Prediction of air permeability and effective thermal conductivity of multifilament polyester yarn by finite element analysis

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Abstract: The effective thermal conductivity and air permeability of a multifilament polyester yarn used in sports T-shirts was investigated by computer modeling using finite element analysis (COMSOL Multiphysics, ABAQUS/CAE). It has been shown that the number of fibers, the porosity of the yarn and the proportion of fibers in the volume fraction of the yarn have a direct effect on the effective thermal conductivity and air permeability of the multifilament yarn. It was found that with the increase in the number of fibers, the porosity of the yarn decreases linearly, while the volume fraction of the fibers increases, and thus the effective thermal conductivity increases. In addition, air permeability decreases exponentially.

Keywords: sportswear, thermal conductivity, air permeability, finite element analysis.

Przewidywanie przepuszczalności powietrza i efektywnej przewodności cieplnej wielowłókienkowej przędzy poliestrowej za pomocą analizy elementów skończonych

Streszczenie: Zbadano efektywne przewodzenie ciepła i przepuszczalność powietrza wielowłókienkowej przędzy poliestrowej stosowanej w koszulce sportowej poprzez modelowanie obliczeniowe z użyciem analizy elementów skończonych (COMSOL Multiphysics, ABAQUS/CAE). Wykazano, że liczba włókien, porowatość przędzy oraz udział objętościowy włókien w przędzy mają bezpośredni wpływ na przewodzenie ciepła i przepuszczalność powietrza przędzy wielowłókienkowej. Wraz ze wzrostem liczby włókien porowatość przędzy maleje liniowo, natomiast zwiększa się udział objętościowy włókien, a tym samym efektywne przewodnictwo cieplne. Ponadto przepuszczalność powietrza maleje wykładniczo.

Słowa kluczowe: odzież sportowa, przewodzenie ciepła, przepuszczalność powietrza, analiza elementów skończonych.

Air permeability and thermal conductivity are the most notable features of textile materials. These parameters depend on the fiber properties and the fabric structure. Conduction, convection, and radiation are the methods of transferring heat through textile materials. Yarn is a heterogeneous material. It consists of fibers and air. Bigger airflow through the fabric can facilitate heat transfer by convection. Moreover, thermal insulation is closely related to the air movement in textiles. The air and heat flow through the fabric depends on the fabric construction and plays an important role in the textile materials performance.

An air-permeable substance is likely to be water-permeable in vapor or liquid form. Air permeability and moisture-vapor permeability are usually linked. On the other hand, the fabric thermal resistance is greatly influenced by the enclosed still air, which, like the air permeability, is affected by the fabric structure. Finally, a very air-permeable fabric may be sheer or have a very open structure, causing psychological or physical discomfort for the wearer due to aesthetic aspects such as modesty, dimensional stability, drape, and handling [1].

Methods for the evaluation of air permeability and thermal conductivity

It is difficult to determine the relationship between the fabric structural parameters and air permeability. However, two methods are used to evaluate the fabric

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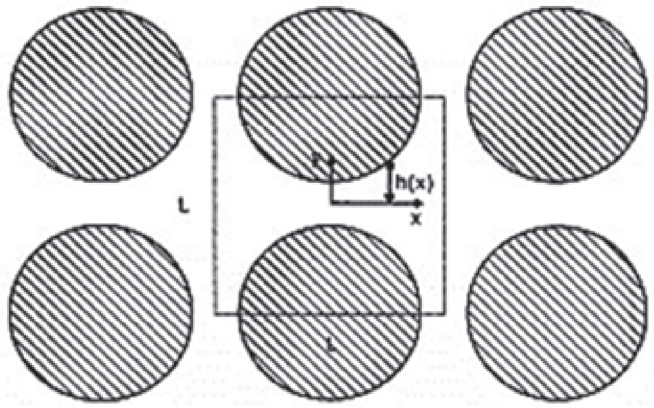
a)



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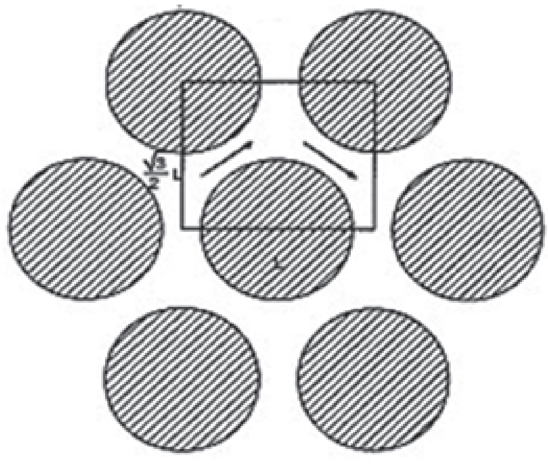

