Development of an instrument to study thermal resistance of fabrics

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An instrument has been developed to measure thermal resistance of fabrics under steady state condition using guarded hot plate method. This instrument can be used to test a given fabric in absolute method as well as comparator method under convective or non-convective measurement conditions. It is observed that the instrument gives repeatable results up to two decimal places of thermal resistance value. Effect of change in ambient temperature and test plate temperature has also been studied and it is found that there is no significant change in measured thermal resistance of the fabric within the range of room temperature and test plate temperature used. The study on the effect of wind speed on the thermal resistance of woven fabrics shows that the thermal resistance reduces with increase in wind speed.

Keywords: Heat transfer, Polyester, Thermal insulation, Thermal resistance, Viscose

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1 Introduction

The differences in thermal insulation between fabric materials have been recognized for many centuries. Linen has always been regarded as cool and wool as warm fabric materials. Morris observed that the opinion on the warmth of textiles was extremely variable. The apparent disagreement and the confusion of thought that existed were partly due to the indiscriminate use of expressions. For example, a fabric considered warm under certain conditions may not be so under a different set of conditions. Therefore, he suggested that the factors under consideration should be mentioned when a fabric is referred to as warm or cold.

Close analysis of the effects of factors, like temperature, relative humidity and test method, on the thermal transmission behaviour is required to understand the subject. When the fabric is put in contact or close to a hot surface, the heat is partly absorbed by it and partly transmitted through it. The transmission of the heat through the fabric may take place in various modes, such as conduction, convection and radiation, and if the surface is wet or the fabric is wet, through evaporation. Therefore, a complete analysis of heat transfer should take into account all these modes under steady state.

In most of the testing methods, transmission of heat through fabrics has been investigated in either a steady state or a transient state. The thermal parameter most commonly measured in steady state method is the thermal resistance and that in transient state method is the thermal diffusivity.

The determination of thermal resistance in textile materials is accompanied by certain difficulties inherent in the nature of materials. The thermal conductivity of a cloth is, in general, not predictable from theory because of the effect of air layers trapped within the fabric. It is possible at least in theory and usually in practice to measure the thermal conductivity of the fabric forming polymeric material itself or that of the aggregate fibre-air system composing the cloth, but not to predict the one from the other. The theory of heat flow through fibre batts is highly complicated and intractable. The reason for this is the difficulty of separating the effects of conduction, radiation and convection and of defining the shape of the space between the fibres. In case of woven or knitted fabrics, the heat flow is even more complicated.

In spite of these difficulties, the researchers have studied this subject using various techniques over the years and tried to put forward some theoretical explanations. The recent trend of the study is, however, inclined to a shift from observing the steady state behaviour to observing the transient state by simulating actual conditions of the use of fabric.

Nevertheless, the measurement based on standard steady state dry heat transfer method has its own advantages and importance. Advantages are the...
experimental simplicity and low cost equipments. The lack of any concrete theory regarding dry heat transfer through woven fabrics in it indicates that the knowledge in this field is still incomplete and hence much scope for theoretical and related experimental work is still there.

The objective of the present study is to design and fabricate an instrument which can be used to study the steady state thermal transmission behaviour of fabrics under various testing conditions using different methods. The present paper describes the design of the instrument and the effect of testing conditions on the test results obtained using this instrument.

1.1 Measurement of Thermal Resistance of Fabrics

Thermal transmission behaviour of fabrics has been observed by several methods. Transmission of dry heat through a fabric can be measured when a steady state is established in hot surface-fabric-environment system, or it can also be measured in transient state.

For the measurement of thermal resistance of a fabric in steady state, various types of instruments have been used. The different methods used for this purpose are discussed below:

- Cooling method—In this method, a hot body is surrounded by a fabric whose outer surface is exposed to air and the rate of cooling of the body is determined.

- Disc method—This method is, in effect, an application of the Lee’s disc apparatus to textiles. The fabric is held between two metal plates at different temperatures and the rate of heat flow is measured. Pressure is exerted on the fabric and so its properties may be altered.

- Constant temperature method—In this method, the fabric is wrapped around a hot body and the energy required to maintain the body at a constant temperature is found.

Among these methods, the constant temperature method may be considered as the best for obtaining the thermal insulance of fabrics and it gives the most accurate results. The chief advantage of this method lies in the fact that the measurement of heat is replaced by those of electrical energy and can, therefore, be used more easily and more accurately.

Three basic types of instrument have been tried by various workers to measure thermal resistance of fabrics by constant temperature method. These are given below:

- Hot cylinder type—Useful description of variations in this instrument is available in literature. Marsh adopted such measurement technique to measure the TIV values of woolen, flannel, cotton, celanese, silk and linen fabrics. The fabrics were wrapped around a cylinder kept at constant temperature. This cylinder was contained within another coaxial cylinder immersed in water. These types of instrument have the disadvantage of introducing a seam into the fabric which is unadvisable.

