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Short Communications

Modeling of heat transfer for interlock knitted fabric using finite element method

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This study focuses on the applicability of finite element method (FEM) to analyze the heat transfer behavior of plain interlock weft knitted fabrics. An interlock weft knitted fabric model is developed and analyzed using FEM software. A comparison of the experimental measurements with the numerical solutions shows that the FEM model developed for the heat transfer measurement including interlock knitted fabric produces promising results.

Keywords: Finite element method, Heat transfer, Interlock fabric, Weft knitted fabric

The heat transfer in textile fabrics has been widely recognized as an important aspect for understanding the thermal comfort of clothing during wear[1–4]. Thermal transfer from a simulated sweating skin surface is strongly correlated with different physical fabric properties such as porosity and air permeability.

Hatch *et al.*[5] confirmed that the fabric structural features, not component fibres, are the most important controllers of thermal dissipation in the presence of moisture diffusion. Moreover, heat transfer is highly related to fabric thickness, bulk density and air volume fraction. Holcombe and Hoschke[6] showed that a relationship exists between the thermal conductivity of the fabric and the thermal conductivities of air and fibre, together with the packing factor of the construction. The entrapped air is by far the greatest determinant of fabric conductivity and within the range of typical textile fibre conductivities, the contribution of fibre is relatively small. Hossain *et al.*[7] investigated the airflow and heat transfer through fibrous webs via a mathematical model developed and interpreted by commercial software – Fluent. Li *et al.*[8] showed that the heat transfer process, which is influenced by fabric thickness and porosity, significantly impacts moisture transport processes.

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Cimilli *et al.*[9] modeled a plain weft knitted fabric using CATIA and finally, simulated the heat transfer measurement setup (unit) including the fabric model using ANSYS Workbench software. The results obtained from this simulation have been compared with those obtained experimentally and they have observed that FEM analysis gave reasonably accurate results. It is necessary to explain that this analysis was done without assuming the effect of air flow.

Kothari and Bhattacharjee[10,11] predicted the thermal resistance of woven fabrics with the help of a first principles based model and application of computational fluid dynamics (CFD) to simulate convective heat transfer. They stated that thermal resistance of woven fabrics can be calculated using a lumped model. It was also stated that the sum of conductive and radiative heat transfer based on the mathematical model developed gives good prediction of the thermal resistance values when compared with the existing experimental data.

This study analyzes the heat transfer behavior of plain interlock weft knitted fabrics using a finite element method (FEM). The effect of air flow has been considered in this analysis.

Modeling

Exact amounts of fabric specifications such as density, heat conduction coefficient, thermal expansion coefficient, specific heat and diameter are required in order to simulate heat transfer in a fabric. Conversion of fibre circular cross-section to quadrangular one facilitates modeling procedure. It would be feasible by transforming a circular cross-section with “D” diameter to a square with “C” side length[12] as is shown in following equation and in Fig. 1:

$$C = \frac{\sqrt{\ }}{2} D \qquad \ldots (1)$$

All elements in yarn structure including filament fibres and air were modeled as a square. A filament surface area and its corresponding air were determined via diving yarn surface area by the number of its filament. Microscopy experiment was carried out to find out a filament diameter with which previously mentioned parameter like its corresponding air was measured. Considering quadrangular yarn surface alongside its length, some

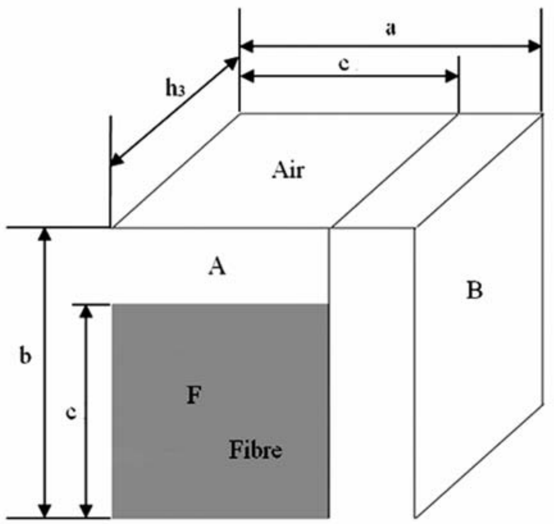

Fig. 1—Defining thermal yarn properties regarding a filament and its corresponding air

filaments make it possible to measure yarn transfer coefficient. A filament surface area was obtained using a microscope since its quadrangular cross-section assumption makes the diameter measurement attainable. Defining yarn density would be viable, knowing filament diameter value and its cross-section area via scanned image. The following equations give heat conduction coefficient of yarn (R_y) according to Fig. 1 (ref. 12):

