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Thermal Resistance of Denim Fabric under Dynamic Moist Conditions and its Investigational Confirmation

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Abstract
The goal of this study was to examine whether there is a correlation between the moisture content in fabric and the thermal resistance thereof. Denim fabric made of five different compositions of fibre content was used for testing thermal resistance under dynamic moist conditions. An ALAMBETA semi-automatic non-destructive thermal tester was used to check the thermal resistance. A mathematical equation was developed for prediction of the thermal resistance of denim fabric submersed in water at different moisture levels. This model is based on the relationship between the density ratio of the fibre and fabric, the thickness of the fabric and the amount of moisture therein. A number of simulations were tried and finally one arrangement found that has significant agreement with actual values. This model can be used for other types of fabric because there is no role of the geometry of fabric in it. The model proposed exhibits a substantial link with the experimental data.

Key words: *thermal resistance, thermal conductivity, denim.*

Introduction

The thermal resistance of fabric depends upon the effective thermal conductivity and thickness thereof. Moreover the thermal conductivity of fabric relies upon the ratio and alignment of different fibres present therein. A change in thermal conductivity or thickness will have a big impact on the thermal resistance of fabric and finally the wearer will experience discomfort [1 - 7].The extant literature has a sufficient number of predictive models for thermal resistance under normal conditions. The structure of fabric and composition of fibres are used as independent variables[1, 4, 8 - 15]. However, these models facilitate the measurement of the thermal resistance of fabric in dry conditions only; these models cannot be used to predict the thermal resistance of fabric for different moisture levels. The current study is an attempt to address this issue. The axiological aspect of this study is the formulation of an instrument that helps to measure the thermal resistance of wet fabric with various levels of dampness.

In this study researchers used five different denim samples that were made using cotton, polypropylene, and polyester fibres. The thermal resistance of the samples was measured at various moisture levels and compared with the equation developed for the prediction of thermal resistance under varying degrees of wet conditions. Results support the effectiveness of the newly developed equation for the prediction of the thermal resistance of diverse types of fabric under wet conditions. This equation is based on the ratio of different fibres, porosity and thickness of the fabric, not on the geometry of fabric.

Thermal resistance of wet fabric

The thermal resistance of fabric depends upon its thermal conductivity and thickness. Partially wet fabric is composed of fibres, moisture and air. There is considerable variation in thermal conductivity values of fibre, air and moisture. Under a dry climate, there is a continuous change in the ratio of fibre, air and moisture due to the evaporation process. Air replaces the moisture molecules, which results in a decrease in the moisture share and an increase in the ratio of fibre and air. Such change affects the effective thermal conductivity of fabric. Consequently the thermal resistance of the fabric is changed. Prediction of the thermal resistance with a change in all the above parameters is the main issue focused on this study.

Thermal conductivity of blended fabric

In the case of the usage of more than one fibre for fabric manufacturing, estimation of the thermal conductivity of the fabric produced can be carried out with the help of the following equation [16]:

$$\lambda_{ab} = r\lambda_a + (1 - r)\lambda_b \qquad (1)$$

In this equation 'a' and 'b' are the types of fibre, λ_a and λ_b - their thermal conductivities, r - the portion of fibre'a', and λ_{ab} is the estimated thermal conductivity of the blend. ***Equation 1*** was used for the development of the thermal resistance prediction model.

Thermal resistance prediction model under wet conditions

The total thermal resistance of wet fabric is the sum of the thermal resistance of fibre, air and moisture therein. For calculation of the total thermal resistance of partially wet fabric, it is important to measure the thermal resistance of fibres, air and moisture at different moisture levels. Due to the continuous evaporation process ratio of moisture, the air and polymers present in the fabric remain in a dynamic condition. There is a change in the total thermal resistance of the wet fabric due to change in the ratio of the polymer, air and moisture.

