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Conjugate heat transfer analysis of knitted fabric

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Abstract The thermal properties of fabric have significant impact on thermal comfort of the wearers. This research work covers the development of geometrical models of plain weft knitted fabric structures and evaluation of the thermal properties by using the fluid surface interaction technique. The results obtained from the numerical method were compared with the experimental results, and it was found that they were highly correlated. Furthermore, the validated models were utilized to evaluate the velocity and temperature profile of air at out-plane created over the surface of knitted fabric.

Keywords Effective thermal conductivity · Conjugate heat transfer · Co-simulation · FSI

Introduction

A textile fabric as non-homogeneous material contains heterogeneous mixture of fibre substance and air. Heat can be transferred through textile fabrics by means of conduction, convection, and radiation. Convection heat transfer is subjected to the movement of substances and, if occurring, it occurs only at the surface of a normal solid material. Heat transfer through conduction mainly depends on the temperature gradient, and when that temperature gradient is small, heat transfer via radiation can be ignored [1]. The term thermal conductivity should be replaced by the overall thermal conductivity which is defined as the rate of heat flow through fabric by all means of mode of heat transfer per unit area of fabric at unit temperature difference [2]. The overall or effective thermal conductivity (K_{eff}) of fabric can be calculated by Fourier's law of conduction:

$$K_{eff} = \frac{Q \cdot t}{A \Delta T} \tag{1}$$

where Q is the heat flow, A is the surface area, t is the thickness of fabric, and ΔT is the temperature difference.

The most important thermal property of fabric is insulation against the heat flow in cold environment to keep the normal body temperature. The insulation property of fabric is measured by thermal resistance. Thermal resistance (R) of fabric is defined as the ratio of temperature difference to the rate of heat flow per unit area. It can be expressed by electrical analogy according to the Ohm's Law:

$$R = \frac{\Delta T}{Q/A} \tag{2}$$

where Q is the heat flow, A is the surface area, and ΔT is the temperature difference.

Thermal resistance can also be calculated by the effective thermal conductivity of fabric:

$$R = \frac{t}{K_{eff}} \tag{3}$$

where t is the thickness of fabric.

Many researchers tried using different techniques to predict the effective thermal conductivity of fibrous materials. Schuhmeister in 1987 [3] used a method which was developed by Stefan to calculate the thermal conductivity of gases. In the research, bulk fibres were placed between the two side-by-side cylinders. The cylinder which was in the middle for the measurement of the temperature

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was used as air thermometer. Schuhmeister concluded that the result obtained from this method can be expressed by the following equations:

$$K_m = K_g + fx \quad (4)$$

where K_m is the conducting power or effective thermal conductivity of mixture of gas and fibre, K_g is the conducting power of gas, f is the mass of textile fibre present in mixture, and x is constant.

The above equation can be modified by using the volume occupied by fibres:

$$K_m = K_g + a\rho_f \quad (5)$$

where ρ_f is the bulk density of fibre and a is constant.

Schuhmeister [3] also developed a relationship to calculate the thermal conductivity of mixture of air and fibre, and the following assumptions have been taken as follows:

a. In all directions, solid fibres were uniformly distributed;
b. One-third of the bulk solid fibres was placed parallel to the heat flow; and
c. Two-thirds of the bulk solid fibres were placed series or perpendicular to the heat flow.

The developed relationship on the basis of the above assumptions is:

$$K_m = \frac{1}{3}(K_a V_a + K_f V_f) + \frac{2}{3}\left(\frac{K_a K_f}{K_a V_f + K_f V_a}\right) \quad (6)$$

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 $V_a + V_f$.

The first part of the above equation described that fibres are parallel to the direction of heat flow and the second part presented that fibres are oriented perpendicular to the direction of heat flow.

Farnworth [4] utilized the first part of the equation $(K_a V_a + K_f V_f)$ in order to obtain the conductive heat flow in fibrous batts which were placed between the two plates having a temperature gradient. He considered the two mechanisms, heat flow conduction and radiation, and the effect of convection heat transfer can be neglected because there was no significant evidence of convective heat flow even though the experimental conditions were favourable for convection heat transfer.

Ismail et al. [5] developed a mathematical model which determines the effective thermal conductivity of woven fabric by using unit cell approach. The following assumptions were made to the simple plain woven fabric structure in the model:

1. No consideration of moisture content;
2. Uniform thermal properties and fibre distribution in fabric elements (warp and weft);
3. Through thickness one-dimensional steady-state heat transfer;
4. Neglect the effect of temperature change at the boundary radiation and of air and fibre;
5. The total thermal conductivity of fabric obtained is the combination of conduction, convection, and radiative heat transfer; and
6. Warp element, weft element, and at crossover point (combined warp and weft element) were considered as two-phase elements, i.e. air and fibre.

They also transformed the warp and weft elements into equivalent element of uniform thickness in the model.

Kothari and Bhattacharjee [6] considered Peirce's geometrical model based on the fact that fabric at intersection behaves like a plain woven structure for the prediction of thermal resistance of woven fabrics by using thermal electrical analogy technique. They used second part of Eq. (6) to calculate the thermal conductivity of yarn. They stated that the thermal resistance of fabric obtained from the developed mathematical model based on the principal of heat transfer gives close results to the experimental results [7].

Yamashita et al. [8] developed structural models of yarns, plain woven fabrics, and plain woven fabric/resin composites and theoretical formulas for the effective thermal conductivity which was derived from these models. They developed two models to calculate the effective thermal conductivity of woven fabrics and their composites. In their model 1, they considered that heat was transferred in both longitudinal and transverse directions of the yarn and in model 2 only considered heat flow in transverse direction of the yarn. They concluded that model 1 was more effective than model 2 in order to calculate the effective thermal conductivity in comparison with the existing experimental results. They also concluded that the influence of fibre anisotropy on the effective thermal conductivity in transverse direction was much less. Zhu and Li [9] developed a fractal effective thermal conductivity model for woven fabrics with multiple layers.

