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
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 $\Delta T$ across the thickness of the sample ($d$) and the thermal conductivity ($\lambda$). In one dimension, the heat flux through the sample surface ($A$) is:

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

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

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

Where, $\lambda_a$ is the thermal conductivity of air. To clarify, $\lambda_a$ 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:

$$ \varepsilon_0 = \frac{V_a}{V} \quad (3) $$

Where, $V_a$ stands for the total volume of air gaps (in the case of a dry sample), and $V$ 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 $m_i$ and the mass of the dry jersey sample $m_i$ [33]:

$$ r = \frac{m_t}{m_s} \quad (4) $$

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:

$$ \lambda_{ef} = \lambda_f + r \frac{\lambda_a - \lambda_f}{1+r}. \quad (5) $$

Here, $\lambda_f$ is the thermal conductivity of the liquid used to moisten the sample (in the case of water $0.64$ Wm$^{-1}$K$^{-1}$) [34], and $r$ 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 Equation (2). In the linear approximation, it holds that [8]:

$$ \lambda_{ef} = \lambda_a \frac{1}{1+r} + \lambda_f \frac{r}{1+r}. \quad (6) $$

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:

$$ \varepsilon(r) = \varepsilon_0 - \rho_s \frac{\rho_0}{\rho_i} \quad (7) $$

Where, $\rho_s$ and $\rho_0$ 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:

$$ \lambda_{ef} = \frac{\lambda_f(1 - \varepsilon(r)) + \lambda_0 \varepsilon(r) + \lambda r}{1+r} \quad (8) $$

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

$$ \rho_s = \rho_s(1 + r), \quad (9) $$

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 gsm$^{-2}$ and 220 gsm$^{-2}$, 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.

| 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%)    |

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 homogeneous 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:

\[
\frac{1}{m_0} \left( \frac{m_1 + m_2}{2} - m_2 \right).
\]

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.

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 \( r_e \), which marks the end of the linear increase in the effective thermal conductivity. It is noticeable that for smaller relative amounts, \( r \leq r_e \equiv 2.5 \) for C1 and \( r \leq r_e \equiv 2.3 \) 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, \( r > r_e \), 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-
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]:

\[ \text{MSSD} = \frac{1}{n} \sum_{i=1}^{n} (\lambda_{\text{exp},i} - \lambda_{\text{ef},i})^2. \]  

Here, \( \lambda_{\text{ef}} \) and \( \lambda_{\text{exp}} \) 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 immersion, 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 Polyphenol 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.

References

1. Parsons K. Human Thermal Environments: The Effects of Hot, Moderate and Cold Environments on Human Health, Comfort and Performance, 2nd ed. London: Taylor & Francis, 2003.
2. Fanglong Z, Weiyuan Z, Minzhi C. Investigation of Material Combinations for Fire-fighter’s Protective Clothing on Radiant Protective and Heat-Moisture Transfer Performance. FIBRES & TEXTILES in Eastern Europe 2007; 15, 1(60): 72-75.
3. Hagh A. Mechanism Of Heat And Mass Transfer In Moist Porous Materials. Journal Teknologi. 2002; 36: 1-14.
4. Les L, Loghin C. Heat, Moisture and Air Transfer Properties of Selected Woven Fabrics in Wet State. Journal of Fiber Bioengineering & Informatics 2009; 2: 141-149.
5. Hock W, Sookne A, Harris M. Thermal Properties of Moist Fabrics. Journal of Research of the National Bureau of Standards 1994; 32: 229-252.
6. Yoo H, Hu Y, Kim E. Effects of Heat and Moisture Transport in Fabrics and Garments Determined with a Vertical Plate Sweating Skin Model. Textile Research Journal 2000; 70: 542-549.
7. Romoli D, Barigozzi G, Esposito S, Rosace G, Salesi G. High Sensitivity Measurements of Thermal Properties of Textile Fabrics. Polymer Testing 2013; 32(6): 1029-1036.
8. Slavinec M, Repnik R, Klemencic E. The Impact of Moisture on Thermal Conductivity of Fabrics. Anali PAZU 2016; 6(1/2): 8-12.
9. Michalak M, Felczak M, Wićcek B. Evaluation of the Thermal Parameters of Textile Materials Using the Thermographic Method. FIBRES & TEXTILES in Eastern Europe 2009, 17, 3(74): 84-89.
10. Afzal A, Ahmad S, Rasheed A, Mohsin M, Ahmad F, Nawab Y. Characterization and Statistical Modelling of Thermal Resistance of Cotton/Polyester Blended Double Layer Interlock Knitted Fabrics. *Thermal Science* 2015; 00: 201.

11. Feng A, Wu G, Pan C, Wang Y. The Behavior of Acid Treating Carbon Fiber and the Mechanical Properties and Thermal Conductivity of Phenolic Resin Matrix Composites. *Journal of Nanoscience and Nanotechnology* 2017; 17(6): 3786-3791.

12. Pac M, Bueno M, Renner M, Kasi M. Warm-Cool Feeling Relative to Tribological Properties of Fabrics. *Textile Research Journal* 2001; 71(9): 806-812.

13. Uçar N, Yılmaz T. Thermal Properties of 1×1, 2×2, 3×3 Rib Knit Fabrics. *FIBRES & TEXTILES in Eastern Europe* 2004; 12, 3(47): 34-38.