- Hot semi-cylinder type (Guarded)—Baxter and Cassie developed this type of instrument and gave a theory for the measurement of thermal behaviour, which was based on Newton’s law of cooling. This instrument, unlike the hot cylinder type instruments, overcame the necessity of having a stitch in the test specimen.

- Hot plate type (Guarded)—This type of instrument has been used by many workers. The Shirley Togmeter is also based on the hot plate principle. Guarded hot plate measurement technique has been employed in two modern internationally accepted standards [ASTM standard D1518 (ref. 9) and BS 4745 (ref. 10)]. A new version of this type of instrument is the sweating plate type, which can be used to observe simultaneous transmission of heat and moisture through fabrics.

2 Materials and Methods

Some experiments were done with the instrument designed, mainly to check the repeatability of results, most suitable testing method and time required to do a test accurately. Thereafter, the effect of small variation in test conditions, mainly the ambient temperature and the test plate temperature, was studied. Then, the effect of wind speed on the thermal behaviour was studied. The details of the fabric samples used are given in Table 1.

2.1 Design and Fabrication of Instrument

The principle underlying the instrument arises from Fourier’s law of heat conduction and the fulfillment of the necessary boundary conditions that simulate
unidirectional heat flow condition. The unidirectional heat flow condition has been simulated through the adaptation of guarded hot plate method. A schematic representation of the basic system is shown in Fig. 1 (ref. 13).

The test area comprises a square copper plate of 100 inch² area, being surrounded by a guard ring of the same metal with same thickness, having width of 5 inch on all sides. The differential thermocouple fitted between the test plate and the guard ring indicates any deviation from thermal equilibrium between them. The test plate and the guard ring are heated independently by means of heater assemblies. The guard ring is heated to the same temperature of the test plate to have a zero temperature gradient along the plane parallel to the test plate surface and this minimizes the lateral heat losses. The flow of heat from the bottom of the plates is restricted by using proper insulation system. The temperatures are measured by RTD transducers. Heat flow rate may be measured by noting the rate of electrical energy that has to be supplied to maintain the temperature of the plate invariant. This rate of electrical energy input can be calculated by measuring the current and voltage input to the test plate heater. The entire apparatus comprises two main parts, namely the test section and wind tunnel.

The sectional view of the test section is shown in Fig. 2. It consists of the following elements: (i) heating units (test plate and guard ring, heater assembly, and insulating board); (ii) insulation; (iii) standard thermal resistance; (iv) top plate; (v) wooden casing to house the above elements; and (vi) associated measuring and control elements.

The insulation system used at the bottom of the plates is a reflective insulation comprising 24 parallel bright aluminum foils at a spacing of 20 mm from each other.

The standard thermal resistance selected for the measurement in comparator method is a 12 mm thick asbestos mill board, having an estimated thermal conductivity of 0.167 W/mK at 32°C. Hence, the expected thermal resistance is around 0.092 m²K/W.

The top plate is constructed out of expanded polystyrene. It is designed so as to exert a pressure of 0.07 gf/cm² on the fabric. The top plate serves the dual purpose of shielding the fabric against the ambient air in case of measurement under non-conductive method and measuring the ambient air temperature in the case of single-plate method of testing.

The wind tunnel can be used to study the influence of wind over the fabric surface on the thermal resistance of the fabric. It comprises contraction cone, air flow straightener, test section, diffuser and a fan with regulator system. Measurement may be carried out under the following conditions: (i) with the fabric top face covered, the top plate being in position above the fabric specimen (two-plate method); (ii) with the fabric top face exposed to the ambient air (single-
plate method; (iii) absolute method; and (iv) comparator method.

3 Results and Discussion

3.1 Repeatability of Instrument

A single fabric was repeatedly tested and the observed thermal resistances of the fabric were compared. In each case, the test conditions were kept same. The tests were done using absolute convective method with zero wind speed. The results are shown in Table 2. It appears from the data that the results are consistent and repeatable up to two decimal places.

3.2 Comparison of Convective and Non-convective Methods

Same fabric was tested using same ambient and test plate temperatures once by absolute convective method and then by non-convective method. The results are shown in Table 3. The wind speed was kept zero again, so effectively the convective method had an extra mode of heat loss by means of natural convection. Although the results of the two methods do not show very large differences, it is clear that the thermal resistance of the fabric when tested by non-convective method is slightly higher.

3.3 Evaluation of Testing Time

To get accurate and consistent results, an experiment under absolute convective method takes the least time for completion. But even this time may sometimes be as high as 5-6 h. The time required to bring the room temperature at a desired value by using a thermostat and an air-conditioner may amount to an additional 2.5-4 h, depending on the required temperature.