Due to dynamic conditions, it is difficult to measure the thickness of air layers and the water column, which are the main variables of the equation used to measure thermal resistance. During the experimentation, different situations were presumed, tested and finally got maximum support from the actual results for the assumptions mentioned below. The following assumptions were made regarding the model:

1. The sample thickness and geometric properties of fibres are considered as constant while the moisture content varies.
2. Part of the air is substituted by moisture in the fibre

In the following section the procedure to measure the thermal resistance of moisture, air and fibres at various moisture levels is described. Six different techniques were used to sum up the thermal resistance of moisture, air and fibre. Out of the six possible ways, four equations yielded results very close to the actual values, which led the researchers to propose an equation which has a minimum sum of squares of difference and a sum of the absolute of differences.

Thermal resistance of fibre in wet fabric

Wet fabric is composed of organic or inorganic materials, air layers and moisture (present in different parts of the fabric). The researchers did not apply any geometry of the fabric to calculate the thermal resistance of fibres in the wet fabric because it was not in the scope of this study to address all issues related to it. The most complex factor was the amount of moisture present inside or outside the fibres. Many situations were assumed and the following proposition finally agreed on because it gave results which are closer to the values measured.

$$R_f = \frac{h\varepsilon}{\lambda_f} \quad (2)$$

In ***Equation 2***, R_f is the thermal resistance of the fibre in m^2KW^{-1}, h the thickness of the fabric in m, λ_f the thermal conductivity of fibres in $m^{-1}K^{-1}W$, and ε is the ratio (in percentage) of fibres present in the fabric. In a dry state the fabric is composed of air and fibres. The density of this fabric is less than that of the fibres in a compact state. The ratio of fibre and fabric density gives the amount of fibres in a unit area of fabric. ***Equation 2*** was used to calculate the thermal resistance of fibre present in the fabric. For estimation of the thermal resistance of the fabric, the ratio of fibre to fabric was used, which does not indicate the dimension and is denoted by ε in %. Its highest value is 100, which indicates that the density of the fibre is equal to that of the fabric. Less than 100 means that the fabric is composed of air and fibres. Fabric with a low amount of fibres shows the trapping of a large quantity of air in the fibre.

For ***Equation 2*** we need the height of the fabric for calculation of the thermal resistance of fibres. The fabric is composed of fibres as well as air and water molecules which are also present inside the fabric. To resolve this issue, the researchers reduced the thickness by multiplying it with ε, which is the ratio of fibre and fabric, indicating that the fabric is not exclusively composed of fibres; moisture and air are also present along with them.

Thermal resistance of air gaps (cells)

The second substance in the wet fabric is air, which exists in different parts of it. It may be inside the amorphous region of fibres, among them or between courses and wales of knitted fabric. Exact information about the amount and thickness of air layers cannot be found. Thickness is required to calculate the thermal resistance, which is not possible in partially wet fabric. To overcome this limitation, many situations have been assumed; the ***Equation 3***, which was developed during this experiment, was finalized as the one which can give results very close to the values measured.

$$R_a = \frac{h(1-\varepsilon)}{\lambda_a(1-\mu)} \quad (3)$$

The variables given in the above equation are R_a which is the thermal resistance of air in m^2KW^{-1},'h' the thickness of the fabric in m, λ_a the thermal conductivity of air in $Wm^{-1}K^{-1}$, ε the ratio of fibres present in the fabric in % and μ represents the percentage of moisture in the fabric. These variables were used to calculate the thermal resistance and can be re-written as in ***Equation 4***:

$$m = (m_0 - m_1)/m_0 \times 100 \quad (4)$$

were: m_0 - weight of wet fabric, m_1 - weight of dry fabric.

Equation 3 is instrumental in calculating the thermal resistance of air present in fabric. The moisture μ will be zero when the fabric is fully dry, as is shown by the zero value, making the absence of moisture axiomatic. ***Equation 4*** is significant because it represents the actual amount of moisture present in a wet sample. The researchers reduced the thickness of the fabric by multiplying it with the porosity in ***Equation 3***.

Porosity (1 - ε) indicates the area of the fabric filled by air and moisture; air is present inside the fibres and between yarns. Moreover it is assumed that the fabric is partially filled with air. The thermal conductivity of air is multiplied with the amount of air present in the fabric. For this purpose we deducted the moisture amount (μ) from 1, showing the amount of air present in the fabric.

