Thermal Analysis of Conventional and Performance Plain Woven Fabrics by Finite Element Method
Siddiqui, Muhammad Owais Raza; Sun, Danmei

Published in:
Journal of Industrial Textiles

DOI:
10.1177/1528083717736104

Publication date:
2018

Document Version
Peer reviewed version

Link to publication in Heriot-Watt University Research Portal

Citation for published version (APA):
Thermal Analysis of Conventional and Performance Plain Woven Fabrics by Finite Element Method

Abstract
The research reports the development of geometrical models of woven fabric structures and evaluation of fabric thermal properties by using finite element method. A mesoscopic scale modelling approach was used to investigate the effective thermal conductivity and thermal resistance of woven textile structures. Various techniques, including Scanning Electron Microscopy and experimental methods, have been adopted to obtain the actual three dimensional parameters of the fabrics for finite element analysis. The research revealed that the thermal anisotropy of fibres, fibres material orientation and temperature dependent thermal conductivity of fibre have a significant impact on the effective thermal conductivity of fabrics because experimental and simulated results were highly correlated with the consideration of above-mentioned factors.

Keywords: Effective thermal conductivity, woven fabric, finite element analysis, protective clothing

1. Introduction
Clothing comfort can be categorised into three groups: psychological which is related to fashion, tactile which includes the mechanical interaction of the fabric with skin and has a strong relationship with fabric surface and mechanical properties, and thermal comfort related to the ability of a fabric to regulate the temperature of the skin through heat and moisture transfer [1].

Thermal insulation properties of textile materials play a significant role in engineering design of protective clothing. In case of extreme cold condition it is necessary to restrict the heat flow from the body to the external environment, therefore, the purpose of a fabric is supposed to act as an insulator [2]. It means that the fabric is required to have low thermal conductivity or higher thermal resistance. The thermal conductivity is an important material property because it affects the heat flow in the material. Heat can be transferred from clothing to the environment to maintain its thermal balance through conduction, convection and radiation.
In the case of natural fibres, high performance fibres such as Nomex® and Twaron® are widely used in fire protection and body armour clothing respectively [3-9]. The heat transfer behaviour of these materials is necessary to be analysed when they are subjected to the intense environment.

Heat flow through the clothing assembly mainly depends on the thermal conductivity of the fibrous material, fibre volume content, construction of the fabric, and orientation of fibre with respect to the heat flow direction [10, 11]. Significant research work has been carried out to determine the effective thermal conductivity ($K_m$) and thermal resistance of fabric by using mathematical modelling and numerical analysis. Schuhmeister [12] developed a relationship to calculate the thermal conductivity of the mixture of air and uniformly distributed solid fibres:

$$K_m = \frac{1}{3} \left( K_a V_a + K_f V_f \right) + \frac{2}{3} \left( \frac{K_a K_f}{K_a V_f + K_f V_a} \right)$$  

where $K_a$ is the thermal conductivity of air, $K_f$ is the thermal conductivity of fibre, $V_a$ is the fractional volume of air, $V_f$ is the fractional volume of fibre, and $V_a + V_f = 1$.

The first part of the above equation describes that fibres are parallel to the direction of heat flow. The second part presents that fibres are oriented perpendicular to the direction of heat flow, which is demonstrated in Figure 1.

![Figure 1: Heat flow mechanism in solid and gas are in: (a) Series; and (b) Parallel](image)

Farnworth [13] developed a theoretical model to evaluate the modes of heat flow in fibrous batts which were placed between the two plates having a temperature gradient. There was no significant evidence of convective heat flow even though the experimental conditions
were favourable for convection heat transfer and heat transfer via radiation could be ignored when the temperature gradient is small [14]. The thermal and radiative conductivity ($K_{\text{rad}}$) of the fabric can be calculated by the first part of $(K_a V_a + K_f V_f)$ Equation 1, and Equation 2 respectively.

$$K_{\text{rad}} = 8\sigma T^3 R f \varepsilon$$

where $\sigma$ is the Stephen Boltzmann constant, $T$ is the mean temperature between heat source and sink (K), $R$ is the radius of fibre, $f$ is the fibre volume fraction and $\varepsilon$ is the thermal emissivity of the surface.

Stark and Fricke [15] developed models to calculate the combined thermal conductivity of air and solid fibre. In their basic model, they considered the mean orientation of fibre in terms of $Z$ which defined the fraction of fibre perpendicular to the direction of heat flow. On the basis of the assumptions of Bhattacharyya [16], they developed the relationship of combined thermal conductivity of solid fibre and air in the following equation:

$$\lambda_{sg}^{BM} = K_f \cdot \left(1 + \frac{\alpha - 1}{\beta(1 + Z(\alpha - 1)/(\alpha + 1))}\right)$$

where $\lambda_{sg}^{BM}$ is the combined thermal (effective) conductivity of solid fibre and air, $K_f$ is the thermal conductivity of solid fibre, $\alpha$ is the ratio of thermal conductivity of air to thermal conductivity of solid fibre $(K_a/K_f)$, $\beta$ is the ratio of volume fraction of solid fibre $(V_f/V_a)$ and volume fraction of air, and $Z$ is the portion of fibre oriented upright to the direction of macroscopic heat flow.