Fig. 1. Fiber arrangement in: a) square, b) hexagonal distribution [4]

air permeability. One is the pores number per the fabric unit area. Air permeability directly depends on the fabric porosity, which depends on factors such as pore area, pore depth, and number of pores in the fabric [2]. The second method is based on measuring the amount of fluid that can flow through the fabric under different pressure conditions [3].

Darcy's Law [4] is most used to measure flow resistance for fabrics. This law applies to the flow of Newtonian fluid in a porous medium, and defines the total volumetric flow per unit of time (Q) in a given cross-sectional area of a porous medium (As). The pressure difference (ΔP) is inversely proportional to the length (L) in the direction of flow, and K is the permeability and μ the fluid viscosity.

$$Q = \left[K \cdot \frac{As}{\mu} \cdot \frac{\Delta P}{L}\right] \quad (1)$$

In this way, the permeability of the fibers arrangement in repetitive patterns can be calculated according to Equations 2 or 3, and the flow can be measured by taking one representative cell. The flow through the fiber is considered to be highly anisotropic. If the fibers are too close, they will form a channel having narrow gaps and the angle between a channel wall and the central line will be small at all the points. The two fiber packing arrangements i.e. square and hexagonal are used in order to determine the air flow relative to the cross-section of the fiber, as shown in Fig. 1 and 2.

$$K_{Sq} = \frac{16}{9\pi\sqrt{2}} R^2 \left(\sqrt{\frac{V_{fmax}}{V_f}} - 1\right)^{\frac{5}{2}} \quad (2)$$

$$K_{Hex} = \frac{16}{9\pi\sqrt{6}} R^2 \left(\sqrt{\frac{V_{fmax}}{V_f}} - 1\right)^{\frac{5}{2}} \quad (3)$$

where: V_{fmax} is the maximum fiber volume fraction, R is the fiber radius, V_f is the fiber volume fraction; for square

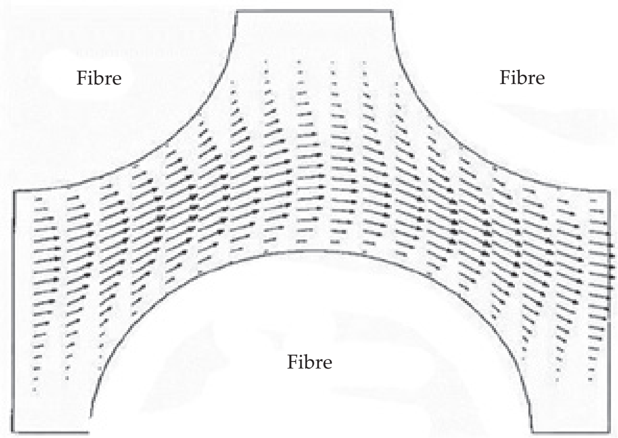

Fig. 2. Velocity field in hexagonal arrangement (V_f = 0.5) [4]

and hexagonal packing $V_{fmax} = \frac{\pi}{2\sqrt{3}}$

When simulating flow in porous media, a homogenized macroscale approach can be useful for simplifying the geometric complexity of the porous material. While using the macroscale approach to model porous media flow, Darcy's law can provide insight into a variety of physical processes where a completely resolved microscale system is difficult to reproduce. The macroscale approach assumes that the pore space behavior is quantified by two averaged values, *i.e.*, porosity and air permeability. Porosity is the average surface speed, which determines the pores volume fraction. Permeability is related to the resistance to air flow through the pores.

The surface speed is the analogous speed in the homogenized domain, as if the microscopic flow through the pores were uniformly dispersed on a macroscopic scale. If these parameters are unknown, experimental results are required to quantify porosity and permeability [5]. Numerical simulations can also be used to investigate fully resolved problems of voids and solid particles [6]. The following parameters are important to characterize the flow and acquire information about the macroscopic equations:

– porosity (the ratio of pore volume to total volume, which can be estimated using geometry),

– pressure decreases along the flow longitudinal direction, which can be estimated or predetermined,

– volumetric flow rate by the entire cross-sectional area also known as the surface velocity.