Das et al. [10] developed a mathematical model for the prediction of thermal resistance of multilayer clothing in non-convective environment without consideration of geometrical parameters of woven fabric. Ran et al. [11] developed a 3D mathematical model to measure the coupled heat and mass transfer in woven fibrous materials by taking into consideration of the geometrical parameters. The finite volume method was utilised to separate the governing equations, and Tri-Diagonal Matrix Algorithm was used to solve the linear individual equations. They assumed that the cross section of yarn was non-deformable circular and isotropic thermal conductivity of the fibre.

Matusiak [12] developed a thermal resistance model of woven fabrics and assumed that the yarn cross section shaped in square referred to the research work taken by Yamashita [8]. However, in reality the cross section of yarn in a woven fabric is hardly in square shape. They also applied the same method on twill woven fabric and claimed that the developed model could be used to predict the thermal resistance of single-layer plain woven fabric and their derived woven structures; however, it is not applicable to multi-layered fabric and fabrics with complex woven structures.

The thermal conductivity increased with the increase in loop length of knitted fabric and it decreased with the increase in yarn linear density because more air was entrapped in the yarn [13]. Prakash and Ramakrishnan [13] also studied the effect of blend ratio, loop length, and bamboo component in the yarn on thermal comfort properties of single jersey knitted fabrics.

Fayala et al. [14] and Majumdar [15] developed a model to predict the thermal conductivity of knitted fabrics based on Artificial Neural Network (ANN) studies. Artificial neural network is a tool used to predict the response on a given set of input data after a model is trained. The model was trained to learn the pattern between the input and the corresponding output responses. The disadvantage of artificial neural network is that it requires abundant amount of data to train a model.

The heat transfer phenomenon across the knitted fabric depends on the air volume distribution within the fabric, capillary structure of the component fibres and yarns, as well as yarn surface geometry [16]. The thermal insulation property of different structures of knitted fabrics depends on the amount of fibre per unit which has direct relation to the amount of entrapped air in the fabric. Yarn twist has no impact on the thermal conductivity of fabrics [17].

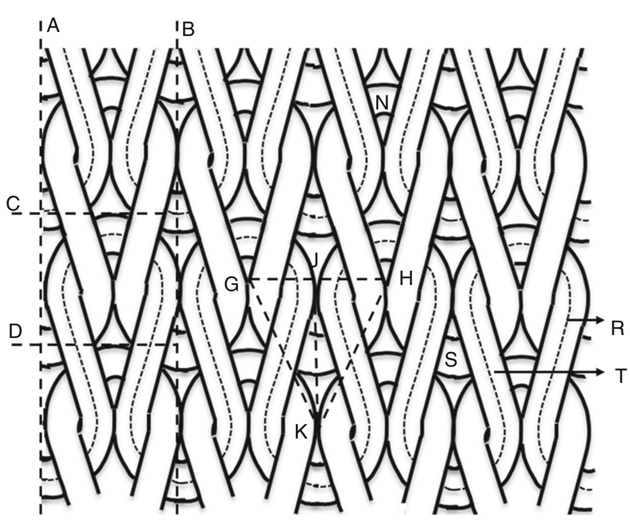

Fig. 1 Chamberlain's plain knitted loop

Dias and Delkumburewatte [18] developed a theoretical model as shown in Eq. (7) to predict the thermal conductivity (K) of knitted fabric in terms of porosity ($\varnothing$), thickness, and moisture content in pores (m). They found that the thermal conductivity of knitted fabric increased with the increase in thermal conductivity of fibre and moisture content, and thermal conductivity also increased while the porosity of fabric decreased.

$$K = \frac{K_m K_a K_W}{(1-\phi)K_a K_W + (\phi - pm)K_m K_W + \phi w K_m K_a} \quad (7)$$

where K_m, K_a, and K_W are thermal conductivity of material, air, and water, respectively.

Ucar and Yılmaz [19] determined the natural and forced convection of rib knit fabric. They also analysed the effect of fabric parameters on the thermal behaviour of fabric and concluded that the conductive heat loss due to fibre and entrapped air was more important than the convective heat loss.

Cimilli et al. [20] analysed the heat transfer of plain knitted fabric by Finite Element Method (FEM), their objective is to investigate the applicability of a FEM to textile problems. For that purpose, they developed a model of weft knitted fabric and compared the post-processing results with results from experiment. However, in their analysis air was not considered in the modelling when the knitted fabric was placed between the two plates.

Fan et al. [21] evaluated the heat transfer behaviour of Biomimic woven fabric by applying temperature-specified boundary condition. They compared the predicted thermal conductivity evaluated by using unit cell approach with the experimental results, but there was no consideration of thermal anisotropy nature of fibre.

Hasani et al. [22] analysed the heat transfer behaviour of interlock weft knitted fabric by using finite element method. They developed the model of knitted structure and analysed the steady heat transfer analysis by applying temperature on one side of the fabric and placed in air which has temperature less than the applied temperature which allows the heat to flow, using two modes of heat flow, i.e. conduction and convection. However, they ignored the interaction between the air and fabric considering fabric space was not removed from the air domain which was unrealistic. In this research work, Fluid Surface Interaction technique (FSI) is used to evaluate the effective thermal conductivity of plain weft knitted fabric by using conjugate heat transfer method.

This paper will report the finite element model of plain weft knitted fabric by considering actual environment of experiment using hybrid finite element and finite volume method.