In the modified model they considered that the effect of thermal resistance was caused by the contact between fibres; the thermal conductivity of individual solid fibre, air and the coupling effects could be calculated. The diagram of thermal resistance is shown in Figure 2(a), where $R_{BM}$, $R_{ct}$ and $R_g$ represent the thermal resistance of the basic model, the contact resistance between fibres and the thermal resistance of air respectively. Figure 2 (b) demonstrates the unit cell of solid fibre and the contact between two fibres. In the modified model the unit cell height is $(m+1)r$; however in the basic model, it was expressed by
which is less than that of the modified model. Furthermore, they compared the results obtained from the derived model with experimental results for model validation.

The relationship between heat transfer behaviour of clothing with their structural parameters have been investigated by many researchers, namely Ismail et al. [17], Kothari and Bhattacharjee [18], Yamashita et al. [19] Zhu and Li [20], Das et al. [21], Ran et al. [22], Matusiak [23]. However, all the foregoing research works related to the modelling of thermal conductivity of textile fabrics are lack of accuracy without consideration of the following that are very important elements need to be considered.

a) The actual cross-section of yarn in woven fabric

Cross-section of yarn has significant influence on fibre content in a model. Fibre content or volume fraction of fibre in a model can be defined as the ratio of fibre volume to the total volume of the model. A textile fabric as non-homogeneous material contains heterogeneous mixture of fibre substance and the air, usually. The thermal conductivity of air is less compared to that of textile fibres. If an inaccurate or non-realistic cross-section of yarn was used for geometrical modelling of woven fabric this would give more amount of fibre than the actual case. The resulted overall thermal conductivity of the fabric will be more than it should be because the model has less air or vice versa.
b) Fibre orientation and influence of fibre anisotropy behaviour on the effective thermal conductivity of fabric

Textile fibres are transversely isotropic in nature; the transversely isotropic material is a special kind of orthotropic material. An orthotropic material is a subset of an anisotropic material. Transversely isotropic materials are those in which properties are symmetrical in one plane of fibre diameter (transverse) direction which is perpendicular to the other plane of longitudinal direction of fibre. The thermal conductivity of fibre is higher in the longitudinal direction than the transverse direction. Therefore, it is necessary to get the material orientation assigned for the material property during finite element modelling process. The assumption of yarn and fabric as isotropic material made by published research works [12, 13, 15, 17-23] was incorrect and results from those models could give more deviation from the experimental results.

c) Temperature dependent thermal conductivity of fibre

The thermal conductivity of fibre increases with the increase of temperature and a similar pattern is followed by the air. Therefore, to estimate the effective thermal conductivity in the high-temperature environment it is necessary to consider the temperature-dependent thermal conductivity.

In this research work, all the aforementioned factors will be taken into consideration to evaluate the effective thermal conductivity and thermal resistance of textile structures by using finite element method. The models were validated by experimental results. Furthermore, the thermal properties of the fabrics were predicted based on the validated models.

2. Methodology

The following methodology is adopted to calculate the effective thermal conductivity and thermal resistance of woven fabrics:

(1) development of finite element models of plain woven fabrics;
(2) calculation of the effective thermal conductivity of yarn; and
(3) investigation of the effective thermal conductivity and thermal resistance of fabrics by using finite element method.
2.1 Finite Element Model

Physical, mechanical and thermal properties of fabrics mainly depend on their structural parameters once a specific fibre material has been selected. In order to predict these properties accurately, it needs to define the correct geometrical models of the fabric structures. However, the fabric geometry is very complicated and it is difficult to consider a single cross-section of yarn because yarn cross-section is dependent on many factors such as the level of twist in yarn and normal force induced during the weaving process. In addition, the measurement of the accurate geometrical parameter is not an easy task.

If we consider one factor only e.g. level of twist in yarn, for the sake of argument, then yarn would form a round bundle of fibres if yarn has a higher twist which will be less subjected to force to flatten the yarn. On the other hand, in the case of lower level of twist of yarn, the yarn crimp is also low, as a result, yarn will be flatter up to a single level of fibre [24].

In this research the unit cell model of plain woven fabric is developed by using TexGen [25]. TexGen is open source software, distributed under the general public license and developed by Textile Composite Research group at the University of Nottingham. TexGen can generate woven geometrical structure by taking few input parameters such as yarn width, yarn height, yarn spacing and thickness of fabric.

In TexGen yarns are generated by two dimensional cross-sectional shapes of yarn sweep along the path of yarn. Yarn path can be defined by more flexible and generic way using discrete points and these points are interpolated by Bezier spline, natural cubic spline and linear spline [26].

The developed model of woven structure can be exported to CAD (Computer Aided Design) software. TexGen has the following advantages:

1. Yarn can be created with variable and combination of different shape cross-section because it contains hybrid section.
2. Control point can be adjusted manually.
3. Intersections between yarns can be avoided by using the above two options.