On the microscale geometry, the porosity and permeability of the porous medium can be calculated by solving the Navier-Stokes equations (or its linear approximation for small Reynolds numbers, called Stokes flow or creeping flow) [6].

Before solving the Stokes or creeping flow equations in COMSOL Multiphysics, the thermal model should be discussed and analyzed to select the most efficient model for determining effective thermal conductivity (K_{eff}).

The total rate of the heat flow across a fabric involving conduction, convection, and radiation of heat transferring per unit area of fabric at unit temperature difference is called the effective thermal conductivity (K_{eff}) which should be used in place of thermal conductivity [7]. For conduction, Fourier's law is used to calculate the fabric effective thermal conductivity (K_{eff}):

$$K_{eff} = \frac{Q \cdot t}{A \cdot \Delta T} \tag{4}$$

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

Schuhmeister [8] calculated the thermal conductivity of gases using a method devised by Crepeau [9]. In this method, bulk fibers were put between cylinders placed side by side. The cylinder, which was in the center for the temperature measuring, served as an air thermometer. According to [8], the following equation can be used to express the outcome/result of this method:

$$K_m = K_g + f \cdot C \tag{5}$$

where K_m is the conducting power or effective thermal conductivity of gas and fibers mixture, K_g is the conducting power of gas, f is the weight of textile fiber in this mixture and C is constant. Using volume occupied by fibers, this equation can be modified as:

$$K_m = K_g + \alpha \cdot \varrho_f \tag{6}$$

where: ϱ_f is the bulk density of fiber and α is constant.

In addition, Schuhmeister [8] derived a relationship for calculating the fiber and air mixture thermal conductivity, making the following assumptions:

– uniform distribution of fibers in all directions,

– ⅓ of fibers arranged parallel to the direction of heat transfer,

– ⅔ of fibers arranged perpendicularly to the direction of heat transfer.

Relationship is derived according to above assumptions:

$$K_m = \frac{1}{3}\left(K_a \cdot V_a + K_f \cdot V_f\right) + \frac{2}{3}\left(\frac{K_a \cdot V_v}{K_a \cdot V_f + K_f \cdot V_a}\right) \tag{7}$$

where: K_a – air thermal conductivity, K_f – fiber thermal conductivity, V_a – air fractional volume, V_f – fiber fractional volume, and $V_a + V_f = 1$.

The first part of the equation shows the arrangement of the fibers parallel to the direction of the heat flow, and

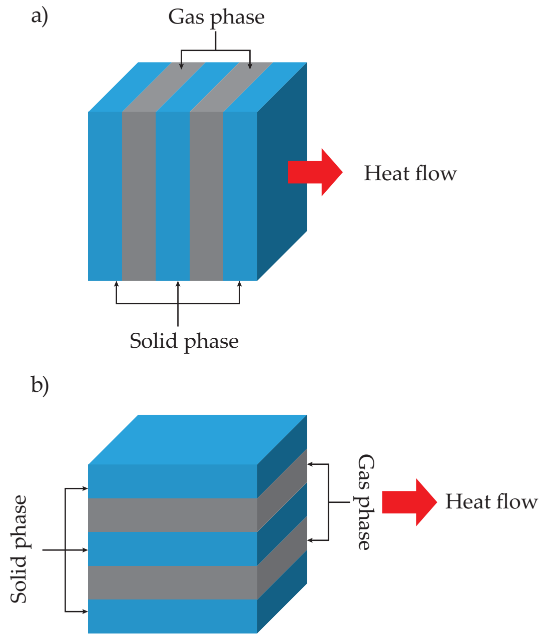

Fig. 3. Heat flow through solid and gas space: a) in series and b) parallel [10]

the second part of the equation shows the arrangement of the fiber's perpendicular to the direction of the heat flow, as shown in Fig. 3 [10].