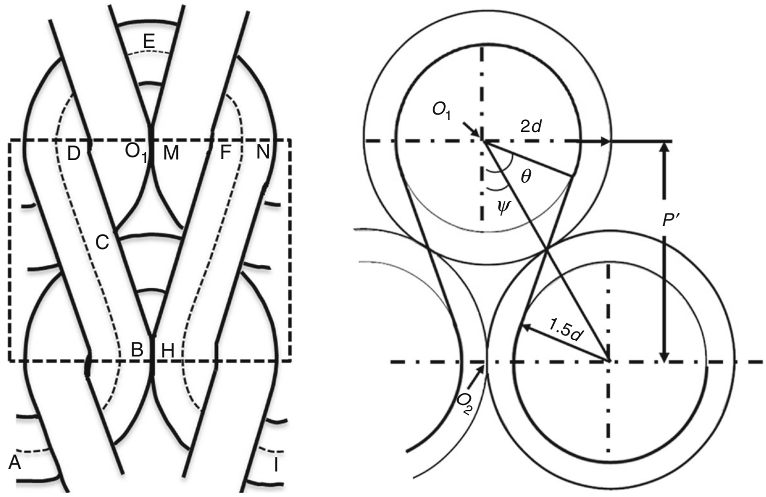

Fig. 2 Planed structure of Peirce's loop

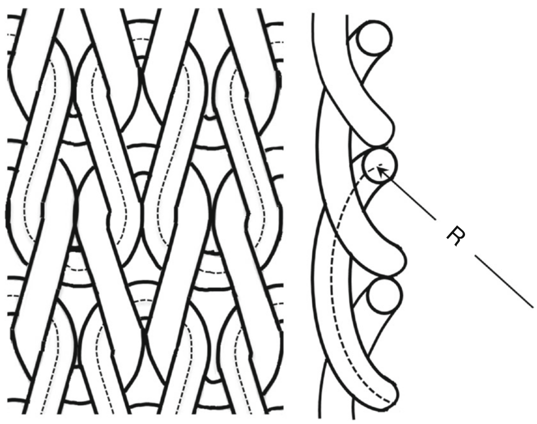

Fig. 3 Three-dimensional Peirce's loop structure of plain weft knitted fabric

Methodology

The following methodology is adopted to calculate the effective thermal conductivity of knitted fabric:

1. Development of finite element models of plain weft knitted fabric;
2. Calculation of the effective thermal conductivity of yarn;
3. Assignment of material orientation of yarn; and
4. Investigation of the effective thermal conductivity of knitted fabrics by using conjugate heat transfer technique.

Geometrical modelling of plain weft knitted fabrics

Many researchers analysed the geometrical model of knitted fabrics. In 1926, Chamberlain [23] presented a two-dimensional loop structure of plain knitted fabric. The

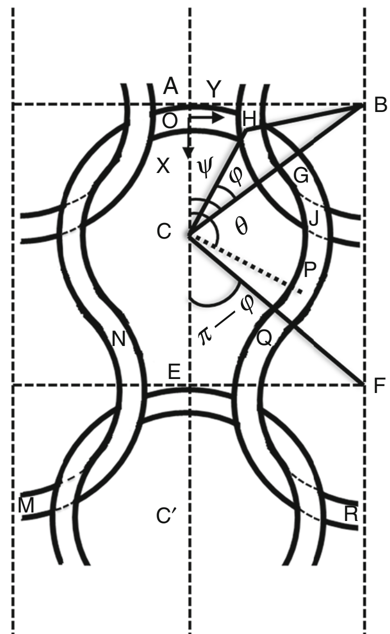

Fig. 4 Leaf and Glaskin's model of plain weft knitted fabric

theoretical corrected fabric is shown in Fig. 1 where GH represents the distance between the centres of two loops, GKH represents the equilateral triangle, and KJ bisects the equilateral triangle. In order to produce fabric with maximum cover factor and minimum mass, it is only possible when GH is the distance between the loops in horizontal direction and KJ is the correct length between the loops in longitudinal direction should have the relation of $JK = \sqrt{3}/2 \times GH$.

In the model proposed by Chamberlain, there was no consideration of loop in third dimension so the length of loop cannot be predicted with high accuracy. In 1947, Peirce [24] developed a geometrical model of plain weft knitted fabric based on the assumption that the loop is composed of circular arc and straight line and the yarn central axis follows a path on the surface of cylinder following the direction of a course. In order to develop the relationship of stich length in terms of yarn diameter, wales, and course spacing, he considered the flat structure of plain weft knitted fabric as shown in Fig. 2.

In his compact planned structure, the course (p') and wales (w) spacing can be calculated by Eqs. (8) and (9), respectively,

$$p' = \sqrt{(4d)^2 - (2d)^2} = 3.4643\ \mathrm{d} \tag{8}$$

where d is the diameter of yarn.

$$w = 4\ \mathrm{d} \tag{9}$$

Stich length of loop can be calculated by the following equations.

$$l/4 = 3d(\pi - \theta) + 2d\ \sin(\theta - \psi) \tag{10}$$

ψ and θ as shown in Fig. 2 can be calculated by the following expressions:

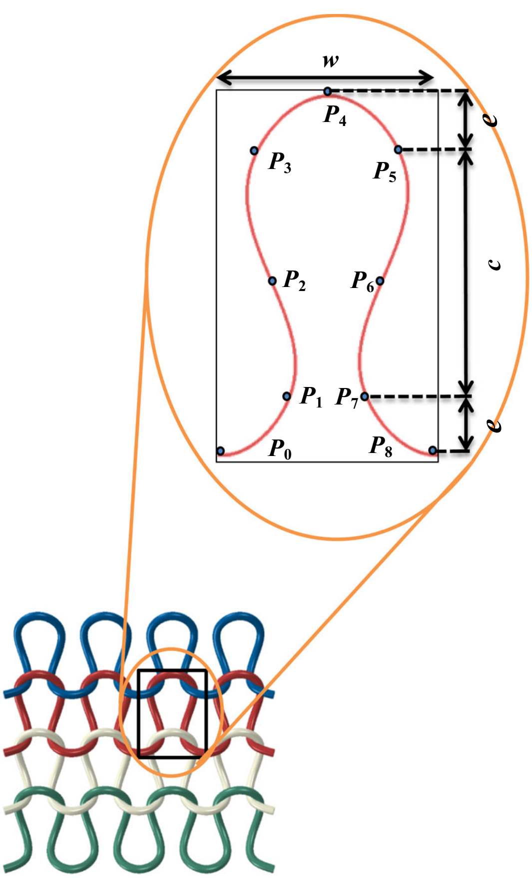

Fig. 5 Path of yarn central axis

$$\begin{aligned} \psi &= \sin^{-1}\frac{1}{2} = 30^\circ = 0.5236 \\ \theta - \psi &= \cos^{-1} 1.5/2 = 41^\circ 24.58' = 0.7228 \\ \theta &= 1.2464 = 71^\circ 24.6' \end{aligned} \tag{11}$$

Stich length (l) can be calculated:

$$\begin{aligned} l/4 &= 2.8428 + 1.3229 = 4.1657 \\ \text{Stich length}(l) &= 16.6628\ \mathrm{d} \end{aligned} \tag{12}$$

In all the above equations, there was no consideration of the bending effect of yarn. In order to include this effect, it was assumed that the loops laid on the cylinder gave three-dimensional effect to the knitted loop. It was found that radius of curvature R was only satisfied when providing space for interlocking, and it could be obtained by multiplying 4.172 by the diameter of yarn shown in Fig. 3.

