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Modelling the Impact of Moisture on the Thermal Conductivity of Cotton Jersey

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Abstract
In the design of innovative, protective clothing, thermal comfort is of great importance. One of the key factors affecting thermal comfort is the thermal conductivity of clothing. This study aims to show through theoretical estimations that the effective thermal conductivity of moist clothing could expedite the development process. In this study, we present two theoretical models: a linear model and upgraded model. The upgraded model considers the thermal conductivity of air within the clothing and its volume porosity. For verification of the models presented, the impact of moisture on the thermal conductivity of cotton knit fabric was examined experimentally using the contact hot plate method. Correlation analysis shows that the upgraded model has an important advantage as it can predict the stabilisation of effective thermal conductivity.

Key words: *modelling, thermal conductivity, moisture, knit fabric, cotton, single jersey.*

Introduction

The thermal balance between the human body and the environment has a great effect on thermal comfort, especially under extreme weather and working conditions [1]. Extreme working conditions demand the best possible protective equipment to ensure good physical and mental strength. As a result, the manufacture of optimal personal protective equipment requires a thorough understanding of the physical properties of clothing and heat transfer mechanisms [2]. Consequently, several studies are [3-10] currently examining the thermal conductivity of clothing. Thermal conduction plays a key role in heat transfer through clothing. The thermal conductivity of clothing depends on the type of textile fibres it is made of [10], the treatment of the fibres [11], and the clothing structure [12-16]. It was shown that a change in the blend ratio, in this case, polyester and cotton, has a significant impact on thermal conductivity [10]. The clothing structure is also important since it affects the volume porosity [17]. If there are air gaps within clothing, its overall thermal conductivity is smaller, since air is a good thermal insulator. In addition to the parameters mentioned above, previous studies [18, 19] show that the specific heat of fibres, the yarn linear density and the fabric stitch length influence the thermal conductivity. The comprehensive theoretical prediction of a fabric's thermal resistance, inversely proportional to its thermal conductivity, is described in [20], where fabric geometry, conduction, and radiation were considered in detail.

In this paper, we study the impact of moisture on the thermal conductivity of a knit fabric made of cotton, both theoretically and experimentally. The samples tested are of the single jersey type and made of cotton, hereinafter referred to as cotton jersey. Such fabric is widely used in the textile industry in the production of t-shirts and undershirts. The latter is also the reason for our selection, as cotton undershirts are often essential under the protective clothing system. In addition, undershirts often have a basic plain weave structure, which is also true for our samples. The previous research showed that the plain weave structure results in the highest thermal resistance and is therefore optimal for use in a cold environment [21].

This study aims to design a theoretical model to evaluate the effective thermal conductivity of moist fabric, which could help to create the background for further development of fabrics and the design of protective clothing systems. Despite the focus on cotton jersey, we wanted the model to be flexible so as to evaluate the effective thermal conductivities of other fabrics as well.

When cotton jersey is in contact with moisture, for example, water, it starts absorption. The rate of absorption depends on the absorbing factor of the fibres [3, 22]. Interactions between water and fibres are described in detail in [4]. The thermal conductivity of water is 25 times higher than that of air; thus, the effective thermal conductivity of moist clothing increases. The impact of water on the thermal properties of clothing, especially on thermal conductivity, is of great interest to textile researchers [23, 24] as well as to physiologists who are focused on human thermal comfort and thermal balance concerning the environment and clothing.

Experimental studies show [7, 8] that the thermal conductivity of clothing is linearly dependent on relatively small amounts of absorbed liquid (moisture). For higher relative amounts of absorbed liquid, the effective thermal conductivity stabilises around the value of the thermal conductivity of the liquid [8]. To achieve high accuracy of experimental data, one needs to follow precise sample preparation and measurement procedures. Often a steady-state technique is used, such as the Skin Model [25], which simulates heat and moisture transfer through clothing. In terms of time efficiency, it is reasonable to develop a theoretical model that best estimates the effective thermal conductivity of the sample. Several recent studies used thermal resistance models [26, 27] and estimated the effective thermal conductivity analogous to the calculation of the total equivalent resistance of resistors in an electric circuit. To obtain the best possible correlation of modelled and measured results, they consider combinations of different resistor arrangements. The best combination is determined using two criteria: the sum of squares of deviations and the sum of absolute deviations from the measured results. These thermal resistance models show small deviations from the measured results.