Farnworth [11] calculated the conductive transfer of heat in fibrous material placed between two plates with a temperature gradient using the first part of the equation. Even though experimental conditions were ideal for convection, there was no considerable evidence of convective heat flow. He considered two mechanisms for the transmission of heat, conduction, and radiation. Stark and Fricke [12] created three models for determining the thermal conductivity of fiber and gas mixture (fibrous insulation). The Z parameter was used in the basic model. It corresponds to the fibers fraction oriented perpendicularly to the macroscopic heat flow. For all perpendicularly oriented fibers Z=1, and for randomly oriented fibers Z=0.66. Based on Bhattacharyya's assumptions [13], to represent the relation between the combined fiber and air thermal conductivity, Fricke and Stark derived an equation:

$$\lambda_{sg}^{BM} = K_f\left(1 + \frac{\alpha - 1}{\beta\left[1 + Z(\alpha - 1)(\alpha + 1)\right]}\right) \tag{8}$$

where: λ_{sg}^{BM} is the combined fiber and air thermal (effective) conductivity, K_f is the fiber thermal conductivity, α is the ratio of air thermal conductivity to fiber thermal conductivity (K_a/K_f), β is the fiber and air volume fraction ratio (V_f/V_a), and Z is the part of fibers which are orientated perpendicularly to the heat flow (macroscopic).

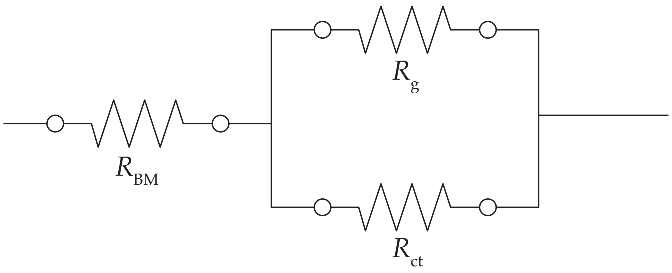

Fig. 4. Thermal resistance diagram of the modified model (R_{BM} thermal resistance of basic model, R_{ct} thermal resistance of a contact, R_g thermal resistance of air) [10]

Since the fibers are in contact with each other and the contacts between the fibers act as thermal resistance, an improved model was developed. The thermal conductivity of the modified model was calculated using the thermal resistances (Fig. 4).

The following assumptions were also considered (Fig. 5). The unit cell height in the modified model is $(m+1)\cdot 2r$ (in the basic model is $m\cdot 2r$). In the modified model, the contact area is A_{ct} and the effective area of air volume acting as a parallel resistance (R_s) is $o\cdot A_{ct}$. The combined thermal conductivity of the designed model was calculated from the formula:

$$\lambda_{ss}^{MM} = \left(1 + \frac{2r(m+1)}{S_{cell} \cdot \left[R_{BM} + \left(\frac{1}{R_g} + \frac{1}{R_{ct}}\right)\right]}\right) \tag{9}$$

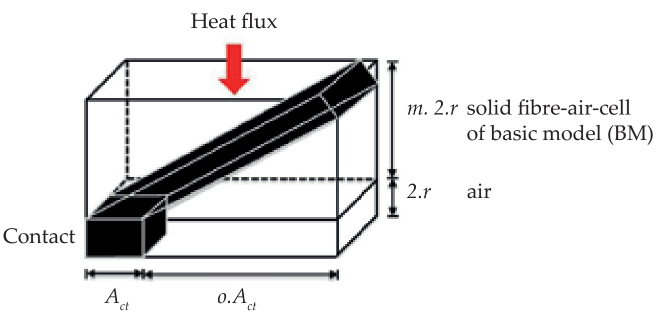

Fig. 5. Unit cell of the modified model [10]

where: m is height of the fiber-air cell in units of the fiber diameter, r is radius of a fiber, and S_{cell} is area of a fiber-air cell, $S_{cell} = A_{ct} + (o\cdot A_{ct}) = (o+1)A_{ct}$, o is area of the fiber-air cell in units of the contact area.

In fact, not all adjacent fibers are in direct contact with each other, so a different model was proposed. The new cell consists of eight cells of the previous model. The following relationship between the effective thermal conductivity between air and fiber was found.

$$\lambda_{sg}^{MMC} = (m+1)\left\{\frac{m}{\lambda_{sg}} + \frac{o+1}{o}\frac{1}{K_a + \frac{4K_s\cdot A\cdot r}{o\pi\cdot a_{ct}}}\right\} \tag{10}$$

where: A is the constant (connection parameter) and its mean values are 0.5384, 0.6836 and 0.611 respectively, r is the radius of fiber, a_{ct} is the contact radius, o+1 is the size parameter calculated by:

$$o+1 = \left(\frac{1}{r}\right)^{\frac{2}{3}} \cdot \frac{\left(0.5\sin\vartheta_o\right)^{\frac{1}{3}}}{\pi\left(1.5\left(1-\mu_o^2\right)\frac{P_{ext}}{Y_o}\right)^{\frac{2}{3}}} \tag{11}$$

where: r is the radius of fiber, ϑ_0 is mean orientational fiber angles, μ_0 is Poisson's number of the fiber material, and p_{ext} is external pressure.