The wale spacing is not affected in three-dimensional loop structure but the course spacing as it was observed in the plane of the cloth as:

$$p = 3.364\ \mathrm{d} \tag{13}$$

Peirce also developed a relationship among wale spacing, course spacing, and stich length for open structure of plain weft knitted fabric. A space 'εd', along the wale line O_1O_2, was defined by inserting a straight line in parallel to the course line. Similarly, a straight length 'ξd' was defined in the centre of each loop as shown in Eqs. (14)–(16), respectively,

$$w = 4d + 2\varepsilon d \tag{14}$$

$$P = 3.364d + \xi d \tag{15}$$

$$l = 2P + w + 5.94d \tag{16}$$

Shinn [25] also analysed the two-dimensional geometrical model of plain weft knitted fabric based on Peirce's model [24]. He compared the experimental results with the theoretical results obtained from the expression generated from the Peirce two-dimensional geometrical models. He also modified the Tompkins's formula [26] where mass per square yard was predicted by using relations of stich length, course, and wale spacing.

In 1955, Leaf and Glaskin [27] pointed out that the stable knitted fabric loop structure could not be produced by the model proposed by the Peirce [24]. They showed that Peirce considered the radius of curvature $R = 4.172$ d for all types of loops which gave the discontinuity in the torsion of yarn and eventually affected the shape of loops. They proposed a geometrical model of plain weft knitted fabric in which central axis of yarn passed over a series of circular cylinder and their model was composed of circular arcs as shown in Fig. 4.

In 1959, Munden [28] developed the relationships between stich length and wale and course spacing. He

Table 1 Specifications of plain weft knitted fabric

Fibre type	Yarn count/tex	WPC	CPC	SL/mm	*t*/mm	Areal density/g m^{-2}
Polyester (MF)	27.0	7.4	9.0	5.020	0.49	92.0

MF monofilament, *WPC* wales per cm, *CPC* course per cm, *t* thickness, *SL* stich length

Table 2 Thermo-physical properties fibre [36]

Property	Polyester
Density/kg m^{-3}	1390
Specific heat/J kg^{-1} K^{-1}	1030
Thermal conductivity/W m^{-1} K^{-1}	1.260 (K_{fa})
	0.157(K_{ft})

K_{fa} Thermal conductivity along fibre axis

K_{ft} Thermal conductivity perpendicular to the fibre axis

Table 3 Thermo-physical properties of polyester and copper

Property	Polyester	Copper
Density/kg m^{-3}	1390	8940
Specific heat/J kg^{-1} K^{-1}	1030	390
Thermal conductivity/W m^{-1} K^{-1}	1.260 (K_{fa})	401
	0.157 (K_{ft})	
Thermal expansion coefficient/1 K^{-1}	20 × 10^{-6}	16.6 × 10^{-6}

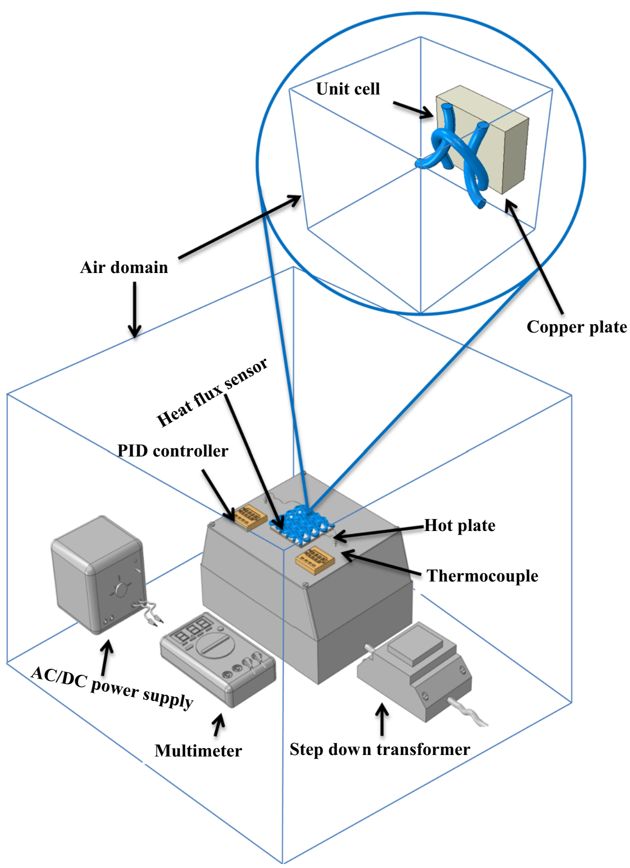

Fig. 6 Experimental set-up for conjugate heat transfer

proved that the ratios between course and wale spacing per stich length were independent of fabric cover.

Hurd and Doyle [29], Postle [30], and Kurbak [31] also studied the geometry of plain weft knitted fabrics. Furthermore, Demiroz and Dias [32] developed a mathematical model to generate 3D images of plain weft knitted fabric. They developed a stitch model by using cubic spline as the central axis. The software used to develop the model required input parameters such as yarn diameter, stich length, course and wale spacing, and other fabric parameters which were calculated by a software program developed using C programing language.