Thermal resistance of moisture in wet fabric

The third substance in wet fabric is water present in different parts thereof. It may be inside the amorphous region of fibres, between fibres, and/or attached to the fibre surface. The researchers did not have precise information about the location and amount of water inside and on the surface of the fabric. Different situations were assumed and finally the maximum agreement between simulated and measured values was obtained from the ***Equation 5***:

$$R_w = \frac{h(1-\varepsilon)}{\lambda_w \mu} \quad (5)$$

Where, R_w is thermal resistance of water in m^2KW^{-1}, h the thickness of the fabric in m, λ_w the thermal conductivity of water in $Wm^{-1}K^{-1}$, ε the ratio of fibres present in the fabric, and μ is the percentage of moisture in the fabric. It was important to know the height of water present in the fabric for calculation of the thermal resistance. Water is present in various parts of the fabric and there is no continuous line. The height of water was multiplied with the porosity, which shows spaces among fibres for moisture and air. Moreover we multiplied the thermal conductivity of water with the amount of moisture present in the fabric.

Thermal resistance model for fabrics in a wet state

The total thermal resistance depends upon the arrangement of the thermal resistance of fibres R_f, the thermal resistance of air cells R_a, and the thermal resistance of water cells R_w. There are two limit arrangements of thermal resistances:

Model 1: Thermal resistance in serial arrangement

The total resistance R_t is calculated by the relation:

$$R_t = R_f + R_a + R_w \quad (6)$$

Model 2: Thermal resistance in parallel arrangement

The total resistance R_t is calculated by the relation

$$R_t = (R_f^{-1} + R_a^{-1} + R_w^{-1})^{-1} \quad (7)$$

The parallel arrangement gives the higher limit value, while the serial formula deals with the lower limit. Out of these two limit models, six possible combinations can be formed:

Model 3 $$R_t = \frac{R_a R_f}{R_a + R_f} + R_w \quad (8)$$

Model 4 $$R_t = \frac{R_a R_w}{R_a + R_w} + R_w \quad (9)$$

Model 5 $$R_t = \frac{R_f R_w}{R_f + R_w} + R_a \quad (10)$$

Model 6 $$R_t = \frac{R_w (R_a + R_f)}{R_w + R_a + R_f} \quad (11)$$

Model 7 $$R_t = \frac{R_a (R_w + R_f)}{R_w + R_a + R_f} \quad (12)$$

Model 8 $$R_t = \frac{R_f (R_w + R_a)}{R_w + R_a + R_f} \quad (13)$$

Experimental part

Testing procedure

Determining the level of thermal resistance and conductivity of fabric in a wet state requires the use of a special testing instrument which augments measurement accuracy and efficiency while keeping the level of moisture constant during the measurement. Alambeta (Sensora, Czech Republic) measures thermal resistance, thermal conductivity, thermal absorption, thickness and heat flux simultaneously in less than three minutes. This instrument is widely used due to its accuracy and non-destructive testing method [4, 17 - 19].

Samples were dried at 105 °C for 30 minutes in an oven. The area weight in kg in a dry state and thickness in m in a dry state were obtained for use in the calculation of porosity. Then the sample was submerged in drinking water which had 1% non-ionic detergent for two hours. The level of impurities in drinking water is minimum. One should be careful in using hard water since highly impure water has higher thermal conductivity due to the presence of salt etc. After that the sample was kept freely in a horizontal position on a net made up of nylon strings to allow free evaporation of water molecules.

After five minutes, the sample was weighed and put on an Alambeta plate, and the thermal resistance of the wet sample (R_t) was measured. After noting the values, samples were put back on the net for five minutes. During this period, there was continuous water evaporation without any external force in open-air under laboratory conditions, where the temperature was kept between 20 - 22 °C and the relative humidity was between 24 - 25%. This practice was repeated 11 times, gaving a gradual decrease in moisture in the fabric. Finally the researchers obtained a sufficiently reduced amount of moisture. Measurements of thermal resistance were carried out on Alambeta testing equipment to measure the thermal resistance under a contact pressure of 1,000 Pa.