Results obtained from the model were compared with experimental results for validation. Yamashita *et al.* [14] made models related to the yarns and plain-woven fabrics (model 1), and plain-woven fabric/resin composites (model 2), as well as theoretical formulations for effective thermal conductivity to be determined from these models. They discovered that, contrary to current experimental data, model 1 is more effective in determining effective thermal conductivity than model 2. They also discovered that the fibers anisotropy had much less impact on the effective thermal conductivity in the transverse direction.

Iqbal *et al.* [15] developed 3D models of the yarn and investigated the effect of thermoregulation and effective thermal regulation, and verified the theoretically calculated data to check the relative agreement with the values obtained experimentally with ABAQUS/CAE. The finite element method was used to study the thermal behavior of phase change materials to protect the consumer in extreme weather conditions [15]. They developed three models, each with a different set of properties. The obtained results reflected the heat regulation time for the models of 2, 5 and 17 min, respectively.

In the case of an air permeability model, specialized COMSOL software is often used to recreate scanned image data, especially for complex 3D geometries, after viewing a 2D cross-section such as that created with a scanning electron microscope (SEM). To solve the Navier-Stokes equations, the inertial term must be neglected, and the creep interface should be used for a water-like fluid with a density in kg/m^3 and a viscosity in Pa · s. The Reynolds number (Re) may be less than 1 [16].

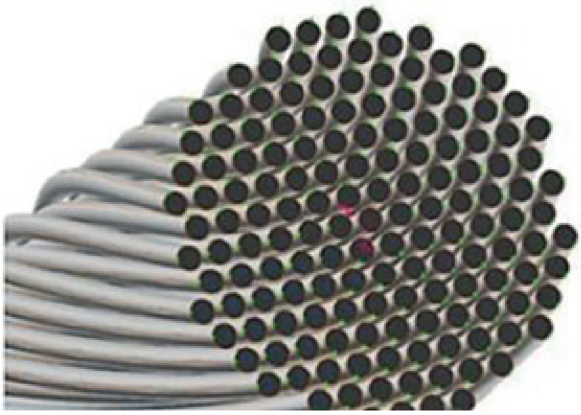

Fig. 6. Multifilament synthetic fiber model [18]

Fig. 6 simulates the permeability of one synthetic yarn that is composed of many individual fibers and provides a protective twist [17]. Despite the fact that the shape and geometry are flawless, their solution still takes a lot of time [16]. The fiber is represented by a fiber with a circular cross-section packed into a cylindrical array in the transverse dimensionless permeability model of an idealized unidirectional composite reinforcement material, as shown in Fig. 7 [18].

When the Reynolds number is extremely low (Re<<1), the Stokes equations or the creep equations in COMSOL Multiphysics should be solved [19]. A unit cell model is created, and boundary conditions are applied as follows. The pressure drop is applied to the walls of the unit cells. The upper and lower limits are then given a symmetry condition, and the cylinder limit is defined as no slip for the wall boundary. The unit value determines the fluid's density and the dynamic viscosity. When the fiber fraction surface area (A_f) is larger, the fibers practically touch each other and cross-linking takes place with very small mesh sizes, which helps in the calculation of high-speed profiles between two fibers.

To obtain the effective yarn thermal conductivity, Anand *et al*. developed a random model consisting of randomly arranged microfibers and varying influencing parameters [17]. They studied the effect of various parameters on the effective thermal conductivity and air permeability of the yarn cross-section by simulation. The results showed that the thermal conductivity of the yarn changes with the change of arrangement for the constant packing fraction, and the geometrical parameters play a key role for asymmetric microfiber structures. Moreover, the packing fraction has the biggest influence of all the parameters. The simulation results were characterized by approx. 10% deviation of the thermal conductivity value for different number of fibers and random arrangements for the same packing fraction.

