater by the PID operation mode. The PID controller provides proportional with integral and derivative control. This controller combines the proportional control with two additional adjustments, enabling the unit automatically compensate any changes in the system. The proportional, integral and derivative terms must be individually adjusted or “tuned” to a particular system, using a “trial and error” method. It provides the most accurate and stable control over on/off and proportional controller. In fact, the temperature of the hot plate is controlled indirectly by a heater which gives more stable temperature control of ±0.1°C of the surface of the hot plate.
Figure 7: Experimental Setup; (a) hot plate arrangement of experimental setup (Siddiqui, 2015) and (b) photograph of experimental setup during testing.
Cold Plate Development

A fan heat sink was used to maintain the temperature gradient between hot and cold plates. An aluminum plate was connected with fan heat sink which has a K-type thermocouple. A thermocouple was connected similarly to the hot plate. A fan heat sink from StarTech as shown in Figure 7 (b) is used to connect to the aluminum plate acted as a cold plate, the amount of pressure applied by the cold plate is 3.2 gf/cm² which is less than the Thermo-Lab-II (KES-F7, 1983). The selection criteria are: the dimension of the aluminum heat sink is 50 × 50 mm and fan speed is around 5000 rpm to meet design specification of sample size and capability of maintaining the surface temperature of the cold plate which is up to 25 ºC. AC/DC power supply is used to provide 12V DC to the fan heat sink. Kapton® Flexible heater works on 115Vac input voltage and CN7800 PID controller works in the range of input voltage of 100-240Vac, therefore a Step-down transformer is used to step down the voltage from 230 to 115 Vac.

Heat Flow Data Acquisition

A CAPTEC flat plate heat flux sensor (50 × 50 mm) shown in Figure 7(b) is used to measure the heat flux passing through the fabric. The sensor is constructed by a thin foil sensor which is sandwiched between the two copper plates. The thin foil sensor is made of the thermoelectric panel which is laminated between the polymeric layers.

When the thermal sensor comes in contact with the surface of fabric sample which produces or absorbs heat, it creates the temperature difference across the surface of a sensor. The temperature difference generates the voltage which is proportional to the heat flow through the sensor. The selection criteria are: (1) the operating temperature range and sensitivity of sensor are -180 ºC to 200 ºC and 16.8 $\mu$Volt/(W/m²) respectively; and (2) the operating temperature range and size of the sensor match with the heater.
A MASTECH MS8218 Multimeter shown in Figure 7 (b) is used to measure the voltage generated from the heat flux sensor. The selection criteria are: (1) it has 50000 counts measurement capability with maximum 0.01Ω resistance resolution and 1µV voltage resolution; (2) it can be connected to a computer by RS-232C connector; and (3) it is able to record and analyze collected data by software MS2818 V1.6.

**Testing Procedure for Thermal Conductivity and Thermal Resistance Measurement**

The entire test was conducted in standard conditions at temperature of 20±2°C and 65±2% relative humidity. The samples were cut in a defined square shape 50 × 50 mm dimension and conditioned for 24 hours before they were tested. During the testing, the sample was placed between the hot and cold plate as shown in Figure 7 (b).

The hot plate temperature was maintained by the PID controller at 35 °C which is within the range of normal human body temperature. The temperature of the cold plate is controlled by a fan heat sink. A heat flux sensor with a sensitivity of 16.8 \( \mu \text{volt}/(\text{W/m}^2) \) was used with a cold plate to measure the amount of heat flow through the sample caused by the temperature difference. Temperature sensors were connected with hot and cold plates to measure the temperature difference across the sample. When steady-state condition has been achieved the voltage generated from the heat flux transducer will be obtained from a software MS2818 V1.6.

MS2818 V1.6 is capable of generating voltage report received from the heat flux sensor, the voltage report is then exported in CSV (Comma Separated Values) file which can be analyzed in Microsoft Excel spread-sheet applications. It is very useful to obtain the heat flux values with respect to time for MicroPCMs coated fabric.

The data obtained from the heat flux sensor in millivolt needs to be converted to heat flux in order to calculate the thermal conductivity. Voltage value can be converted into heat flux by dividing the sensitivity value of heat flux sensor as shown in Equation 10.
\[ Q = \frac{V}{S} \]  

(10)

where \( V \) is the output of heat flux sensor and \( S \) is heat flux sensor sensitivity.