Choi and Lo [33] developed a model of plain weft knitted fabric to describe the mechanical properties and dimensional change in a fabric through energy approach. Their model is also capable of predicting biaxial tensile property of knitted fabrics. Kyosev et al. [34] developed two models of plain weft knitted fabrics. Their first model was pure geometrical model based on research work done by Choi and Lo [33] taking into consideration of the yarn cross section as elliptical. Their second model was made in considering discretization of yarn into small element and mechanical interaction between the yarns.

Lin et al. [35] developed geometrical models of weft knitted fancy structures on the basis of Non-uniform Rational B-splines (NURBS) curve. They generated the yarn central axis by using a set of points at intermeshing position of yarn adopting NURBS method and created the solid shape of knit loop by sweeping the sphere along the yarn. They developed a program to generate the 3D surface loop model by using Visual C++ programing language and OpenGL.

The geometrical model of plain weft knitted fabric was developed in this work by sweeping uniform circular cross section of yarn over the central axis of yarn. The central axis was defined by using cubic spline curve in Abaqus/CAE as shown in Fig. 5. The central axis was constructed by the help of nine connecting points, the distance between each points can be calculated by parametric analysis of plain weft knitted fabric. The value of course spacing (p) and wale spacing (w) can be calculated by the number of courses and wales per unit length, respectively. The parametric value of '*e*' is the critical value which influences the loop length and differentiates between the generic and parametric models, it also controls the tightness and length of the loop. The value of 'e' can be calculated for image analysis of the actual weft knitted fabric, and the difference between the average loop height and course spacing provides the value of 'e'. Table 1 shows the specifications of the fabric. Table 2 presents the thermo-physical properties of fibre of the fabric which were used for Finite Element Analysis (FEA).

Because of thermal anisotropic nature of fibre, material of yarn is considered as transversely isotropic in nature. The thermal conductivity of yarn can be defined by using tensor of thermal conductivity. In this work, monofilament plain weft knitted fabric was used; therefore, the thermal conductivity along the fibre axis (longitudinal direction) and perpendicular to the fibre axis (transverse direction) can be used directly. In case of multifilament and staple fibre yarn, the thermal conductivity of yarn in both longitudinal and transverse directions can be calculated by composite approach. The thermal conductivity of yarn can be defined in Abaqus/CAE by using discrete orientation technique, and the details can be found in previous published paper [37].

Conjugate heat transfer by using co-simulation

In this section, conjugate heat transfer analysis of the developed plain weft knitted fabric will be analysed by using co-simulation technique in Abaqus/CAE. Conjugate heat transfer refers to the heat transfer between solid (mainly by conduction) and fluid (mainly by convection).

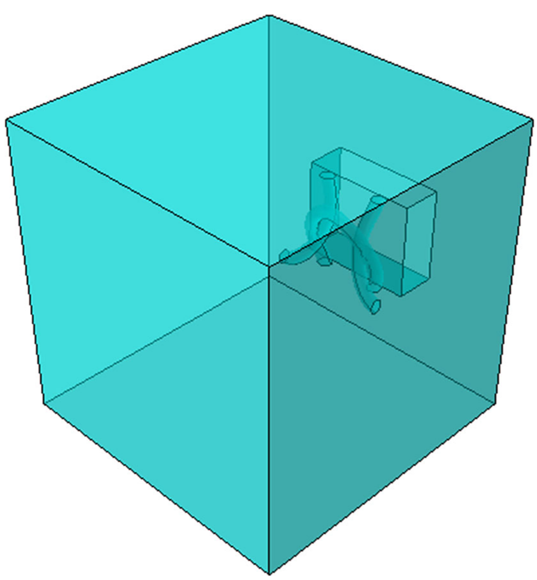

Fig. 7 Scaled down of air domain model

Figure 6 shows the experimental set-up in which one side of plain weft knitted fabric was placed on a hotplate and the other side was exposed to ambient air which has temperature of 298.15 K. Heat was transferred from hotplate to the solid plain weft knitted fabric mainly by conduction modelled in Abaqus/Standard. The time-dependent heat transfer in solid is expressed by:

$$\rho C_p \frac{\partial T}{\partial t} = K\nabla^2 T + Q \tag{17}$$

Heat transfer from hotplate to plain weft knitted fabric and the ambient air by buoyancy-driven natural convection using Boussinesq approximation and modelled in Abaqus/CFD. The governing equations for fluid flow in CFD are as follows:

$$\rho \frac{\partial V}{\partial t} + \rho\nabla \cdot V = 0 \quad \text{(Continuity Equation)} \tag{18}$$

$$\nabla \cdot V = 0 \quad \text{(Incompressible flows)} \tag{19}$$

$$\rho \frac{\partial V}{\partial t} + \rho\nabla \cdot V = -\nabla p + \mu\nabla^2 V + \rho g \quad \text{(Conservation of momentum)} \quad \text{(Incompressible Navier - Stokes Equation)} \tag{20}$$

Table 4 Thermo-physical properties of air

Property	Air
Density/kg m^{-3}	1.17032
Specific heat/J kg^{-1} K^{-1}	1006.96
Thermal conductivity/W m^{-1} K^{-1}	0.02614
Viscosity/kg m^{-1} s^{-1}	1.836×10^{-5}
Thermal expansion coefficient/1 K^{-1}	3.337×10^{-3}