In the previous study [8], we presented a different analytical approach using a linear model to estimate the effective

Table 1. *Properties of cotton jersey samples C1 and C2. Measured values of thickness, density, and volume porosity, with errors in percentage in brackets.*

Sample label	Jersey structures	Material	Density, kgm^{-3}	Thickness, mm	Volume porosity
C1	flat plain	100% cotton	298 (± 18%)	0.6 (± 17%)	0.71 (± 6%)
C2	flat plain	100% cotton	248 (± 15%)	0.9 (± 14%)	0.69 (± 6%)

thermal conductivity of moist fabric. The main disadvantage of the linear model is that one must determine critical relative amounts of water at which the sample saturates. Our goal in the present study is to develop a model that only requires data from a dry sample. In this paper, we present an upgrade of the linear model. We introduce two additional factors into the model: the volume porosity and the thermal conductivity of air. Despite additional parameters, only data of a dry clothing sample are required. Furthermore, this paper aims to verify both theoretical models. To test the theoretical results, the impact of moisture on the effective thermal conductivity was measured using the hot plate method [28]. Measurements based on the thermographic method turned out to have lower accuracy as a result of liquid evaporation. We state here that the testing method used in the experimental study has lower precision. Nevertheless, we expect this affects only the absolute values of the thermal conductivities measured and not the trend of the dependency of thermal conductivity on moisture levels.

Theoretical modelling

The heat transfer through a cotton sample depends on the temperature difference ΔT across the thickness of the sample (d) and the thermal conductivity (λ). In one dimension, the heat flux through the sample surface (A) is:

$$P = -A\lambda \frac{\Delta T}{d}. \qquad (1)$$

The thermal conductivity of a cotton sample depends on the thermal conductivity of fibres (λ_f) and the volume porosity (ε). For a dry sample, it holds that [26, 29]:

$$\lambda_s = (1-\varepsilon)\,\lambda_f + \varepsilon\,\lambda_a, \qquad (2)$$

Where, λ_a is the thermal conductivity of air. To clarify, λ_s is the effective thermal conductivity, which comprises the thermal conductivity of fibres and air. The volume porosity has a major impact on the thermal conductivity of an absorbent cotton sample [17]. Higher volume porosity means that many air gaps can be replaced by water or any other liquid when moisturising. The volume porosity of a dry sample can be calculated as:

$$\varepsilon_0 = \frac{V_a}{V_s}, \qquad (3)$$

Where, V_a stands for the total volume of air gaps (in the case of a dry sample), and V_s represents the total volume of the sample. In other studies, different approaches to determine porosity are used [30-32]. Assuming that the jersey sample is evenly moist throughout the volume, the relative amount of moisture is defined as the ratio between the mass of absorbed moisture m_l and the mass of the dry jersey sample m_s [33]:

$$r = \frac{m_l}{m_s}. \qquad (4)$$

For lower relative amounts of moisture, measurements show a linear dependency of the effective thermal conductivity [4, 8, 33] and can therefore be estimated by the linear model:

$$\lambda_{ef} = \lambda_f + r\frac{\lambda_l - \lambda_f}{r_c}. \qquad (5)$$

Here, λ_l is the thermal conductivity of the liquid used to moisturise the sample (in the case of water ~0,64 Wm^{-1}K^{-1}) [34], and r_c stands for the critical value of relative moisture when the sample is saturated. The main limitation of the linear model is the need to determine the critical value r_c, which differs for each specific combination of the textile sample and liquid use in moisturising. This means that to estimate the effective thermal conductivity of moist samples theoretically, one should already have experimental data. In the upgrade of the linear model proposed, the thermal conductivity of air and the volume porosity of samples are taken into account.

Using the model of effective physical quantities, the effective thermal conductivity of a moist sample can be calculated as the weighted average value of the thermal conductivity of moisture (liquid, in our case water) of a dry sample, see ***Eqation (2)***. In the linear approximation, it holds that [8]:

$$\lambda_{ef} = \lambda_s \frac{1}{1+r} + \lambda_l \frac{r}{1+r}. \qquad (6)$$

With an increasing amount of absorbed moisture, the proportion of air entrapped in the sample is reduced and replaced by moisture. Therefore, the volume porosity of the sample, as defined by ***Equation (3)***, depends on the relative amount of moisture:

$$\varepsilon(r) = \varepsilon_0 - r\frac{\rho_{s,0}}{\rho_l}, \qquad (7)$$

Where, $\rho_{s,0}$ and ρ_l stand for the density of a dry sample and the density of moisture (liquid), respectively. Combining ***Equation (2)***, ***(6)*** and ***(7)***, the effective thermal conductivity is written as:

$$\lambda_{ef} = \frac{\lambda_f\big(1-\varepsilon(r)\big) + \lambda_a\varepsilon(r) + \lambda_l r}{1+r} \qquad (8)$$

Furthermore, we consider the linear increase in the density of a moist sample with a relative amount of moisture:

$$\rho_s = \rho_{s,0}(1+r), \qquad (9)$$

which is confirmed experimentally. To estimate the effective thermal conductivity of a moist sample by ***Equation (8)***, one must determine its density and initial volume porosity. Both parameters can be obtained by measurement of a dry jersey sample, which is an essential advantage of the upgraded model over the linear model, where measurements of moist samples are required.