Sample development

Five types of denim were developed for testing purposes. Details are given in ***Table 1***.

Table 1. *Sample description.*

Description	Denim 1	Denim 2	Denim 3	Denim 4	Denim 5
Warp yarn	Cotton				
Warp tex	49.25	49.25	49.25	49.25	49.25
Weft yarn	Spun PP	1)SBC PP	2)AT PP	3)PET	Cotton
Weft tex	54.00	38.00	47.78	37.00	49.25
Warp set, yarns·cm^{-1}	24.01	24.01	24.01	24.01	24.01
Weft set, yarns·cm^{-1}	17.71	22.24	20.07	20.86	17.32
Weight after washing, g·m^{-2}	315	320	328	351	320

Table 2. *Comparison of models using criterion SSD.*

Sample No	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
1	**0.000003**	0.000188	**0.000005**	**0.000006**	**0.000005**	0.000015
2	**0.000002**	0.000110	**0.000002**	**0.000003**	**0.000002**	0.000008
3	**0.000003**	0.000156	**0.000004**	**0.000005**	**0.000004**	0.000012
4	**0.000002**	0.000160	**0.000002**	**0.000003**	**0.000002**	0.000010
5	**0.000002**	0.000150	**0.000002**	**0.000003**	**0.000002**	0.000008

Table 3. *Comparison of models using criterion SAD.*

Sample No	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
1	**0.00074**	0.00535	**0.00087**	**0.00097**	**0.00089**	0.00153
2	**0.00050**	0.00410	**0.00057**	**0.00067**	**0.00059**	0.00107
3	**0.00066**	0.00486	**0.00077**	**0.00088**	**0.00080**	0.00137
4	**0.00051**	0.00497	**0.00061**	**0.00068**	**0.00063**	0.00120
5	**0.00051**	0.00486	**0.00057**	**0.00067**	**0.00059**	0.00114

Table 4. *Comparison of models using correlation technique*

Sample No.	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
1	**0.846**	-0.855	**0.910**	**0.909**	**0.909**	-0.721
2	**0.809**	-0.904	**0.881**	**0.880**	**0.879**	-0.795
3	**0.810**	-0.862	**0.877**	**0.875**	**0.875**	-0.753
4	**0.885**	-0.877	**0.941**	**0.940**	**0.940**	-0.718
5	**0.843**	-0.874	**0.908**	**0.907**	**0.907**	-0.749

Results and discussion

The theoretical thermal resistance R_t was calculated in accordance with models from number 3 to 8, mentioned above. The thermal conductivities of dry air λ_a = 0.024 Wm^{-1}K^{-1}, water λ_w= 0.6, PET fibres λ_{PET} = 0.30 and compacted cotton in a dry state λ_{cot} = 0.352 [20] were used.

Statistical significance of models

The researchers developed six possible simulated arrangements of summing up the thermal resistance of fibres, air and moisture, which helped to develop equations. Taking the difference between measured and predicted values into consideration, with the help of models, the researchers were able to test the simulations.

The criteria applied were the sum of squares of deviations SSD, the sum of absolute deviations SAD from the theoretical models, and the results measured. Furthermore a correlation technique to measure the correlation between measured and simulated values was also applied.

$$MSSD = \frac{1}{n}\sum_{i=1}^{n}(R_{tm,i} - R_t)^2 \quad (14)$$

$$MSAD = \frac{1}{n}\sum_{i=1}^{n}\left|R_{tm,i} - R_t\right| \quad (15)$$

In the equation above 'i' is the i-th measurement of thermal resistance R_t. Since the value of deviation is squared, it shows that according to criterion SSD the larger