$$\frac{1}{R_y} = \frac{1}{R_B} + \frac{1}{R_A + R_{FT}} \quad \ldots (2)$$

$$R_A = \frac{b-c}{{}_A h_3 c}, R_B = \frac{b}{{}_B (a-c) h_3 c}, R_{FT} = \frac{1}{{}_{FT} h_3} \ \ldots \quad (3)$$

where R_Y is the thermal resistance of model structure body; h_3, *the filament yarn length* R_A, R_B, and R_{FT}, the thermal resistance of air and the fibre; $\square_A$, $\square_B$, and $\square$ $\square_{FT}$ are assumed to be the thermal conductivities of air space *A* and *B*, and the thermal conductivity of the transverse direction of the fibre respectively.

A multifilament polyester yarn with 36 filaments and 100 denier was utilized in this investigation. Each filament has an average diameter of 18 micrometer. Heat transfer coefficient in both alongside and perpendicular direction to yarn was considered as 0.08368 and 0.049 W/m.K respectively. Density and specific heat were calculated with regard to yarn diameter. Mass ratios were also provided by porosity. Yarn expansion coefficient was considered the same as that of polyester, due to negligible effect of air. Interlock weft knitted fabric was produced using a circular knitting machine (E18, 36”, 144 feeders). The physical properties such as fabric thickness (0.820 mm), fabric stitch density (80 loops/cm^2) were measured under standard conditions.

In this work, guarded hot plate method was used to calculate the thermal properties of fabrics. The guarded hot plate method is now recognized as the most accurate technique for determining the thermal properties of materials. A guarded hot plate instrument was designed and manufactured. The instrument is equipped with a heat sensor connected to a PID control unit that adjusts the hot plate temperature to the desired value with an accuracy of 1°C. The whole set is placed inside an aluminium chamber. To complete the apparatus and reduce radiation error, the outside faces of aluminium chamber were covered with a thin and flat aluminium foil that had a low emissivity. An Infrared thermometer was used to measure the temperature. The latter has a lens that focuses transmitted infrared energy of samples on a detector. This detector changes infrared energy to electrical signal that shows target temperature on the monitor. The thermometer sensor is fixed on the top of the apparatus and is connected to a PC computer for data acquisition[13].

Simulation of interlock fabric was carried out according to previous investigation[14]. Simulation procedure was done for only half of a loop and generalized to all the loops in a course. Passing a line through representative course dots, a course curve, was attained. Sweeping a circle with the same radius as thickness of yarn provides a bulky course. The smooth and even yarn formation is owed to cubic equation of course curve created by passing a line through representative dots. Assuming an ideal fabric in which loops coordinates are alike, simulated course geometry can be generalized to the whole fabric (Fig. 2a).

A cube with proportional dimensions to fabric size is responsible for creating fluid flow in a fabric. Laid parts of fabric in fluid have to be neglected since they don’t affect fluid flow transit. It is drastically time consuming to lessen or subtract fabric geometry from fluid (Fig. 2b).

ASTM C177-97 provides all detailed information about source position. The heat source size is defined with respect to the simulated fabric and usually equals

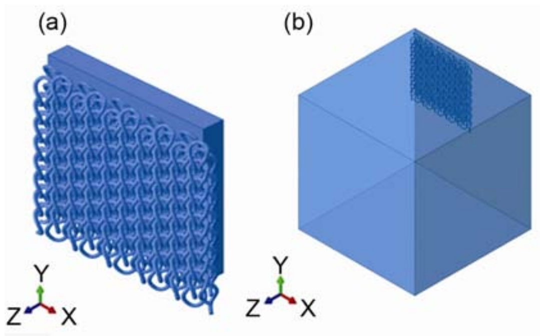

Fig. 2—(a) Simulated fabric and heat source position and (b) A scheme of surrounding fabric fluid

to 90% of fabric size in order to be completely covered by fabric (Fig. 2a). The following assumptions have been made:

- Interlock fabric was produced using non-elastic and non-condensable filaments as it does not affect the results and the analyzed procedure.
- All loops construction on the fabric surface was alike.
- Despite fibre friction, no plastic deformation occurred and subsequently fibre contact area remained circular.

It is clear that little amount of cross-section deformation was neglected. Different yarn characteristics such as heat transfer coefficient, density and specific heat were ascribed regarding obtained data.

Temperature-bond fluid characteristics such as density, heat transfer coefficient, expansion coefficient, specific heat (in constant pressure) and viscosity were assigned to the fluid for further analysis. This makes the fluid characteristics the same as those of air in addition to facilitating numerical solution. Heat source is hypothetically made of steel. None of source characteristics affects solution procedure except its temperature. However, heating duration for sources with different metals is not the same.