In order to develop the finite element model of plain woven fabric, it needs to find out the geometrical parameters which would be used as input parameters in TexGen.
2.1.1 Fabric Geometric Parameters

In this work, the effective thermal conductivity and thermal resistance of plain woven fabrics were examined. Woven fabrics were selected by considering the different applications such as fire protective clothing, body armour clothing and normal wearing. The fabrics used for this study are listed in Table 1.

Nomex® III fabric is widely used for protective clothing which provides protection against fire. The purpose of selecting Nomex® III fabric in this study is to simulate the realistic effect of heat transfer when it is subjected to extreme temperature environment.

Protective clothing made of Twaron® fibre is used in body armour for ballistic protection. There is a common issue of thermal stress with body armour because of their almost impermeable structure required for high ballistic resistance. Body armour provides insulation to the body and limits the heat exchange to the environment. Clothing insulation property is determined by the thermal resistance and thermal conductivity that need to be studied for better understanding the thermal comfort of body armour.

Poly-viscose fabric is also selected in this research along with cotton and wool fabrics. These fabrics are used for normal wear clothing. In Poly-viscose fabric a special core spun yarn was used in weft and simple polyester yarn in warp.

Table 1: Fabric Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Nomex® III</th>
<th>Twaron®</th>
<th>Cotton</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>132±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>65/55</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>25.5/25.5</td>
<td>27.8/27.8</td>
<td>7.798/19.6</td>
</tr>
</tbody>
</table>

To understand the thermal behaviour of the fabrics is important so as to determine their specific applications. Unit cell models of plain woven fabrics were created by using the actual parametric values of the fabric. For that purpose the following parameters are needed:

1. warp/weft yarn spacing (Wa/Wf);
(2) fabric thickness \((t)\); and 

(3) width of the warp/weft yarn \((W_{dW}/W_{fW})\) and yarn cross-sectional shape.

The warp and weft sett were calculated by using method-A described in British Standard BS EN 1049-2:1994 [27]. Five random samples were selected and conditioned according to the BS EN ISO 139:2005 [28]. Fabric thickness \((t)\) was tested by FAST-1 compression meter under 2gf/cm\(^2\) or 0.196 KPa over the surface area of 10 cm\(^2\). Measured thicknesses of fabrics are given in Table 2.

There are several techniques available such as MicroCT, microscope, electron microscope etc. which can be used to find out the cross-sectional image for further study of yarn width, yarn height, yarn cross-sectional shape and yarn path through image analysis. In this work, Hitachi S-4300 SEM (Scanning electron microscope) was used to examine the geometry of yarn cross-section.

It is very difficult to obtain a very clear cross-sectional image of fabric; the reason is that when the fabric is cut fibres open apart which makes it difficult to obtain the correct dimension of the yarn cross-section. In order to avoid this problem fabric was first coated with acrylic binder without applying pressure. Acrylic binder was applied by brushing manually on one side of the fabric then dried and the same procedure was applied on the other side of the fabric. When fabric dried fully it was then cured under specified temperature before the cross-sectional image was taken by SEM. The image was further analysed by ImageJ [29] which was developed at the National Institutes of Health. It is a public domain, Java-based image processing program. The yarn spacing, width, height and fibre volume fraction of the SEM image were measured in ImageJ. Figure 3 shows the micrograph of Twaron® plain woven fabric. During the image analysis yarn cross-section was examined carefully because all the fabrics except Twaron® have an asymmetrical cross-sectional shape of yarn.

The measured geometric dimensions for the unit cell of the fabrics are listed in Table 2. Unit cell model of Twaron® plain woven fabric was generated from TexGen by using the actual parameters measured using the technique mentioned above and shown in Figure 4.

The cross-sectional image of the developed unit cell model of Twaron® fabric is comparable to the cross-sectional micrograph image from SEM. SEM image digitized in plot digitizer [30] which is a general public licensed software being used to find out the
length of yarn in one unit cell. The length obtained from the SEM image and the model is 2.586 and 2.60319 respectively.

**Table 2:** Measured geometric dimensions of an unit cell model

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Nomex® III</th>
<th>Twaron®</th>
<th>Cotton</th>
<th>Wool</th>
<th>Poly-viscose</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{a_s}/W_{f_s}$</td>
<td>0.431/0.431</td>
<td>1.282/1.282</td>
<td>0.390/0.462</td>
<td>0.363/0.564</td>
<td>0.339/0.299</td>
</tr>
<tr>
<td>$W_{a_d}/W_{f_d}$</td>
<td>0.337/0.337</td>
<td>1.2154/1.2154</td>
<td>0.26/0.277</td>
<td>0.3/0.33</td>
<td>0.1591/0.219</td>
</tr>
<tr>
<td>$t$ (mm)</td>
<td>0.5 (SD:0.01)</td>
<td>0.348 (SD:0.0051)</td>
<td>0.484 (SD:0.0109)</td>
<td>0.408 (SD:0.012)</td>
<td>0.341 (SD:0.007)</td>
</tr>
<tr>
<td>Total length of unit cell (mm)</td>
<td>0.862</td>
<td>2.564</td>
<td>0.924</td>
<td>1.128</td>
<td>0.675</td>
</tr>
<tr>
<td>Total width of unit cell (mm)</td>
<td>0.862</td>
<td>2.564</td>
<td>0.78</td>
<td>0.726</td>
<td>0.598</td>
</tr>
<tr>
<td>Unit cell volume (mm³)</td>
<td>0.3715</td>
<td>2.2878</td>
<td>0.3488</td>
<td>0.3441</td>
<td>0.13766</td>
</tr>
</tbody>
</table>