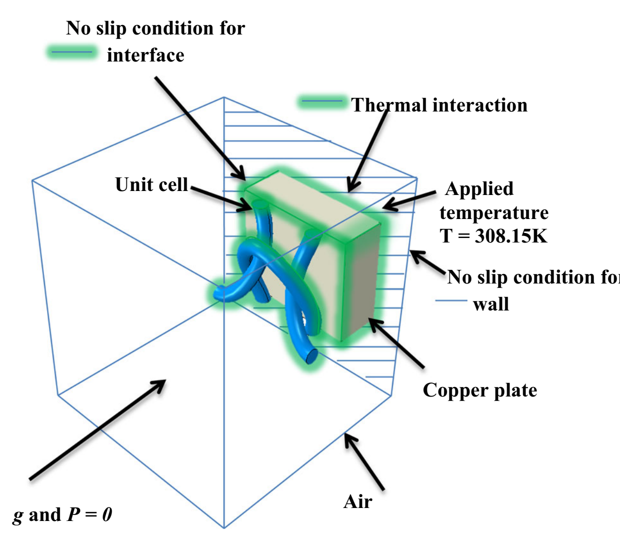

Fig. 8 Simulation set-up

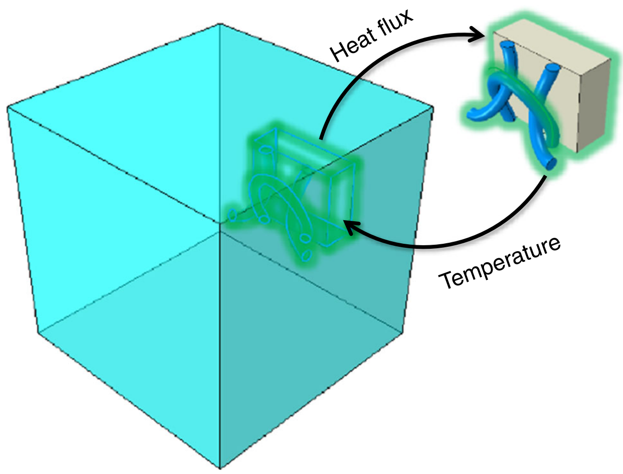

Fig. 9 Abaqus co-simulation through thermal coupling

$$\rho C_p \frac{\partial T}{\partial t} - K\nabla T = \rho C_p V \cdot \nabla T \quad \text{(Conservation of energy)} \tag{21}$$

where ρ is the density of fluid, C_p is the specific heat of fluid at constant pressure, V is the velocity of fluid, μ is the dynamic viscosity of fluid and ρg is the body force.

In buoyancy-driven natural convection heat flow, the density change is caused by temperature and the property of fluid that represents. The variation of density with temperature change is known as the volumetric thermal expansion coefficient, and it can be expressed by:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{22}$$

Boussinesq approximation is defined as the density variation which is too small in fluid except when evaluating the momentum equation where density multiplies by the gravitational acceleration (bouncy force) as shown in Eq. 23.

$$(\rho - \rho_o)\, g \approx -\rho_o \beta (T - T_o) g \quad \text{(at constant Pressure)} \tag{23}$$

Simulation

The enlarged view of Fig. 6 showing the unit cell of plain weft knitted fabric with copper plate and air domain was used to analyse the conjugate heat transfer in Abaqus. The plain weft knitted fabric was analysed in Abaqus/Standard for transient heat transfer analysis.

Table 3 shows the material properties of copper and polyester used for transient heat transfer analysis. All the values will be converted into centimetre–gram–second (CGS) unit.

Figure 7 shows a small-scaled model of air domain in which plain weft knitted fabric and copper plate have been lessened from the domain, and it was analysed in Abaqus/CFD by using the buoyancy-driven natural convection (free convection). Table 4 shows the properties of air which were used as input parameters in analysis.

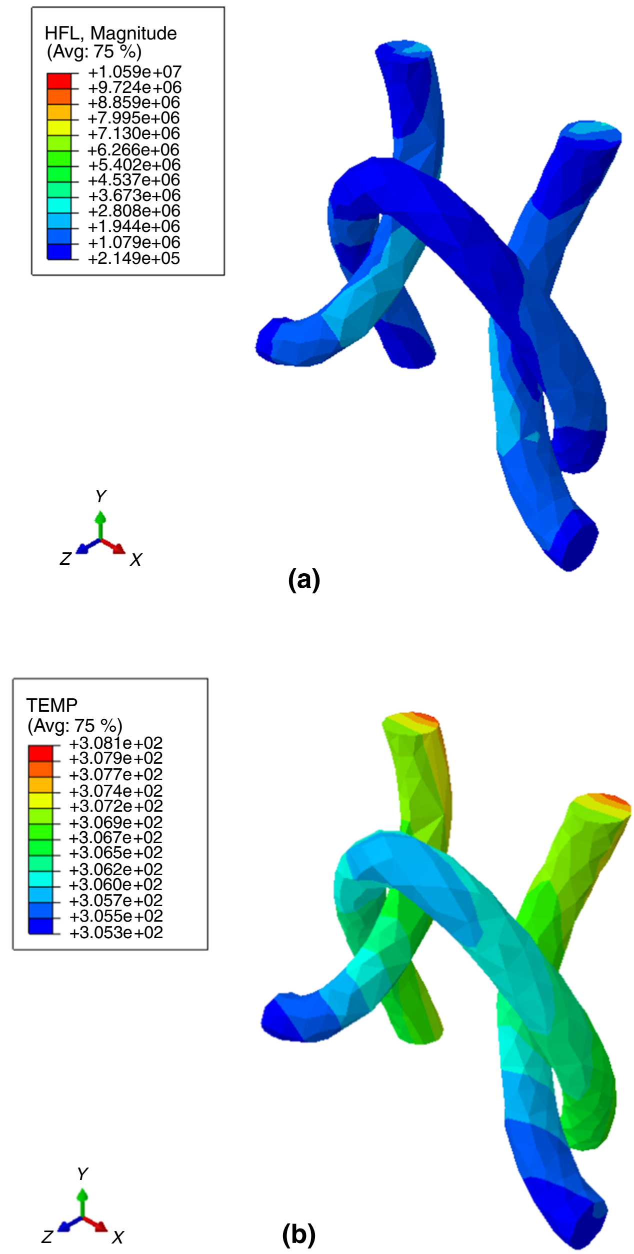

Fig. 10 Contours **a** heat flux and **b** temperature contour of plain weft knitted fabric unit cell

Initial condition

The initial thermal condition was applied to the plain weft knitted fabric, copper plate, and air with a temperature of 298.15 K and considering the initial velocity of air as zero.