Experimental

Materials and methods

The impact of moisture on thermal conductivity was tested experimentally for two cotton jersey samples – C1 and C2, with a GSM (weight of fabric in grams per square metre) of 180 gm^{-2} and 220 gm^{-2}, respectively. Samples were of the single jersey type, made of 100% cotton, and are used for the production of t-shirts. Both samples have a plain weave structure, the different thicknesses and densities of which are listed in ***Table 1***.

Measurements of the thermal conductivity of the cotton jersey samples were conducted using a contact-measuring device based on the hot plate method [8]. The measuring device consists of a cooler with constant water flow and an electric heater connected to a source of constant power supply (***Figure 1***). Above the heater, an aluminium-compensating plate is placed to provide the homogenous distribution of heat over the surface. For temperature measurements, we used four temperature sensors with a systematic error of ± 0.2 °C and resolution of 0.03 °C. ***Figure 1*** depicts the position of each sensor. During the experiment, ambient conditions, the water flow rate, and water temperature were maintained at a constant level, as presented in ***Table 2***. The heater power was set to a constant value of 5.3 W and controlled by voltage and current measurements.

Experimental procedure

Before the experiment, both cotton jersey samples were stored in a dry, dark place with an average temperature of 21 °C and relative humidity 49%. First, we performed measurements on dry samples. Knowing the thermal conductivity of cotton fibres and air, the volume porosity of the sample was determined using ***Equation (2)***. The volume porosity of our samples is around 0.7, which is in agreement with the data presented in [21] for weave structure 1/1 plain. Next, the jersey samples were moistened gradually to the desired value of r. For a uniform application of moisture, moisturising was conducted using water vapour. To minimise mistakes caused by liquid evaporation, the mass and thickness of each sample were measured before and after every measurement. Concerning ***Equation (4)***, the relative amount of moisture was estimated as:

$$r = \frac{1}{m_s}\left(\frac{m_1 + m_2}{2} - m_s\right). \qquad (10)$$

Here, subscripts “1” and “2” refer to the initial and final state, respectively. At each relative amount of moisture, three measurements of the temperature difference across the sample were conducted, based on which the average value was calculated.

Results and discussion

Figure 2 presents the average effective thermal conductivity of samples C1 (black circles) and C2 (grey squares) at various relative amounts of moisture. The thermal conductivities of dry cotton jersey samples C1 and C2 are 0.10 $Wm^{-1}K^{-1}$ and 0.12 $Wm^{-1}K^{-1}$, respectively. Previous studies [4, 35] obtained lower values of thermal conductivities for dry cotton samples, which could also be a result of the higher accuracy of the measuring method. Another important factor is the presence of moisture in the initial “dry” state. Textile samples stored under normal conditions already contain some moisture. Nevertheless, the results provide important information on the trend of the change in thermal conductivity with increasing moisture levels, which is of interest.

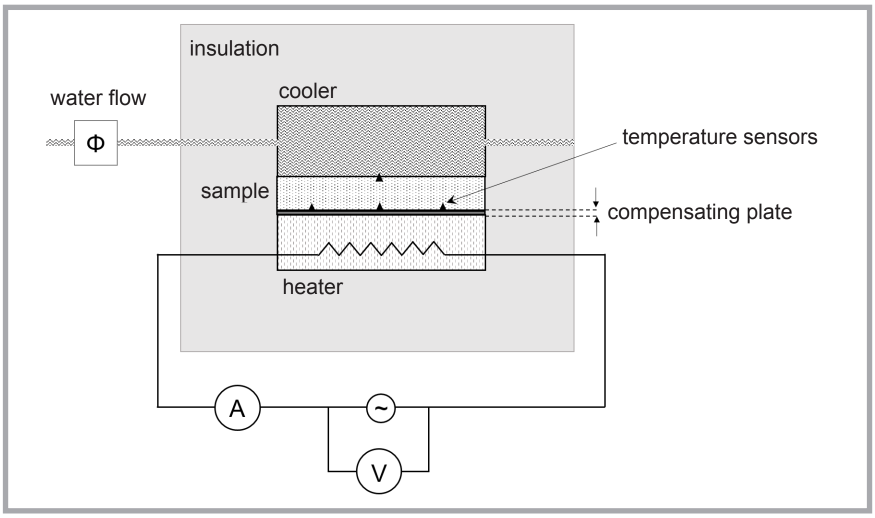

Figure 1. *Simplified schematic representation of the contact measuring device. Temperature sensors (black triangles), positioned at the compensating plate, form a triangle shape.*