14. Ozdi N, Marmali A, Kretzschmar S. Effect of Yarn Properties on Thermal Comfort of Knitted Fabrics. *International Journal of Thermal Sciences* 2007; 46(12): 1318-1322.

15. Rosace G, Guido E, Colleoni C, Barigozzi G. Influence of Textile Structure and Silica Based Finishing on Thermal Insulation Properties of Cotton Fabrics. *International Journal of Polymer Science*, 2016.

16. Onofrei E, Rocha A, Catarino A. The Influence of Knitted Fabrics Structure on the Thermal and Moisture Management Properties. *Journal of Engineered Fibres and Fabrics* 2011; 6(4): 10-22.

17. Karaca E, Kahraman N, Omeroglu S, Becerir B. Effects of Fiber Cross Sectional Shape and Weave Pattern on Thermal Comfort Properties of Polyester Woven Fabrics. *FIBRES & TEXTILES in Eastern Europe* 2012; 20, 3(92): 67-72.

18. Afzal A, Ahmad S, Rasheed A, Ahmad F, Ilifkhar F, Nawab Y. Influence of Fabric Parameters on Thermal Comfort Performance of Double Layer Knitted Interlock Fabrics. *AUTEX Research Journal* 2016; 17(1).

19. Afzal A, Hussain T, Mohsin M, Rasheed A, Ahmad S. Statistical Models for Predicting the Thermal Resistance of Polyester/Cotton Blended Interlock Knitted Fabrics. *International Journal of Thermal Sciences* 2014; 85: 40-46.

20. Kothari VK, Bhattacharjee D. Prediction of Thermal Resistance of Woven Fabrics. Part I: Mathematical Model. *The Journal of the Textile Institute* 2008; 99(5): 421-432.

21. Ahmad S, Ahmad F, Afzal A, Rasheed A, Mohsin M, Ahmad N. Effect of Weave Structure on Thermo-Physiological Properties of Cotton Fabrics. *AUTEX Research Journal* 2014; 15(1).

22. Voelker C, Hoffman S, Arens E, Zhang H. Heat and Moisture Transfer Through Clothing. Paper presented at: *Eleventh International IBPSA Conference*; 2009; Glasgow, Scotland.

23. Baltušnikaitė J, Abraitienė A, Stygienė L, Krauledas S, Rubežienė V, Varnaitė-Zaurovila S. Investigation of Moisture Transport Properties of Knitted Materials Intended for Warm Underwear. *FIBRES & TEXTILES in Eastern Europe* 2014; 22, 4(106): 93-100.

24. Cui Z, Zhang W. Study of the Effect of Material Assembly on the Moisture and Thermal Protective Performance of Firefighter Clothing. *FIBRES & TEXTILES in Eastern Europe* 2009, 17, 6(77): 80-83.

25. Standard ISO/TC 38 Textiles: ISO 11092:2014 Textiles – Physiological effects – Measurement of Thermal and Water-Vapour Resistance Under Steady-State Conditions (Sweating Guarded-Hotplate Test).

26. Mangat MM, Hes L. Thermal Resistance of Denim Fabric under Dynamic Moist Conditions and its Investigational Confirmation. *FIBRES & TEXTILES in Eastern Europe* 2014; 22, 6(108): 101-105.

27. Mangat M, Hes L, Bajzik V. Thermal Resistance Models of Selected Fabrics in Wet State and their Experimental Verification. *Textile Research Journal* 2015; 85(2): 200-210.

28. Salmon D. Thermal Conductivity of Insulations Using Guarded Hot Plates, Including Recent Developments and Sources of Reference Materials. *Measurement Science and Technology* 2001; 12(12): 89-98.

29. Morton W, Hearle J. *Physical Properties of Textile Fibres*. Cambridge: Woodhead Publishing Limited, 2008.

30. Zupin Ž, Hladnik A, Dimitrovski K. Prediction of One-Layer Woven Fabrics Air Permeability Using Porosity Parameters. *Textile Research Journal* 2011; 82(2): 117–128.

31. Ogulata RT, Mavruz S. Investigation of Porosity and Air Permeability Values of Plain Knitted Fabrics. *FIBRES & TEXTILES in Eastern Europe* 2010; 18, 5(82): 71-75.

32. Havlová M, Špánková J. Porosity of Knitted Fabrics in the Aspect of air Permeability – Discussion of Selected Assumptions. *FIBRES & TEXTILES in Eastern Europe* 2017; 25, 3(123): 86-91. DOI: 10.5604/01.3001.0010.1695.

33. Slavinec M, Fras M, Zavec Pavlinič D, Melnikov I, Topolnoški Pavlinič D, Melnikov I. Topolnoški Pavlinič D. Thermal Conductivity of Water. *Vlažne Plasti / Heatconducting through Water-Vapour Resistance Under Steady-State Conditions (Sweating Guarded-Hotplate Test).*

34. Ramires M, Nieto de Castro C. Standard Reference Data for the Thermal Conductivity of Water. *Journal of Physical and Chemical Reference Data* 1995; 24(1377).

35. Lloyd J, Clegg W. Effect of Fibre Anisotropy on Composite Thermal Conductivity. *Composite Materials Research* 2008; 59: 148-152.

36. Saad A, Echchelh A, Hattabi M, Ganaoui M. The Identification of Effective Thermal Conductivity for Fibrous Reinforcement Composite by Inverse Method. *Journal of Reinforced Plastics and Composites* 2014; 33(32): 2183-2191.

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