It has been checked whether one could use a constant value of air thermal resistance under a specified testing condition while employing the absolute convective method. For this purpose, a number of data for air thermal resistance was collected by repeated experimentation.

![Fig.2—Sectional view of test section](image-url)

| Table 2—Repeatability test [Fabric sample — Fabric A] |
|---|---|---|---|
| Ambient temp. | Test plate temp. | Thermal resistance of air K.m²/W | Thermal resistance of air + fabric K.m²/W | Thermal resistance of fabric K.m²/W |
| °C | °C | | | |
| 30 | 33 | 0.089 | 0.118 | 0.029 |
| 30 | 33 | 0.089 | 0.120 | 0.030 |
| 30 | 33 | 0.090 | 0.119 | 0.029 |

| Table 3—Testing results under various conditions of testing using absolute test method |
| Condition of testing | Ambient temp. | Test plate temp. | Contact resistance for non-convective K.m²/W | Thermal resistance of fabric K.m²/W |
| | °C | °C | | |
| Convective | 30 | 33 | 0.089 | 0.028 |
| Non-convective | 30 | 33 | 0.059 | 0.033 |
Table 4 — Testing results at different temperatures

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ambient temp. °C</th>
<th>Test plate temp. °C</th>
<th>Thermal resistance K(\cdot)m²/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric A</td>
<td>30</td>
<td>33</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>37</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>33</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>37</td>
<td>0.025</td>
</tr>
<tr>
<td>Fabric B</td>
<td>30</td>
<td>33</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>37</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>33</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>37</td>
<td>0.030</td>
</tr>
</tbody>
</table>

The results show an average value of 0.098 K\(\cdot\)m²/W with a standard deviation of 0.010 K\(\cdot\)m²/W. The relative humidity during these experiments ranges from 48% to 68%.

3.4 Effect of Test Conditions on Thermal Behaviour

Effect of varying test conditions, such as ambient temperature and test plate temperature, was studied on polyester-cotton (70:30) and viscose fabrics. The testing method used was absolute convective type without wind. The results are given in Table 4.

It is observed from Tables 3 and 4 that the change in fabric thermal resistance for a change in test plate temperature is not appreciable within the test plate temperature range studied. The change in thermal resistance of the fabrics for a change in ambient temperatures is also not very appreciable within the ambient temperature range studied.

3.5 Effect of Wind Speed on Thermal Behaviour

The effect of wind speed on the thermal behaviour of the woven fabrics was studied by using the wind tunnel and the exhaust fan. The wind blows through the tunnel in a streamline flow at an angle of 0° to the test plate. Tests were conducted using the absolute convective method. When wind blows, forced convection takes place.

Two types of test were carried out. In one test, the power supplied to the plates was kept constant, and the loss of temperature with increasing wind speed was noted. The test was done once with the bare plate and then with a fabric sample mounted on the plates. The results are shown graphically in Fig. 3. Here, the temperature difference is the test plate temperature minus the ambient temperature. It can be observed from the graph that the plate loses temperature in both the cases. The rate of loss of temperature from the heated surface with respect to increase in wind speed is very high at the low wind speed and the rate reduces as the speed of wind is further increased.

In another study, the change in thermal resistance values with the change in wind speed was studied. The results are graphically plotted in Fig. 4. In this case, it is observed that with the increase in wind speed, the decrease in thermal resistance in the air layer just above the bare surface is much higher than the decrease in thermal resistance of the actual fabric. This is expected as the convective loss in open air would be much more than that in the air trapped inside the pores of the fabric.

4 Conclusions

4.1 An instrument has been designed and fabricated to measure the thermal resistance values of different fabrics under steady state. This instrument is capable of measuring the thermal insulation in absolute
method, as in ASTM method, as well as in comparator method, like the BS standard. The instrument has sufficient flexibility to do tests under both convective and non-convective conditions. Convective condition can be achieved by either allowing the natural convection or by making a streamline flow of wind over the fabric surface at 0° angle to the surface at a controlled speed.

4.2 Few test runs were made using two fabric samples to check the working of the instrument under various conditions. It is found that the instrument gives repeatable results up to two decimal places. In case of measurement under absolute convective method, testing can be made more convenient by using an average value of air thermal resistance. This may, however, be done at the cost of accuracy.

4.3 The instrument is found to be insensitive to any change within the ambient temperature range 26°-30°C and test plate temperature range 33°-37°C.

4.4 The instrument is found to be sensitive to the wind speed range used and the thermal resistance of the woven fabric decreases with the increase in wind speed which is an expected result.

References
2 Slater K, The thermal behaviour of textiles, Text Prog, 8 (3) (1976).