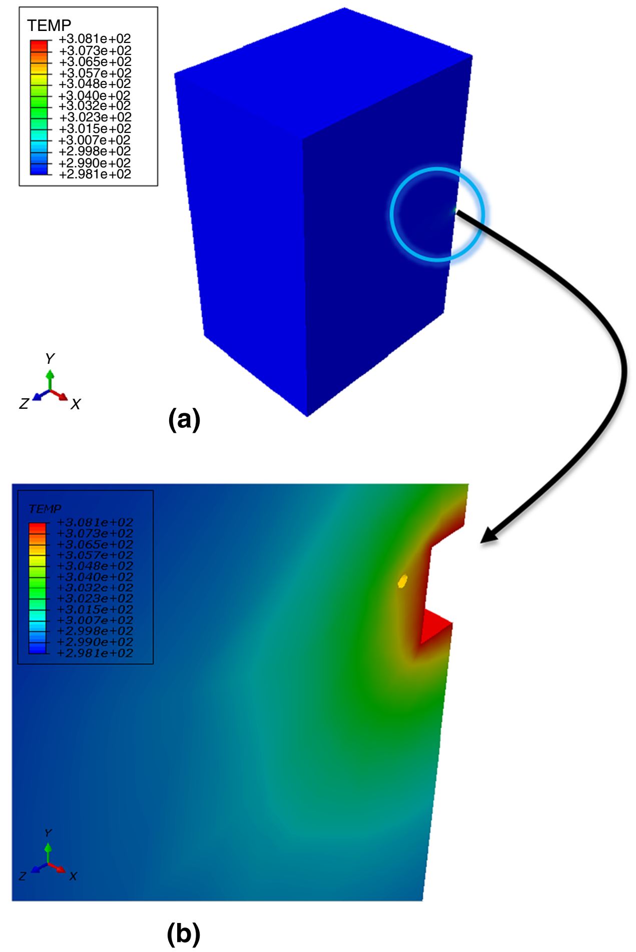

Fig. 11 Temperature contours: **a** air domain (half cut view in *x*-direction) and **b** enlarge view off highlighted portion

Boundary condition, loading, and interactions

No slip condition for interface and air domain wall was considered as shown in Fig. 8. Acceleration due to gravity was applied as load and pressure at the front surface, and it was set as zero. No boundary conditions were added to other surfaces in order to allow the air to flow in these directions. Fixed temperature was applied to the copper plate which is connected to the plain weft knitted fabric unit cell allowing the heat flows from hotplate to the plain weft knitted fabric. Thermal coupling between the solid structure (copper plate and weft knitted fabric) and fluid (air domain) was created in which the common highlighted surface was used as shown in Fig. 8. Heat will be transferred from solid structure to air domain by buoyancy-driven natural convection through the interface.

Meshes

Solid structure was meshed by using 4-node linear tetrahedral elements (DC3D4) for the transient analysis in Abaqus/Standard. Air domain was meshed by using linear hexahedral (FC3D8) fluid elements in Abaqus/CFD.

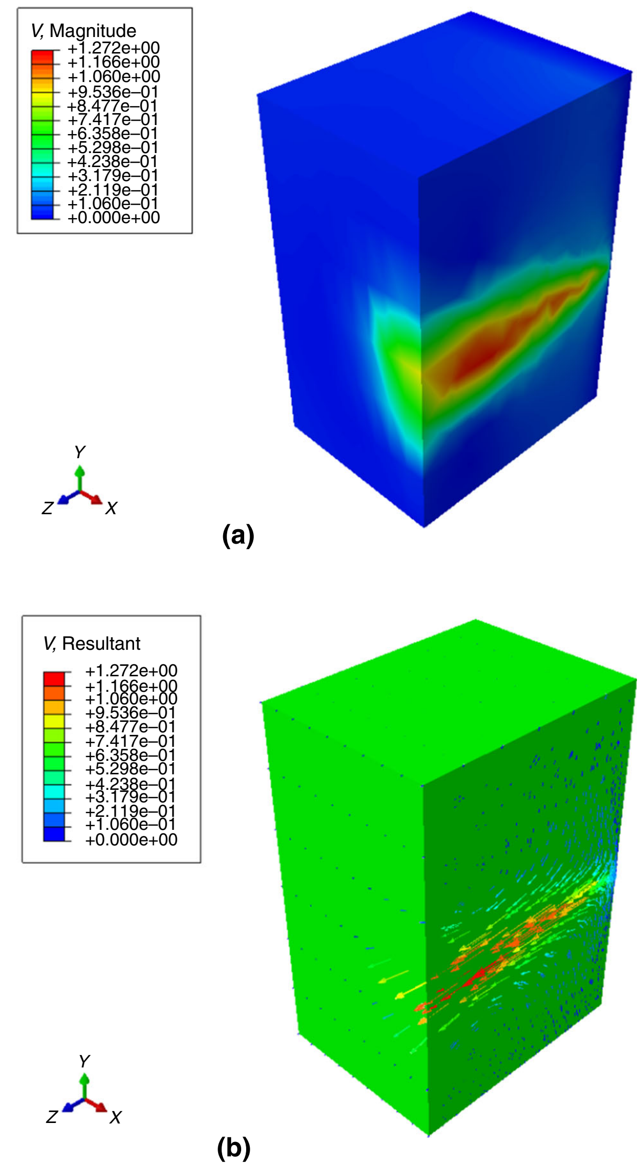

Fig. 12 Velocity contours: **a** air domain (half cut view in *x*-direction) and **b** air domain (half cut view in *x*-direction)

Modelling results and validation

Figure 9 shows the conjugate heat transfer in Abaqus through thermal coupling. Solid structure in Abaqus/Standard exports temperature to fluid domain in Abaqus/CFD and fluid domain exports heat flux to solid structure. When plain weft knitted fabric dissipates heat in the air, the air layer which is close to the hotplate and fabric is thus heated up. The density of the air decreases; as a result, the lighter air moves up and the denser layer moves down; therefore, convection current is developed. Figure 10 shows the heat flux and temperature contour of plain weft knitted fabric.

Figure 11 shows the temperature contour of half cut view in *x*-direction of air domain. The enlarged view clearly shows that the temperature is transferred from plain weft knitted fabric and copper plate to air domain through the thermal coupling interface.