Meshing was made in order to use finite element as a solution. The optimum value of meshes in simulation is yarn diameter. As a result, the average number of meshes reached 110 per each loop and was also considered desirable. Surrounding fluid is partitioned and mesh size is considered the same as yarn diameter. However, mesh size of other parts will be extended gradually from the value of yarn diameter to a value commensurate with the fluid volume.

In initial condition, the temperature of 25 °C was considered for all parts. Simulating one fourth of the

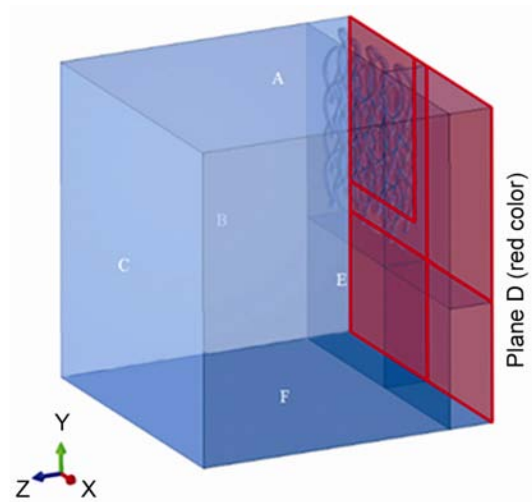

Fig. 3—Planes with boundary

fabric is enough since fabric heat conduction is not influenced by loop structure. For example, simulating a fabric with 16×25 dimensions can provide suitable interpretation for the characteristics of a 32×50 fabric. Implementation needs applying boundary conditions as shown below and considering Fig. 3:

(i) Air speed on A plane along y axis is zero;
(ii) Air speed on B plane along x axis is zero;
(iii) Air pressure on C plane (the upper one) is zero;
(iv) It is impossible for air to pass D plane; and
(v) No condition is considered for E and F planes because air has to flow easily during simulation.

The temperature of lower heat source is adjusted at 50 °C for the whole procedure. Load is applied abruptly so that it takes heat source less than one fourth of second to get hot up to 50 °C. The fabric gets warm before the constant temperature of heat source. Standard and CFD account for Heat transfer analysis in fabric and fluids, respectively. Being provided with the information of one time step, solver started to solve the load of corresponding parts in the fabric-fluid boundary. The more the elements the fluid has, the more time consuming is the equation solution with its process. As soon as both sides temperature remain constant, solution procedure stops. The relevant equation is given below:

$$K = q\frac{x}{\Delta T} \quad \dots (4)$$

The above equation yields thermal conduction coefficient (K), where q denotes the heat flow per square meter per time (J/m^{2}t). The software gives fabric thickness (*x*) and is the same for all samples and models. ΔT is yielded via software as well and described as difference between the "average temperature of top nodes of fabric" and "average temperature of bottom nodes of fabric".

Cool air is less likely to penetrate into highly crimped fabric parts [15]; therefore temperature increase in both fabric sides due to model size growth is more conceivable. Moreover, different heat flow rate resolves constant temperature issue. The solution process keeps continuing until heat transfer coefficient approaches a constant value with model size growth. Otherwise, heat transfer coefficient is probably estimated for large size models referring to heat transfer coefficient versus mesh size curve. This section aims at studying heat transfer coefficient for models with 4×5, 8×10 and 12×15 dimensions. Table 1 shows the results of the model for different model sizes.

Apparently, heat transfer coefficient is not influenced by model size growth. Thus, it can be concluded that in a standard experiment sample size effect on heat transfer coefficient is negligible. Heat transfer coefficient is examined considering only variable model size. For instant, for the model size 8×10 loops the temperature stabilization curve for a fabric in face and back sides is shown in Fig. 4 and following results are achieved:

Table 1—Comparison between results of different model sizes

Heat transfer coefficient W/(m. K)	Heat flow kW/m^2	Difference of temperature between technical back and face, K	Model size (Loops number) X×Y
0.04398	0.116979	2.1806	4×5
0.04419	0.0903472	1.6762	8×10
0.04405	0.0671579	1.2501	12×15