The effective thermal conductivity (\( K_{\text{eff}} \)) and thermal resistance of sample can be calculated by the following Equations:

\[
K_{\text{eff}} = \frac{Q \times h}{\Delta T} \quad \text{(W/m.K)} \quad (11)
\]

\[
R = \frac{h}{K_{\text{eff}}} \quad \text{(m}^2\text{.K/W)} \quad (12)
\]

**Validation of Experimental Setup**

In order to test the accuracy of experimental setup the thermal conductivity of fabric samples was tested using the developed device and the results were compared to results from commercial instruments. The material specifications of samples which were tested for the validation of the in-house developed device are presented in Tables 1 to 4. They were made for different applications such as protective clothing, insulation, and so forth. It is worth noting that not all of the fabric samples used for this research work were tested by all commercial instruments for the purpose of device validation due to limited availability of testing facilities.

**Table 1:** Fabric specifications of plain weave fabric

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Nomex® III</th>
<th>Twaron®</th>
<th>Wool</th>
<th>Poly-Viscose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areal density (g/m²)</td>
<td>170±3</td>
<td>150±4</td>
<td>130±3</td>
<td>98.0±2</td>
</tr>
<tr>
<td>Warp/Weft sett (per inch)</td>
<td>59/59</td>
<td>19.8/19.8</td>
<td>70/45</td>
<td>75/85</td>
</tr>
<tr>
<td>Warp/Weft Yarn linear density (Tex)</td>
<td>33.3/33.3</td>
<td>93/93</td>
<td>27.8/27.8</td>
<td>7.798/19.6</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.5</td>
<td>0.348</td>
<td>0.408</td>
<td>0.341</td>
</tr>
</tbody>
</table>
Table 2: Specifications of plain weft knitted fabrics

<table>
<thead>
<tr>
<th>Fabric Code</th>
<th>Fibre Type</th>
<th>Yarn Count (Tex)</th>
<th>wpc</th>
<th>cpc</th>
<th>SL (mm)</th>
<th>h (mm)</th>
<th>Areal Density (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Polyester (MF)</td>
<td>27.0</td>
<td>3.2</td>
<td>5.6</td>
<td>8.220</td>
<td>0.49</td>
<td>40.4</td>
</tr>
<tr>
<td>F2</td>
<td>Polyester (MF)</td>
<td>20.0</td>
<td>6.4</td>
<td>9.6</td>
<td>4.930</td>
<td>0.47</td>
<td>61.0</td>
</tr>
<tr>
<td>F3</td>
<td>Polyester (MF)</td>
<td>27.0</td>
<td>7.4</td>
<td>9.0</td>
<td>5.020</td>
<td>0.49</td>
<td>92.0</td>
</tr>
<tr>
<td>F4</td>
<td>Cotton (SF)</td>
<td>40.0</td>
<td>6.0</td>
<td>7.5</td>
<td>5.910</td>
<td>0.8</td>
<td>104.62</td>
</tr>
<tr>
<td>F5</td>
<td>Viscose (MFF)</td>
<td>33.5</td>
<td>6.0</td>
<td>9.6</td>
<td>5.083</td>
<td>0.648</td>
<td>102.3</td>
</tr>
</tbody>
</table>

MF: Monofilament; MFF: Multifilament; SF: Staple fibre; SL: Stitch length wpc: Wales per cm; cpc: Course per cm; and h: thickness

Table 3: Fabric specifications of plain weave PCM coated fabric

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Nomex® III</th>
<th>Wool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, mm</td>
<td>0.68</td>
<td>0.56</td>
</tr>
<tr>
<td>Warp/Weft sett (No. ends/picks per inch)</td>
<td>59/59</td>
<td>130±3</td>
</tr>
<tr>
<td>Warp/Weft Yarn linear density (Tex)</td>
<td>33.3/33.3</td>
<td>70/45</td>
</tr>
</tbody>
</table>

Table 4: Fabric specifications of nonwoven fabric

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Sample-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areal density (g/m²)</td>
<td>78.133</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.54</td>
</tr>
<tr>
<td>Fibre Material</td>
<td>polypropylene</td>
</tr>
</tbody>
</table>

Comparisons between the results obtained from developed experimental setup and different commercial instruments are presented in Table 5 and Table 6. Different construction methods of samples have been tested to evaluate the effectiveness of the developed instrument. The results obtained from the Togmeter have a higher absolute error. This is
caused by the high pressure applied on the top plate of Togmeter, as a result, fabrics were
compressed and gave higher thermal conductivity because of less air presented in the fabric
samples. The low mean absolute error between the newly developed device and commercial
instruments tested results of thermal conductivity and thermal resistance was found 7.94276
and 8.554858 respectively. A very high correlation coefficient and coefficient of
determination between results obtained by the developed experimental setup and commercial
instruments are shown in Figure 8 (a) and Figure 8 (b). By using statistical analysis ANOVA,
the significance of the regression model of thermal conductivity and thermal resistance was
computed, by using JMP shown in Figure 8 (a) and Figure 8 (b). The p-values were lower
than 0.0001 for both regression model indicating strong evidence that developed
experimental setup and commercial instruments have a strong linear relationship.