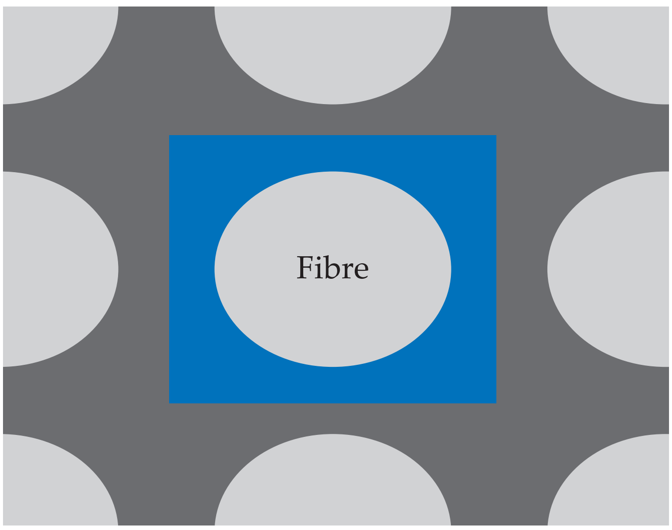

Fig. 7. Unit cell of a circular fiber cross-sectional [19]

Therefore, in this work the effective thermal conductivity and air permeability of a multifilament polyester yarn used in sports T-shirts were investigated by computer modeling using COMSOL Multi and ABAQUS/CAE physics-based finite element analysis. For this purpose the influence of various parameters (fibers number, yarn porosity, and yarn volume fraction) on the effective thermal conductivity and air permeability of the yarn cross-section was studied.

EXPERIMENTAL PART

Methodology

Modelling steps

RVE (representative volume element) is defined as the smallest volume or unit cell by which data can be predicted, evaluated, or measured and the resulting value can be considered representative of the entire unit. Steps in modeling effective thermal conductivity and air permeability are shown in Figs. 8 and 9, respectively.

Air permeability modeling

Fig. 10 shows the air permeability modeling methodology. Creep flow and Darcy's law were assigned to the air permeability model. Creep flow consists in assigning fluid properties (density, dynamic viscosity, Newtonian fluid), initial values (initial velocity V_i = 0 m/s at all axes)

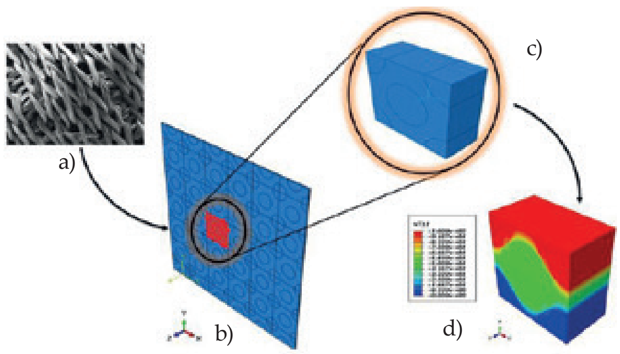

Fig. 8. Steps in modeling effective thermal conductivity: a) SEM images, b) 72-fiber model, c) unit cell model, and d) predicted temperature profile

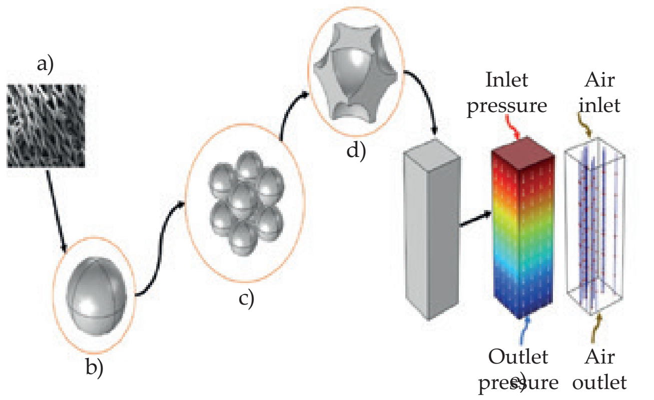

Fig. 9. Air permeability modeling steps: a) SEM images, b) spherical fiber cross-section, c) spherical fibers arrangement, d) air volume difference between the systems, e) porous medium, simulated pressure profile, and Darcy speed field

and inlet and outlet values to the surfaces to create a gradient difference for the air flow and to select the symmetry of the model for the air model cut (component 1). Darcy's law is assigned to a porous medium (component 2) with P_{ref} = 1 Pa in the global coordinate system, initial values (P = 0 Pa) and inlet and outlet pressures.