![Figure 3: Micrograph of the cross-section of Twaron® fabric](image)
Figure 4: Twaron® fabric (a) Unit cell model of Twaron® fabric, (b) Cross-sectional view of Twaron® model, and (c) Cross-sectional view of micrograph of Twaron® fabric

Figure 5 (a) Shows the cross-sectional micrograph of Nomex® III fabric which clearly indicates that the cross-section of yarns is not exactly lenticular, initially the yarn cross-section was considered as lenticular but there was huge interference between the yarn. In order to remove the interference between yarns, a hybrid cross-sectional shape of yarn was used which consists of the combination of power ellipse cross-section of the yarn in TexGen. Figure 5 (b) shows the unit cell model of Nomex® III fabric.

The effective thermal conductivity of yarn was calculated based on the generated unit cell model of plain woven fabric developed by using actual parameters of the fabric.
Figure 5: Nomex® III fabric (a) Micrograph of the cross-section of Nomex® III fabric, and (b) Unit cell model of Nomex® III

2.2 Effective Thermal Conductivity of Yarn

The effective thermal conductivity of textiles mainly depends on two components: conductive heat transfer through solid fibres and air within the fabric [31]. Therefore it is substantial to determine the amount of fibre content or fibre volume fraction that is present in the unit cell of a woven fabric.

2.2.1 Fibre Volume Fraction

Fibre volume fraction in a fabric ($V_f$) was calculated by using Equation 4.

$$ V_f = \frac{\rho}{\rho_f} $$

where $\rho$ and $\rho_f$ are the fabric and fibre density respectively.
Fabric density can easily be calculated by the areal density of fabric and fabric thickness as shown in Equation 5.

\[ \rho = \frac{\text{Fabric Areal Density}}{\text{Fabric Thickness}} \]  

Fibre volume fraction of yarn \((V_{fy})\) in a fabric can be calculated in two ways, i.e. (i) through image analysis [32] and (ii) find out the unit cell fibre volume fraction/fibre volume fraction of fabric \((V_f)\) using Equations 6 & 7 respectively,

\[ V_{fy} = \frac{\text{Total Fibre Volume in Yarn}}{\text{Yarn Volume}} \]  
\[ V_{fy} = \frac{V_f \times V_{uc}}{V_f} \]

where \(V_f, V_{uc}\) and \(V_y\) are the fibre volume fraction of fabric, the volume of the unit cell and volume of yarn in a unit cell respectively.

Fibre volume fraction of same yarn count and the equal number of warp/weft sett of fabric can be calculated by the above equations. However, in the case of cotton, wool and Poly-viscose fabrics they have different yarn count and warp/weft sett; yarn count is utilised to calculate the fibre volume fraction in yarn by the following steps:

1. calculate the individual length of yarn;
2. calculate the individual volume of yarn;
3. multiply the length of yarn with the yarn count which gives the mass of fibre in yarn;
4. convert the mass of fibre in yarn into volume of fibre in yarn through by dividing the mass of fibre in yarn by the density of fibre; and
5. finally divide the volume of fibre in yarn by volume of yarn.

2.2.1.1 Fibre Volume Fraction of Different Yarn Count

Fibre volume fraction of yarn for different yarn count and different number of warp/weft per unit length can be calculated following the above-mentioned steps using Equations 8, 9 and 7.

\[ \text{Mass of fibre in yarn} = \text{Yarn count} \times \text{Lenght of yarn} \]
2.2.1.2  Fibre Volume Fraction of Core Spun Yarn

The weft yarn in the Poly-viscose fabric is a core-spun yarn and warp yarn is simple polyester yarn shown in Figure 6. The core part of the spun yarn is polyester filament covered by viscose fibres. The effective density of fibres for the whole yarn was calculated on the basis of weighted proportion by using Equation 10 [33].

\[
\rho_{eff} = w_a \rho_{af} + w_b \rho_{bf}
\]

where \( w_a, w_b, \rho_{af}, \) and \( \rho_{bf} \), are the weight proportion and density of fibre ‘a’ and ‘b’ respectively.

![Figure 6: Micrograph of Poly-viscose fabric: (a) cross-section of warp yarn, and (b) cross-section of core spun weft yarn](image)

Weight proportion of fibre in core-spun yarn was calculated by using image analysis of SEM image. During image analysis the area of respective fibre within the yarn was calculated firstly and then the weight proportion which was calculated by using Equations 11 and 12.

\[
m_{af} = A_{af} \times l_{af} \times \rho_{af}
\]

\[
w_{af} = \frac{m_{af}}{T_y \times l_y}
\]

where \( m_{af}, A_{af}, l_{af}, l_y \) and \( T_y \) are mass of fibre ‘a’, cross-sectional area of fibre ‘a’, length of fibre ‘a’, length of yarn and yarn count in Tex respectively. In case of
multifilament yarn it was assumed that the length of both yarn and filament fibre was the same.