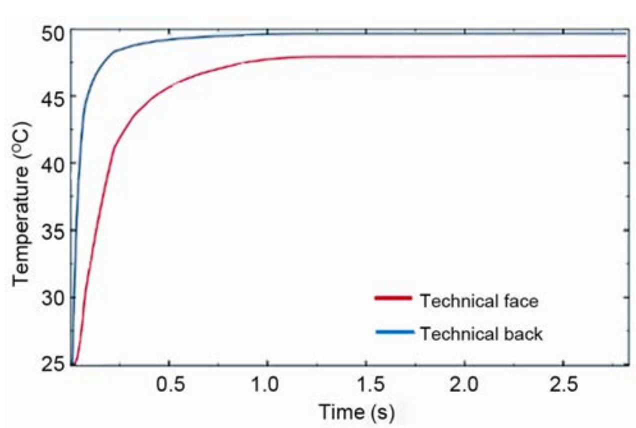

Fig. 4—Temperature stabilization curve for a fabric of 8×10 loops

Face heat flow	: 0.09678 kW/s
Back heat flow	: 0. 08601 kW/s
Face temperature	: 47.98 ˚C
Back temperature	: 49.65 ˚C
Heat flow average	: 0.09034 kW/s
Temperature difference	: 1.676 ˚C
Fabric thickness	: 0.820 mm
Heat transfer coefficient	: 0.0441 W/(m.K)

Figure 5 provides fluid speed in different elements and temperature distribution is illustrated in Fig. 6. Model size increase leads to more uniform heat distribution on fabric length. Heat flow distribution is shown in Fig. 7. A comparison of the experimental conduction coefficient (0.04401) with that calculated via FEM analysis (0.04419) shows that they are very close to each other.

A comparison of the experimental measurements with the numerical solutions show that the FEM model developed for the heat transfer measurement

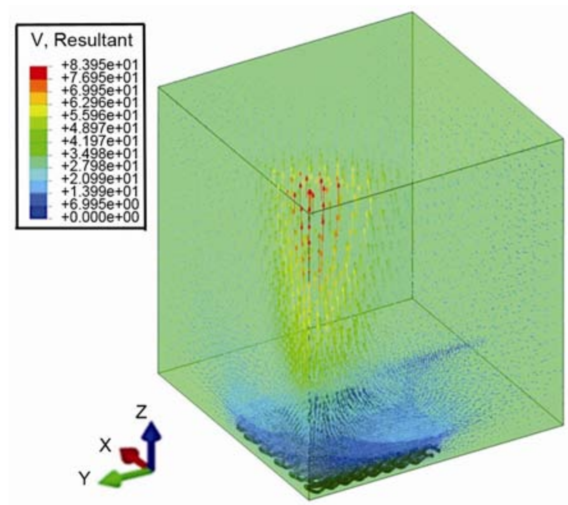

Fig. 5—Fluid steady state

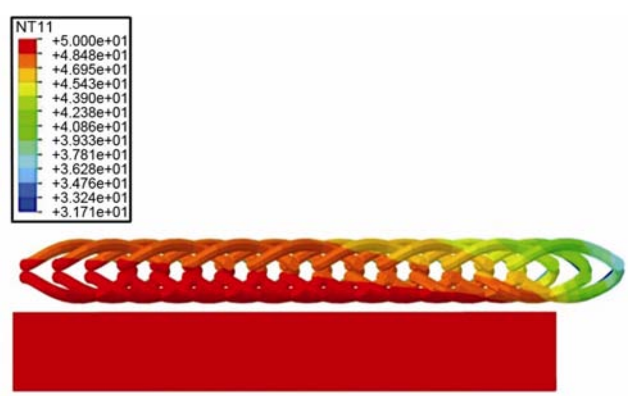

Fig. 6—Temperature distribution on fabric

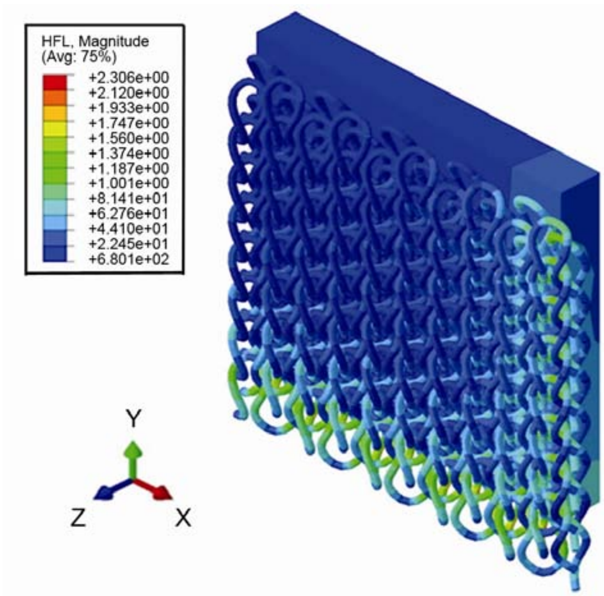

Fig. 7—Heat flow distribution on the fabric

including plain interlock fabric produces exact results. High agreement between numerical and experimental values is observed.

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