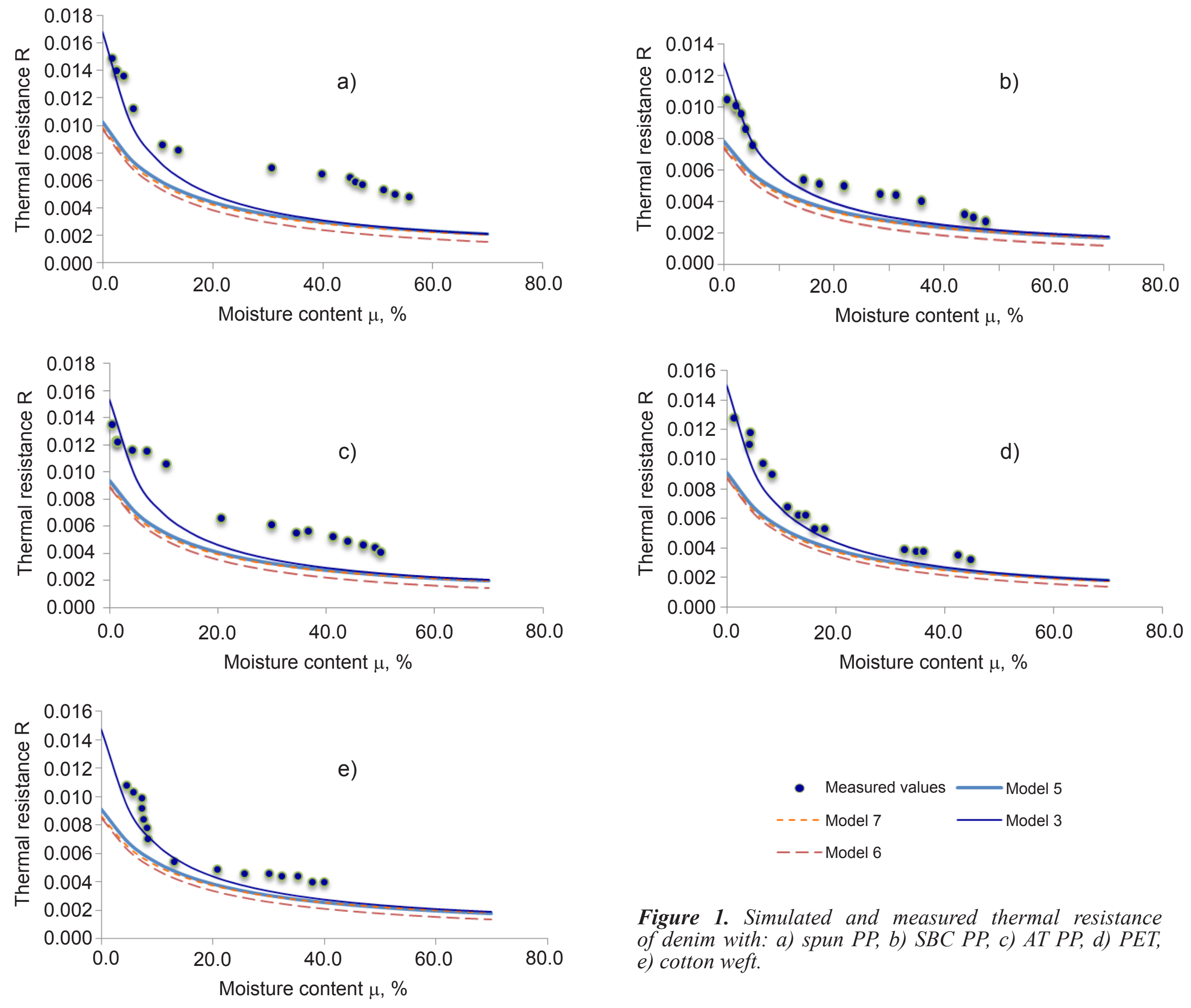

***Figure 1.** Simulated and measured thermal resistance of denim with: a) spun PP, b) SBC PP, c) AT PP, d) PET, e) cotton weft.*

the deviations the higher the weight as compared to the case of criterion SAD.

Results based on calculations are presented in ***Tables 2, 3*** and ***4***. As per the information from these tables, four out of six simulations showed best results. Their correlation value is nearly 0.90, which is highly significant, whereas the sum of the difference from actual values is the lowest possible. Besides this the figures given also depict a considerable agreement between the measured and simulated values.