SEM analysis

The average diameters of yarns and fibers as well as the fibers volume fractions were determined using a scanning electron microscope (SEM), as given in Tab. 1 and 2. For multiple fibers, the fiber and yarn lengths were considered the same. Table 2 lists the measured parametric

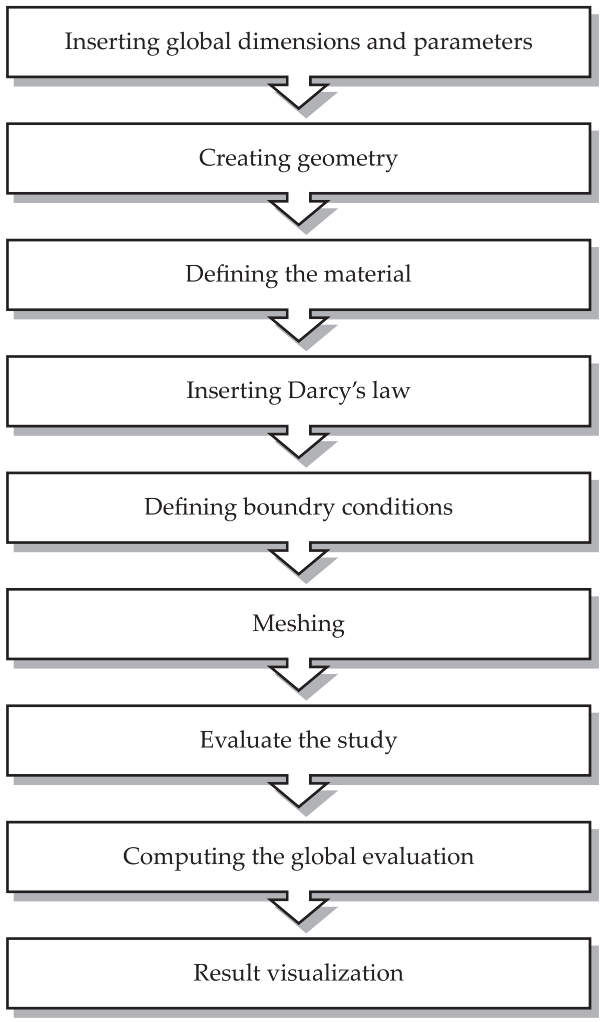

Fig. 10. Air permeability modeling methodology

values of the polyester yarn in a sports T-shirt, and Fig. 11 shows the SEM images.

T a b l e 1. The fiber volume fraction of polyester yarn with different No. of filaments

No. of fibers	Fiber volume fraction
72	0.44379
62	0.36686
52	0.307685
42	0.2485
32	0.18934

Fiber volume fraction (FVF)

The ratio of the fibers volume in a yarn or unit cell to the volume of the yarn is called the fiber volume fraction (FVF) and can be calculated theoretically or using technical methodology. A relatively accurate method of obtaining FVF is SEM analysis.

T a b l e 2. Data obtained from SEM images

Sample no.	Average yarn diameter, mm	Yarn count (Tex) 8.822	No. of fibers 72
		Average fiber diameter, mm	Fiber volume fraction by image analysis
1	0.150	0.009	0.274655
2	0.168	0.012	0.409403
3	0.170	0.012	0.457061
4	0.162	0.017	0.619382
5	0.156	0.012	0.458458
Mean	0.161	0.012	0.443790
SD	0.008	0.003	0.124