Table 3 shows the value of fibre volume fraction in a yarn calculated by aforementioned technique. The fibre volume fraction value of yarn was used to calculate the axial and transverse thermal conductivity of yarn.

Table 3: Fibre volume fraction of yarn and unit cell

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Yarn Fibre Volume Fraction, $V_f$ (%)</th>
<th>Fibre volume fraction of unit cell, $V_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>warp</td>
<td>weft</td>
</tr>
<tr>
<td>Nomex® III</td>
<td>40.00</td>
<td>40.00</td>
</tr>
<tr>
<td>Twaron®</td>
<td>50.87</td>
<td>50.87</td>
</tr>
<tr>
<td>Cotton</td>
<td>40.69</td>
<td>36.4</td>
</tr>
<tr>
<td>Wool</td>
<td>57.50</td>
<td>45.71</td>
</tr>
<tr>
<td>Poly-viscose</td>
<td>44.34</td>
<td>41.67</td>
</tr>
</tbody>
</table>

Table 4 shows the thermal properties of fibres which were used to determine the effective thermal conductive of yarns. The material of yarn orthotropic in nature was considered transversely isotropic. Transversely isotropic materials are those that have the equivalent physical properties at every point in the material about an axis that is normal to the plane of isotropy, so the thermal conductivity of yarn can be defined by the following tensor Equation 13:

$$K = \begin{bmatrix}
K_{11} & 0 & 0 \\
0 & K_{22} & 0 \\
0 & 0 & K_{33}
\end{bmatrix}$$

where $K_{11}$, $K_{22}$ and $K_{33}$ are the thermal conductivity of the yarn along the fibre direction and perpendicular to the fibre direction respectively.

Thermal conductivity of component fibres of the core spun yarn can be calculated by Equation 14:

$$K_{eff} = w_{af}K_{af} + w_{bf}K_{bf}$$

where $K_{af}$ and $K_{bf}$ are thermal conductivity of fibre ‘a’ and ‘b’ respectively.
Table 4: Thermal Properties of Fibres

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_f$ (kg/m$^3$)</td>
<td>1380</td>
<td>1440</td>
<td>1520</td>
<td>1310</td>
<td>1490</td>
<td>1390</td>
</tr>
<tr>
<td>$K_{fa}$ (W/m.k)</td>
<td>1.3*</td>
<td>3.05</td>
<td>2.88</td>
<td>0.48</td>
<td>1.89</td>
<td>1.26</td>
</tr>
<tr>
<td>$K_{ft}$ (W/m.k)</td>
<td>0.13</td>
<td>0.192</td>
<td>0.243</td>
<td>0.165</td>
<td>0.289</td>
<td>0.157</td>
</tr>
<tr>
<td>$C_{pf}$ (J/kg.K)</td>
<td>1200</td>
<td>1420</td>
<td>1350</td>
<td>1360</td>
<td>1590</td>
<td>1030</td>
</tr>
</tbody>
</table>

*Assumed axial thermal conductivity value 10 times than the transverse [36]

Thermal conductivities values of Twaron® assumed same as Kevlar

$K_{fa}$: Thermal conductivity along the fibre axis

$K_{ft}$: Thermal conductivity perpendicular to the fibre axis

After the fibre volume fraction and air fraction in the yarn were calculated, the axial and transverse thermal conductivity of the yarn can then be calculated by a number of models which have been developed.

Yarn axial thermal conductivity ($K_{ya}$) can be calculated by the Parallel model:

$$K_{ya} = K_{fa} V_{fa} + K_{air} (1 - V_{fa})$$  \hspace{1cm} 15

Yarn transverse thermal conductivity ($K_{yr}$) calculated by the Series model as shown in Equations 16.

$$K_{yr} = \frac{K_{ft} K_{air}}{V_{fa} K_{air} + (1 - V_{fa}) K_{ft}}$$  \hspace{1cm} 16

Table 5 shows the thermal conductivity value in both the yarn axial and transverse directions calculated by the equations 15 and 16 respectively. In Table 5 cotton, wool and Poly-viscose yarns show different values of thermal conductivity in warp and weft directions due to the yarn count differences. The material of yarn is transversely isotropic, hence:

$$K_{22} = K_{33} = K_{yr}$$

$$K_{11} = K_{ya}$$
Table 5: Yarn thermal conductivity

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Yarn thermal conductivity in axial direction, $K_{yw}$ (W/m.K)</th>
<th>Yarn thermal conductivity in transverse direction, $K_{yt}$ (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>warp</td>
<td>weft</td>
</tr>
<tr>
<td>Nomex® III</td>
<td>0.5356</td>
<td>0.5356</td>
</tr>
<tr>
<td>Twaron®</td>
<td>1.5643</td>
<td>1.5643</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.1875</td>
<td>1.0646</td>
</tr>
<tr>
<td>Wool</td>
<td>0.2871</td>
<td>0.2335</td>
</tr>
<tr>
<td>Poly-viscose</td>
<td>0.5732</td>
<td>0.7356</td>
</tr>
</tbody>
</table>

2.3 Application of Finite Element Method

The following assumptions have been made for the finite element analysis of fabric thermal properties.