Table 5: Comparison of thermal conductivity obtained from developed experimental setup
and commercial instruments

<table>
<thead>
<tr>
<th>Fabric Code</th>
<th>In-house Developed Experimental Setup (W/m.K) (A)</th>
<th>Commercial Instruments (W/m.K) (B)</th>
<th>Absolute Error (\frac{(B - A)}{B} \times 100) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomex® III</td>
<td>0.0500</td>
<td>0.0521 (Togmeter)</td>
<td>4.03071</td>
</tr>
<tr>
<td>Twaron®</td>
<td>0.0410</td>
<td>0.048 (Togmeter)</td>
<td>14.58333</td>
</tr>
<tr>
<td>Wool</td>
<td>0.0414</td>
<td>0.049 (Togmeter)</td>
<td>15.5102</td>
</tr>
<tr>
<td>Poly-Viscose</td>
<td>0.0484</td>
<td>0.042 (Togmeter)</td>
<td>15.2381</td>
</tr>
<tr>
<td></td>
<td>0.0350</td>
<td>0.0383 (Alambeta)</td>
<td>8.616188</td>
</tr>
<tr>
<td>F1</td>
<td>0.0377</td>
<td>0.0401 (Alambeta)</td>
<td>5.985037</td>
</tr>
<tr>
<td>F2</td>
<td>0.0403</td>
<td>0.0418 (Alambeta)</td>
<td>3.588517</td>
</tr>
<tr>
<td>F3</td>
<td>0.0430</td>
<td>0.044 (Alambeta)</td>
<td>2.272727</td>
</tr>
<tr>
<td>F4</td>
<td>0.0412</td>
<td>0.0399 (Alambeta)</td>
<td>3.258145</td>
</tr>
<tr>
<td>F5</td>
<td>0.0890</td>
<td>0.09 (DTC-25)</td>
<td>1.111111</td>
</tr>
<tr>
<td>Nomex® III with PCM</td>
<td>0.0720</td>
<td>0.08 (DTC-25)</td>
<td>10</td>
</tr>
<tr>
<td>Wool with PCM</td>
<td>0.0373</td>
<td>0.042 (Alambeta)</td>
<td>11.11905</td>
</tr>
<tr>
<td>Sample-1</td>
<td>0.003055</td>
<td>0.042 (Alambeta)</td>
<td>11.11905</td>
</tr>
</tbody>
</table>
Table 6: Comparison of thermal resistance obtained from developed experimental setup and commercial instruments