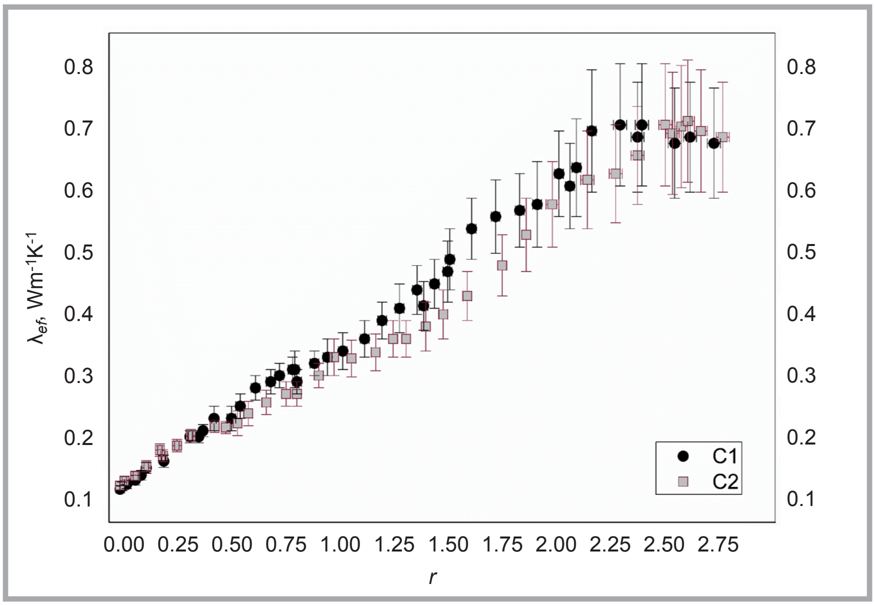

Figure 2. *Thermal conductivities of two cotton jerseys C1 (black circles) and C2 (grey squares) with gradually increasing of the relative amount of water up to r = 2.75.*

Table 2. *Monitored parameters with errors in percentage in brackets.*

Sample label	Ambient temperature, °C	Ambient humidity, %	Water temperature, °C	Water flow rate, l/s	Voltage, V	Electric current, A
C1	23.0 (± 4%)	51 (± 5%)	18.0 (± 3%)	0.03 (± 8%)	10.1 (± 1%)	0.52 (± 2%)
C2	23.0 (± 4%)	53 (± 5%)	18.5 (± 3%)	0.04 (± 8%)	10.2 (± 1%)	0.52 (± 2%)

Measurements confirmed that the effective thermal conductivity increases with an increase in the relative amount of moisture. For further discussion, we introduced the stabilization relative amount of absorbed moisture r_s, which marks the end of the linear increase in the effective thermal conductivity. It is noticeable that for smaller relative amounts, i.e. $r \leq r_s \equiv 2.5$ for C1 and $r \leq r_s \equiv 2.3$ for C2, the effective thermal conductivity shows a linear dependency. In the beginning, the moisture is absorbed from the surface of the sample, which is assumed to result in a linear increase in effective thermal conductivity. Then, the moisture is absorbed by fibres, which slows down the increase. For higher relative amounts, $r > r_s$, stabilisation of the effective thermal conductivity is expected broadly around the thermal conductivity of the absorbed liquid; in this case, water (0.64 $Wm^{-1}K^{-1}$). For both samples, the results show that the ef-