1. Consider still air inside and over the surface of the fabric so the heat is only transferred by conduction.
2. Only one mode of heat transfer was considered i.e. conduction.
3. Yarn is a porous material, consisting of both fibres and the air.
4. Air in a fabric is considered as the fluid matrix (entrapped air between the plate and yarn as shown in Figure 7).

Heat transfer by conduction of fabric is calculated by Fourier’s law:

$$Q_{\text{cond}} = -K_z A \frac{\Delta T}{t}$$

Where $K_z$, $A$, $\Delta T$ and $t$ are the effective thermal conductivity of fabric, surface area of fabric, temperature gradient across the fabric and thickness of fabric respectively.
The unit cell of fabric generated was imported and meshed in a commercial finite element simulation software ABAQUS/CAE. Two material sections were defined, one is for the entrapped air between the plates and the other is for the yarn. The thermal conductivity value of air is constant which is 0.026 W/m.K. In the case of yarn three effective thermal conductivity values $k_{11}$, $k_{22}$ and $k_{33}$ were taken as the input parameters for analysis.

2.3.1 Material Orientation

Yarn is considered as solid orthotropic material with the consideration of transversely isotropic. Figure 8 shows the material orientation in a yarn of woven fabric generated in Abaqus/CAE (Computer Aided Engineering), axis 11 refers to the axis which is parallel to yarn axis, axis 22 and 33 are transverse (perpendicular) to the fibre direction by using discrete orientation technique. Because of the waviness in warp and weft yarns, the material principal may vary from point to point. Unit cell model of one repeat unit length of woven fabric was imported in Abaqus in STP (Standard for the Exchange of Product model data) format. A discrete orientation defines a spatially varying orientation at the centroid of each native or orphan mesh element. The orientation is based on the topology of the part, allowing defining a continually varying orientation. Once the normal axis and primary axis are defined, Abaqus/CAE uses these axes to construct a right-handed Cartesian coordinate system [37]. For that purpose, the surface of the yarn is divided into small faces by partition and the edges and surfaces are selected for the primary and normal axis.

![Material orientation](image)

**Figure 8:** Material orientation
2.3.2 **Meshes**

4-node linear tetrahedral element (DC3D4) was used to mesh the unit cell of fabric because this is the most suitable mesh element to completely mesh the complex geometrical shape [37]. An optimal mesh density was obtained after the verification that further refinement cannot affect the results. Figure 9 shows the meshed unit cell model of Twaron® fabric.

![Meshed unit cell model of Twaron® fabric](image)

**Figure 9:** Twaron unit cell: (a) Meshed unit cell with air fluid-matrix, and (b) Meshed unit cell without air-fluid matrix

2.3.3 **Boundary Conditions and Analysis**

For 1-D steady state heat transfer analysis across the thickness of the fabric \((t)\), the specified temperature boundary conditions were used. The two specified temperature values were defined on both side of the fabric with the assumption of all the other surfaces of the fabric are perfectly insulated. The specified temperatures can be expressed as:

\[
T(0) = T_0 = 298.15 \text{ K} \\
T(h) = T_h = 308.15 \text{ K}
\]

where \(T_0\) and \(T_h\) are the specified value at the face and back side of the fabric respectively.

The effective thermal conductivity across the thickness of fabric can be determined by using Equation 18.

\[
K_z = \frac{Q_z t}{\Delta T_z}
\]

where \(Q_z\) and \(\Delta T_z\) are the overall heat flux value and the temperature difference in \(z\)-direction respectively.

\(Q_z\) of the unit cell can be calculated by using keyword script in the output section of the Abaqus which returns the total section heat flux (SOH) and surface area of the unit cell (SOAREA) [38]. The overall heat flux value along the \(z\)-direction can be calculated by using Equation 19.
The effective thermal conductivity and thermal resistance of plain woven fabric predicted by the unit cell model are listed in Table 6. Figure 10 shows the heat transfer values of the unit cell of Twaron® under the specified temperature boundary conditions. Thermal resistance ($R_z$) of the unit cell in Z-direction can be determined by:

$$R_z = \frac{h}{K_z}$$
Table 6: Predicted effective thermal conductivity and thermal resistance of plain woven fabric

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Predicted effective thermal conductivity of fabric across the thickness, $K_z$ (W/m.K)</th>
<th>Predicted thermal resistance of fabric across the thickness, $R_z$ (m².K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomex®III</td>
<td>0.0552</td>
<td>0.009058</td>
</tr>
<tr>
<td>Twaron®</td>
<td>0.0476</td>
<td>0.007311</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.065</td>
<td>0.007446</td>
</tr>
<tr>
<td>Wool</td>
<td>0.04618</td>
<td>0.008835</td>
</tr>
<tr>
<td>Poly-viscose</td>
<td>0.05088</td>
<td>0.006702</td>
</tr>
</tbody>
</table>

2.4 Validation of Model

Table 7 shows the experimental results obtained from the in-house developed thermal conductivity measuring device. It works on the principal of two plate methods with fixed pressure to avoid the convection heat loss, detailed information about the device can be found in reference [39].