<table>
<thead>
<tr>
<th>Fabric Code</th>
<th>In-house developed Experimental Setup (m².K/W) (A)</th>
<th>SD*</th>
<th>Commercial devices (m².K/W) (B)</th>
<th>SD*</th>
<th>Absolute Error $\left(\frac{B - A}{B}\right)\times100$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomex® III</td>
<td>0.0100</td>
<td>0.000525</td>
<td>0.009597 (Togmeter)</td>
<td>0.000687</td>
<td>4.199229</td>
</tr>
<tr>
<td>Twaron®</td>
<td>0.00849</td>
<td>0.000522</td>
<td>0.00725 (Togmeter)</td>
<td>0.000336</td>
<td>17.10345</td>
</tr>
<tr>
<td>Wool</td>
<td>0.00985</td>
<td>0.000819</td>
<td>0.008327 (Togmeter)</td>
<td>0.000418</td>
<td>18.2899</td>
</tr>
<tr>
<td>Poly-Viscose</td>
<td>0.00704</td>
<td>0.000378</td>
<td>0.008119 (Togmeter)</td>
<td>0.000735</td>
<td>13.28981</td>
</tr>
<tr>
<td>F1</td>
<td>0.01400</td>
<td>0.000424</td>
<td>0.012794 (Alambeta)</td>
<td>0.00042</td>
<td>9.426294</td>
</tr>
<tr>
<td>F2</td>
<td>0.01247</td>
<td>0.000283</td>
<td>0.011721 (Alambeta)</td>
<td>0.000106</td>
<td>6.39024</td>
</tr>
<tr>
<td>F3</td>
<td>0.01216</td>
<td>0.000338</td>
<td>0.011722 (Alambeta)</td>
<td>0.00021</td>
<td>3.736564</td>
</tr>
<tr>
<td>F4</td>
<td>0.01861</td>
<td>0.000974</td>
<td>0.018182 (Alambeta)</td>
<td>0.000413</td>
<td>2.353976</td>
</tr>
<tr>
<td>F5</td>
<td>0.01573</td>
<td>0.000703</td>
<td>0.016241 (Alambeta)</td>
<td>0.000354</td>
<td>3.146358</td>
</tr>
<tr>
<td>Nomex® III with PCM</td>
<td>0.00764</td>
<td>0.000472</td>
<td>0.007556 (DTC-25)</td>
<td>0.000376</td>
<td>1.111699</td>
</tr>
<tr>
<td>Wool with PCM</td>
<td>0.00778</td>
<td>0.000383</td>
<td>0.007 (DTC-25)</td>
<td>0.000528</td>
<td>11.14286</td>
</tr>
<tr>
<td>Sample-1</td>
<td>0.01446</td>
<td>0.001223</td>
<td>0.012857 (Alambeta)</td>
<td>0.00115</td>
<td>12.46792</td>
</tr>
</tbody>
</table>

Mean Absolute error (%): 8.554858

* SD: Standard Deviation (five fabric samples were tested)
(a)

\[ y = 0.938x + 0.0006 \]
\[ R^2 = 0.9411 \]
\[ \text{Correlation Coefficient} = 0.97 \]

Parameter Estimates:
- Intercept: Estimate 0.0005655, Std Error 0.003993, t Ratio 0.14, Prob > |t| 0.8887
- Column 2: Estimate 0.9379847, Std Error 0.074221, t Ratio 12.64, Prob > |t| <0.0001

Analysis of Variance:
- Model: Sum of Squares 0.00270388, Mean Square 0.002704, F Ratio 159.7129, Prob > F <0.0001
- Error: Sum of Squares 0.00016930, Mean Square 0.000169, F Ratio 191.5347
- C. Total: Sum of Squares 0.00287318, Mean Square 0.002873

(b)

\[ y = 0.9802x + 0.0008 \]
\[ R^2 = 0.9523 \]
\[ \text{Correlation Coefficient} = 0.976 \]

Parameter Estimates:
- Intercept: Estimate 0.0007683, Std Error 0.000798, t Ratio 0.98, Prob > |t| 0.3487
- Column 2: Estimate 0.9806102, Std Error 0.069422, t Ratio 14.13, Prob > |t| <0.0001

Analysis of Variance:
- Model: Sum of Squares 0.00014045, Mean Square 0.000140, F Ratio 191.5347
- Error: Sum of Squares 0.00000704, Mean Square 0.000007, F Ratio 7.099e-7, Prob > F <0.0001
- C. Total: Sum of Squares 0.00014749, Mean Square 0.000147
**Figure 8:** Comparison of results between experimental setup and commercial instruments; (a) thermal conductivity and (b) thermal resistance

Furthermore, in order to determine the accuracy of experimental results comparisons were also made between tested results and results obtained through finite element modeling, shown in Figure 9 (a) and Figure 9 (b). The detailed information about the finite element simulation can be found in published work by the authors (Siddiqui & Sun, 2017; Siddiqui & Sun, 2016; Siddiqui & Sun, 2015; Siddiqui & Sun, 2013). In case of thicker fabric, there must be insulation required to cover the heat loss from the edges of the fabric, it should be addressed in the future work.
In this work, an experimental setup has been successfully developed for the evaluation of the thermal conductivity and thermal resistance of textile fabrics and structures. The use of the heat flow meter gives an exact amount of heat that passes through the tested fabric. Such method of testing the thermal conductivity of textile related anisotropic materials has been demonstrated as highly accurate and reproducible.

A good correlation coefficient and coefficient determination between the results obtained from the developed device and commercial instruments show the success and reliability of the developed setup in determining the thermal conductivity and thermal resistance of fabrics. The setup can also be used for transient heat transfer analysis by using software to evaluate the heat flow rate with respect to time, and the cooling rate of a fabric by utilizing the hot plate only.
Declaration of Conflicting Interests

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