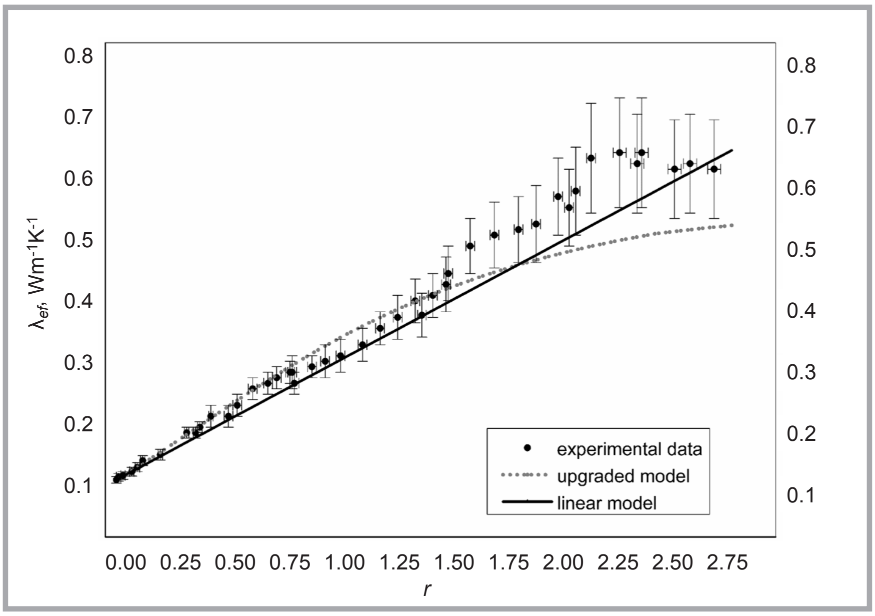

Figure 3. *Experimental results of sample C1 compared with theoretical results of the linear model (black solid line) and e three-parametric model (grey dotted line) for the absorption of water.*

fective thermal conductivity stabilised around the value (0.7 ± 0.1) $Wm^{-1}K^{-1}$, which is within the margin of error expected. In addition, the saturation relative amount was determined as the jersey sample was dripping wet in order to test the linear model. Both jersey samples were saturated with water at $r_c = 2.75$ when the total amount of absorbed water was (42.6 ± 0.4) ml for C1 and (42.9 ± 0.4) ml for C2. Note, several factors influence both values r_c and r_s, such as the density and fineness of thread or yarn, and ultimately the anisotropy of textile materials in general [35].

Figure 3 shows the correlation between the experimental results and those of the linear and upgraded models. It is evident that the linear model (black solid line) and upgraded model (grey dotted curve) results are a good fit at lower values of r. Deviations between the model and the experimental results are larger for higher relative amounts of moisture. In addition, the linear model cannot describe the effective thermal conductivity stabilisation. Furthermore, to estimate the effective thermal conductivity using the linear model (***Equation (5)***), one needs to determine the critical value r_c for that specific jersey sample accurately. Additional data in the upgraded model are the density and volume porosity of the dry jersey sample. The results of the upgraded model describe the stabilisation of the effective thermal conductivity. One of the main advantages of this model r_s is the estimation of the relative amounts at which stabilisation occurs. The error between the estimated and measured is around 10%.

Deviations of the experimental results from theoretical predictions using the linear and upgraded models are analysed by applying the sum of squares of deviations as described in [26, 27]:

$$MSSD = \frac{1}{n}\sum_{i=1}^{n}\left(\lambda_{exp,i} - \lambda_{ef,i}\right)^2. \qquad (13)$$

Here, λ_{exf} and λ_{ef} represent the experimentally and theoretically determined value of the effective thermal conductivity, and i is the i-th of n measurements. Using this criterion, we obtained a deviation of 0.004 for the linear model and 0.007 for the upgraded model. Deviations are a result of different factors, such as the precision of measuring procedures, methods, and changes in the thickness and swelling of fibres. Additionally, the thermal conductivity of water was set to a constant value, which contributed to some deviation. Despite higher deviation, only the upgraded model considers the stabilisation of the effective thermal conductivity. In addition, estimations using the linear model are strongly dependent on the critical value r_c.

Conclusions

Biodegradable poly(lactic acid) is a polymer with a wide range of applications. Suitable modifications, such as impregnation, allow to obtain the material properties expected. Thanks to the method of impregnation proposed, plant polyphenols can be easily introduced onto the PLA surface. Solvent-based impregnation does not require advanced equipment or special experimental conditions. The method presented uses a low temperature in the impregnation process, which does not destroy the natural compounds. Moreover, ethanol is a common and cheap solvent that can be regenerated after impregnation. The layer of polyphenols of plant origin applied effectively increases the resistance of poly(lactic acid) to oxidation. Xanthone and Polyphenon 60 protect PLA against coloUV aging, thermooxidation and weathering. In contrast, quercetin and rut influence of various degrading factors, which is why they can potentially be used as indicators of the aging time of polymers.

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