Figure 11 shows that the simulated results are very close to the experimental results, proving good agreement between the results from FE models and experiments.

The predicted effective thermal conductivity and thermal resistance from the developed FE model were compared with experimental results as shown in Figure 12. The coefficient of determination between the predicted values by using anisotropic thermal conductivity of fibre (with consideration of transversely isotropic material) and experimental results of thermal conductivity and thermal resistance of fabric were found 0.9145 and 0.9278 respectively. The correlation coefficient of thermal conductivity and thermal resistance between FE and experimental results are calculated as 0.956 and 0.96 respectively.

The predicted results of thermal conductivity are higher than the experimental thermal conductivity values as shown in Figure 11 (a). The reason behind that was the pressure applied during the experiment which reduced the waviness of the yarn although the pressure is small. Therefore, the proportion of longitudinal thermal conductivity of yarn reduces in the effective thermal conductivity of fabric and vice versa for thermal resistance as shown in Figure 11 (b).
Table 7: Experimental results of effective thermal conductivity and thermal resistance of plain fabric

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Experimental effective thermal conductivity, $K_{eff}$ (W/m.K)</th>
<th>SD*</th>
<th>Experimental thermal Resistance of Fabric, $R_z$ (m².K/W)</th>
<th>SD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nomex®III</td>
<td>0.0500</td>
<td>0.00256</td>
<td>0.01</td>
<td>0.000525</td>
</tr>
<tr>
<td>Twaron®</td>
<td>0.0410</td>
<td>0.002635</td>
<td>0.008486</td>
<td>0.000522</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.0560</td>
<td>0.00337</td>
<td>0.008643</td>
<td>0.000523</td>
</tr>
<tr>
<td>Wool</td>
<td>0.0414</td>
<td>0.00331</td>
<td>0.009855</td>
<td>0.000819</td>
</tr>
<tr>
<td>Poly-viscose</td>
<td>0.0484</td>
<td>0.002672</td>
<td>0.007045</td>
<td>0.000378</td>
</tr>
</tbody>
</table>

* SD: Standard Deviation

Figure 11: (a) Comparison of predicted effective thermal conductivity with experimental results and (b) Comparison of predicted thermal resistance with experimental results
3. Effect of Thermal Anisotropy of Fibre on Effective Thermal Conductivity

For comparison purposes, to study the effect of thermal anisotropy of fibre on the effective thermal conductivity, two finite element models have been developed by considering the anisotropic and isotropic material property respectively.

Figure 12: (a) Comparison of FE and experimental values of effective thermal conductivity of fabric and (b) Comparison of FE and experimental values of thermal resistance of fabric.
Table 8 shows the comparison between predicted and experimental results.

**Table 8: Comparison of effective thermal conductivity of fabrics**

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Effective Thermal Conductivity $K_{eff}$ (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Nomex®III</td>
<td>0.05</td>
</tr>
<tr>
<td>Twaron®</td>
<td>0.041</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.056</td>
</tr>
<tr>
<td>Wool</td>
<td>0.0414</td>
</tr>
<tr>
<td>Poly-Viscose</td>
<td>0.0484</td>
</tr>
</tbody>
</table>

Mean absolute error (%) = - 11.85 27.84

The mean absolute error between the FE results and experimental can be calculated by Equation 21.

$$\text{Mean Absolute Error} \ (%) = \left| \frac{\text{Actual value - Predicted value}}{\text{Actual value}} \right| \times 100$$  \hspace{1cm} 21

The calculated mean absolute error of thermal conductivity is 11.85 when the anisotropic thermal conductivity of fibre was considered. In the case of an isotropic condition and without material orientation the mean absolute error is much higher compared to the anisotropic condition. The calculated mean absolute error of thermal conductivity for isotropic conditions is 27.84. The predicted values from the anisotropic model agreed well with the actual test values. This means that the model is successful and can be used to predict the effective thermal conductivity of the fabric.

4. **Temperature Dependent Thermal Conductivity of Fibre**

In this section temperature dependent heat transfer analysis was performed by using temperature dependent thermal conductivity of Nomex® III fibre [34] and air [40] as shown in the following relationships:
This equation shows that the thermal conductivity of Nomex® III fibres appears to remain approximately constant after about 700 K; this temperature is close to the temperature range at which thermochemical reactions begins to occur [3].

Nomex® III fibre has been mostly used in the heat protective clothing, for high temperature environment. Heat is transferred by means of radiation and convection outside the protective clothing and within the fabric and air gap, heat is transferred by conduction and radiation. The thermal conductivity value of fibre varies with temperature so that temperature dependent thermal conductivity of fibre was utilized to calculate the yarn axial and transverse thermal conductivity between the temperature ranges from 270K to 700K.