Figures 1 - 5 were modulated based on results drawn from four different equations (***Equations 3, 5, 6*** and ***7***). The moisture content value (μ) is given as a percentage on the x-axis as an independent value per se, showing the amount of moisture in the wet fabric, calculated using ***Equation 4***. The initial value is zero, which implies that the fabric is completely dry. On the Y-axis, thermal resistance values were placed as a dependent variable and a chart was developed for x and y values. Thermal conductivity values of air, fibre and water were taken from secondary sources and the total thermal resistance was calculated using six different equations (***Equations 8, 9, 10, 11, 12, 13***). Thermal resistance in m^2KW^{-1} represents the combined effect of air, moisture and fibre along with the thickness of the fabric. A scattered plot line was used to develop this chart. In this chart X-axis and Y-axis values are plotted; the formation of a smooth line shows the change in one dependent variable (thermal resistance) due to any change in the independent variable (moisture), the relationship of which is based on the inverse proportion.

The moisture percentage was taken along x-axis. These values correspond to those of thermal resistance measured and simulated, being of two types - one is assumed for models while the other is a measured value at which the thermal resistance was measured at each corresponding level. Software does help to get two different sets of values at the same time, but it gives only the range and small units. The models proposed have substantial agreement with the values of thermal resistance measured. There is only one independent variable in these models and one dependent variable, while the rest of the inputs are kept constant.

As regards the findings, most of the values measured are found to be above the line of simulated values. Very few values are below the line of simulated values. It is the outcome of the models and implies that further studies are needed to refine the models for a stronger predictive potential for the thermal resistance of wet fabric.

Error in estimation was found, which can be due to many reasons, for example moisture variation during the testing and alignment of warp or weft fibres. Thermal conductivity is anisotropic in nature and highly depends upon the arrangement of the material. Despite a minor difference in the actual and simulated values of thermal resistance, ***Figures 1 - 5*** shows that there is a significant correlation between the models and the values of thermal resistance measured.

A comparison of theoretical and experimental results is given in the following diagrams.

The figure and statitscal analysis show that **Model 3** gives the best results in terms of the closest values meaured. Although the other three models also give similar results, **Model 3**, mentioned below, gives the best.

$$R_t = \frac{R_a R_f}{R_a + R_f} + R_w \qquad (16)$$

Conclusions

This study was conducted to find a method to measure the thermal resistance of fabric under dynamic wet conditions. Four equations were developed to measure the thermal resistance of fibre, air and moisture at various moisture levels. The total thermal resistance of the wet fabric was calculated using six different approaches. Upon the completion of this experimental study, it was found that results given by the four approaches are very close to the thermal resistance values measured. Criterion techniques were used to find out the best simulations. For this purpose the researchers applied the sum of the square of the difference and the absolute sum of the difference. The correlation was also checked. Results show that **Models 3**, **5**, **6** and **7** provide the minimum sum of the square of the difference and the sum of the absolute difference, which support the findings. Besides this these four models also have a correlation value near 0.9 with the actual measurements, which is highly significant. Out of these six models **Model 3** has maximum agreement with actual values.

Summarising this document, it can be said that **Model 3** can be used for the prediction of thermal resistance, which is very significant to predict any possible changes in the thermal resistance of denim clothing. The use of mathematical equations highlights how denim fabric tends to respond under wet conditions and the changes that occur simultaneously in the texture and composition of fibre and other components under these conditions.

The study is also significant as **Model 3** will help people working under highly humid conditions per se to estimate the possible reduction in thermal resistance due to moisture regained by the fabric. Moreover this model can be used to develop clothing of higher thermal resistance under wet conditions. Denim manufacturers can utilise findings originating from this model to manufacture clothing that offers maximum utility to users. Another important attribute of this model is that its application is not limited to denim fabric only, butalso extends to other variations of fabric, thus proving the flexibility of the model, which is mainly due to the independence of these models from the geometry of the fabric.

Editorial notes

1) *Stuffer Box Crimped PP.*
2) *Air Textured PP.*
3) *Polyethylene Terephthalate.*

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