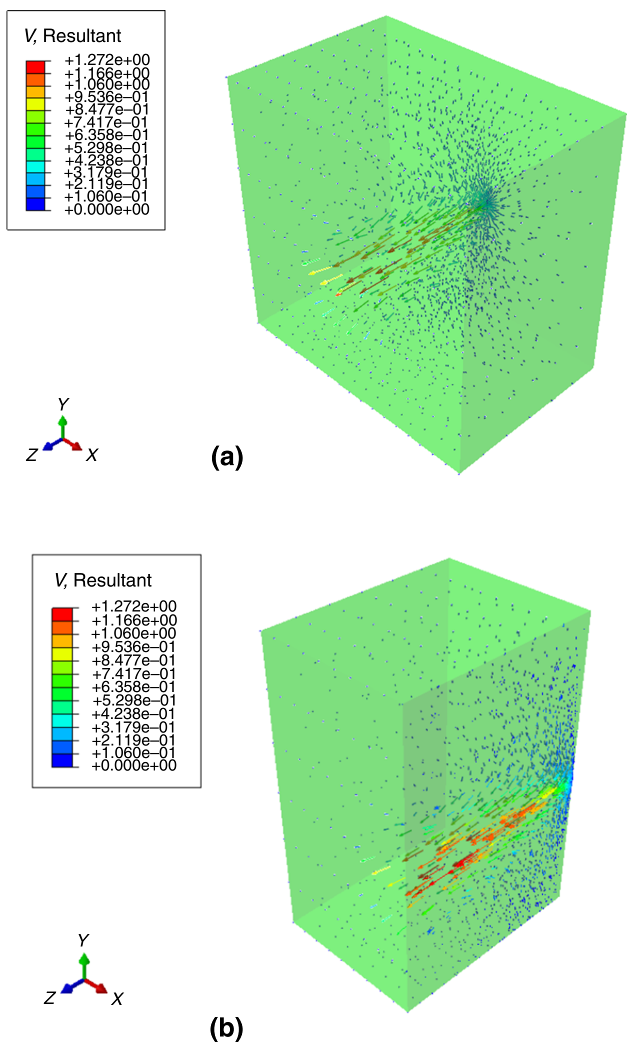

Fig. 13 Velocity vector plot: **a** air domain and **b** air domain (half cut view in *x*-direction)

Figure 12 shows the velocity contour and velocity vector plot of air domain and Fig. 13 shows the phenomena of convection current.

Effective thermal conductivity of plain weft knitted fabric was calculated at steady state; for that purpose, out-plane was created over the surface of knitted fabric to monitor the temperature and velocity. Figure 14 shows that the temperature and velocity reach the steady state. Heat flux value was evaluated on the surface of copper plate and effective thermal conductivity which can be calculated by Eq. (1).

The effective thermal conductivity of plain weft knitted fabric predicted from the hybrid finite element and finite volume method is 0.04971 W/mK.

In order to verify the results obtained from the finite element model, experiment was conducted using an in-house-developed device for thermal conductivity test. It works on the principal of two plates (hot and cold). In case

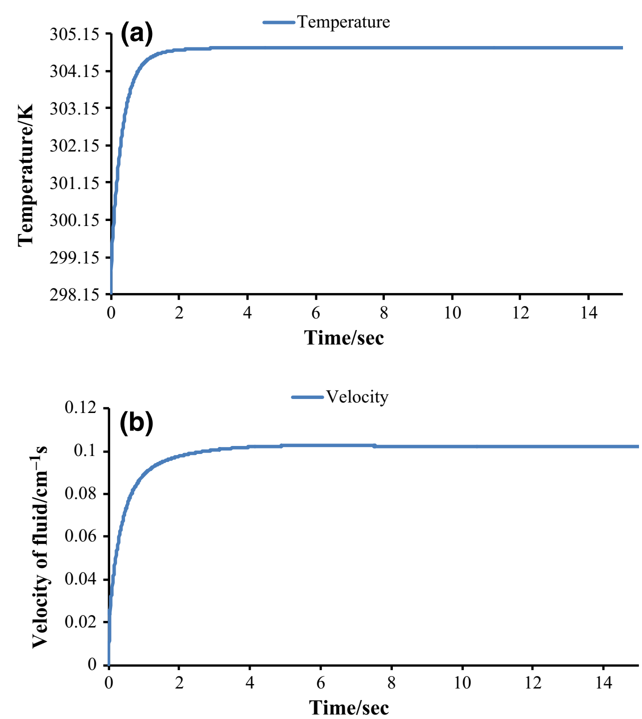

Fig. 14 Relationship between time and **a** average temperature at out-plane and **b** average velocity of fluid at out-plane

Table 5 Comparison of the effective thermal conductivity and thermal resistance between results from FE modelling and experiment

Predicted effective thermal conductivity/W m^{-1} K^{-1}	Experimental effective thermal conductivity/W m^{-1} K^{-1}
Conjugate heat transfer	One-plate method
0.04971	0.044
Predicted thermal resistance/m^2 K^{-1} W^{-1}	Experimental thermal resistance/m^2 K^{-1} W^{-1}
Conjugate heat transfer	One-plate method
0.00986	0.01114

of two-plate method, one plate is to provide an initial environment with temperature difference between the two surfaces of a fabric to be tested; in case of one-plate method, one face of the fabric is exposed to the environment. The details about the instrument and testing technique can be found in reference 37.

Table 5 shows the effective thermal conductivity and thermal resistance of the plain weft knitted polyester fabric obtained from the conjugate heat transfer in comparison with the tested results from experiment.

Conclusions

Conjugate heat transfer FE model was successfully developed by considering actual environment of experiment using hybrid finite element and finite volume method by applying actual boundary conditions. Thermal properties of knitted fabrics obtained from model post-processing are close to the experimental results. In this work, air and fabric interaction was considered and also fabric space was removed from the air domain which is a more realistic approach. The low absolute errors of effective thermal conductivity (12.978%) and thermal resistance (11.490%) show that the generated model is reliable and capable of predicting the effective thermal conductivity and thermal resistance of plain weft knitted fabrics.

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