Air properties were also considered as temperature dependent in simulating the realistic situation. Temperature specified boundary conditions were used for transient analysis. The temperatures applied on face and back of the fabric are 270K and 700K respectively, and the model was run for both cases with and without temperature dependent thermal analysis. The only limitation in this analysis was that there was no consideration of radiative modes of heat transfer.

Figure 13 shows the heat flux distribution in both cases. Further investigation of the model to calculate the heat flux value across the thickness of the fabric is shown in Figure 14. Fabric analysed with temperature dependent thermal properties allows more heat to flow because of the thermal conductivity both fibre and the air increases with the increase of temperature.
Figure 13: Heat flux distribution of unit cell: (a) Nomex®III with temperature dependent thermal conductivity (b) Nomex®III without temperature dependent thermal conductivity
Figure 14: Heat flux with and without temperature dependent thermal conductivity

Figure 15: Temperature of Node: 23960 with and without temperature dependent thermal conductivity

Figure 15 shows the dynamic temperature change with respect to time taking an example node 23960 specified in Figure 13. The node temperature in temperature
dependent thermal conductivity model analysis achieved the equilibrium at 6.7 sec. while in constant thermal conductivity model 9.4 sec. is needed to reach the equilibrium temperature. This means that the heat flows quicker in temperature dependent thermal conductivity analysis. This type of analysis is more significant in heat protective clothing because multilayer fabric is exposed in high temperature environment for a long time. Therefore it is important to take temperature dependent thermal properties to create the realistic environment for simulation of heat transfer of textiles.

5. Effect of Fibre Volume Fraction on Effective Thermal Conductivity

In this section further analysis of the validated models to evaluate some of the properties which cannot be experimentally tested has been carried out. The effect of fibre volume fraction and fibre thermal conductivity on the effective thermal conductivity and thermal resistance of fabric have been analysed. Fabric insulation mainly depends on fibre volume fraction and thermal conductivity of fibre at constant fibre orientation. For this purpose, the validated models were chosen to analyse the effect of fibre volume fraction and thermal conductivity of fibre on the overall heat transfer. Table 9 and Figure 16 show the relationship of effective thermal conductivity with fibre volume fraction of the Twaron® fabric. It is obvious from the figure that the effective thermal conductivity increases with the increase of fibre volume fraction. This can be explained by the fact that with the increase of fibre volume fraction, the decrease of the air content results in the increased thermal conductivity as compared to that with less fibre volume in the fabric.

<table>
<thead>
<tr>
<th>(V_f) (%)</th>
<th>(K_{ya}) (W/m.K)</th>
<th>(K_{yt}) (W/m.K)</th>
<th>(K_{eff}) (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.3284</td>
<td>0.028461</td>
<td>0.03062</td>
</tr>
<tr>
<td>20</td>
<td>0.6308</td>
<td>0.031436</td>
<td>0.03471</td>
</tr>
<tr>
<td>30</td>
<td>0.9332</td>
<td>0.035105</td>
<td>0.03856</td>
</tr>
<tr>
<td>40</td>
<td>1.2356</td>
<td>0.039745</td>
<td>0.04233</td>
</tr>
<tr>
<td>50</td>
<td>1.538</td>
<td>0.045798</td>
<td>0.04618</td>
</tr>
<tr>
<td>60</td>
<td>1.8404</td>
<td>0.054026</td>
<td>0.05025</td>
</tr>
<tr>
<td>70</td>
<td>2.1428</td>
<td>0.065858</td>
<td>0.05473</td>
</tr>
<tr>
<td>80</td>
<td>2.4452</td>
<td>0.084324</td>
<td>0.06000</td>
</tr>
</tbody>
</table>

\(K_{ya}\): Yarn thermal conductivity in axial direction
\(K_{yt}\): Yarn thermal conductivity in transverse direction
6. Conclusions
In this research work, the finite element geometric model of plain woven fabric was successfully developed and analysed by the commercial finite element software Abaqus/CAE. The model was validated by experimental results of effective thermal conductivity and thermal resistance of the fabrics. The validated model was further studied by the use of temperature dependent thermal conductivity of fibre and different fibre volume fractions of fabric.

The following conclusions can be drawn:

- Material orientation and anisotropic thermal conductivity have significant effects on the effective thermal conductivity of fabric.
- The effective thermal conductivity of fabrics was also affected by the anisotropy of thermal conductivity of fibres because fibres have higher thermal conductivity in the longitudinal direction as compared to the transverse direction. This explains the fact that heat also travels along the fibre direction in the yarn when determining the thermal conductivity across the thickness of the fabric.
- Temperature dependent thermal properties have the significant impact on heat flow.

In order to obtain simulated results that are close to realistic, it is vital to take
temperature dependent thermal properties when simulating fabrics for protective clothing to be exposed to an extreme temperature for a long period of time,

- The effective thermal conductivity of fabric can be calculated by considering still air within and outside of the fabric (air as a fluid matrix).
- The results of the parametric analysis show that the effective thermal conductivity across the thickness of fabric increases with the increase of the temperature and fibre volume fraction.

The methods developed in this research are restricted to 2D woven structures; it can be further extended to 3D and multi-layered textile structures with the consideration of radiation heat transfer at high temperature analysis.

References