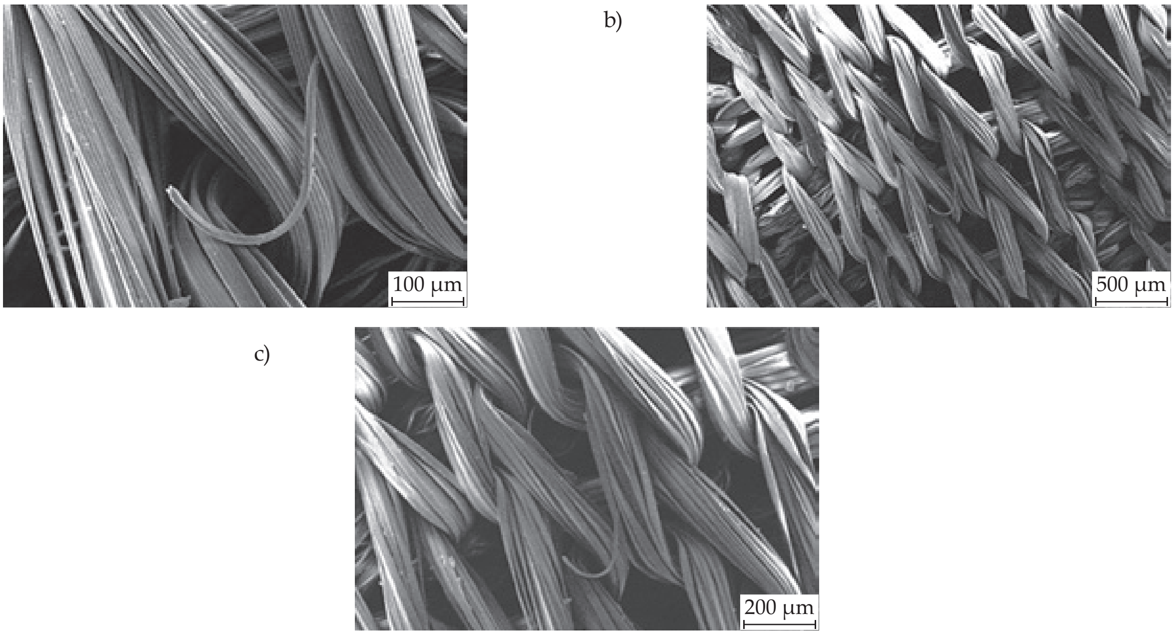

Fig. 11. SEM images of polyester yarn of sports T-shirt at magnification: a) 200×, b) 37×, c) 75×

$$V_f = \text{No. of fibers}\ \frac{(Diameter\ of\ fibre)^2}{(Diameter\ of\ yarn)^2} \tag{12}$$

– fiber diameter = 0.0124 mm
– yarn diameter = 0.1612 mm

Thermal conductivity

The tensor determining the thermal conductivity of a transversely isotropic orthotropic yarn is as follows:

$$K = \begin{bmatrix} K_{11} & 0 & 0 \\ 0 & K_{22} & 0 \\ 0 & 0 & K_{33} \end{bmatrix} \tag{13}$$

where: K_{11}, K_{22} and K_{33} are the thermal conductivity of the yarn along the fiber direction x, y, and z, respectively.

The Parallel and Series models and the Clayton model calculating the axial and transverse thermal conductivity of the models are as follows.

Parallel model:

$$K_{ya} = K_{fa} \cdot v_{fy} + K_{air}(1 - V_{fy}) \tag{14}$$

Series model:

$$K_{yt} = \frac{K_{ft} \cdot K_{air}}{V_{fy} \cdot K_{air} + (1 - V_{fy}) \cdot K_{ft}} \tag{15}$$

Clayton model:

$$K_{yt} = K_{air}\left[\frac{\sqrt{(1-V_{fy})^2 \cdot \left(\frac{K_{ft}}{K_{air}}-1\right)^2 + 4\frac{K_{ft}}{K_{air}} - (1-V_{fy}) \cdot \left(\frac{K_{ft}}{K_{air}}-1\right)}}{2}\right]^2 \tag{16}$$

where: K_{yt} is the thermal conductivity of a yarn in transverse direction W/(m · K), K_{air} is the air thermal conductivity W/(m · K), V_{fy} is the fiber volume fraction of a yarn, K_{ft} is the thermal conductivity of a fiber in transverse direction W/(m · K).

Finite element analysis (FEA)

This technique involves dividing any complex problem into a finite number of elements that are solved relative to each other. FEA provides information and properties that may not be easily obtained through experimentation. Using the ABAQUS/CAE simulation software, a technique was implemented by which air permeability, heat transfer and thermal properties were predicted along with the analysis of heat flow mechanisms within the developed model for a single-component yarn cell for specific conditions. Unit cell models are shown in Fig. 12.

Meshing

Linear tetrahedral elements were used to create the unit cell mesh developed for the yarn. The size was set to

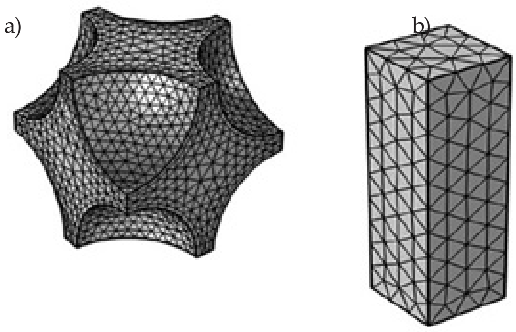

Fig. 12. Unit cell air permeability model of polyester fiber a), and porous medium b)

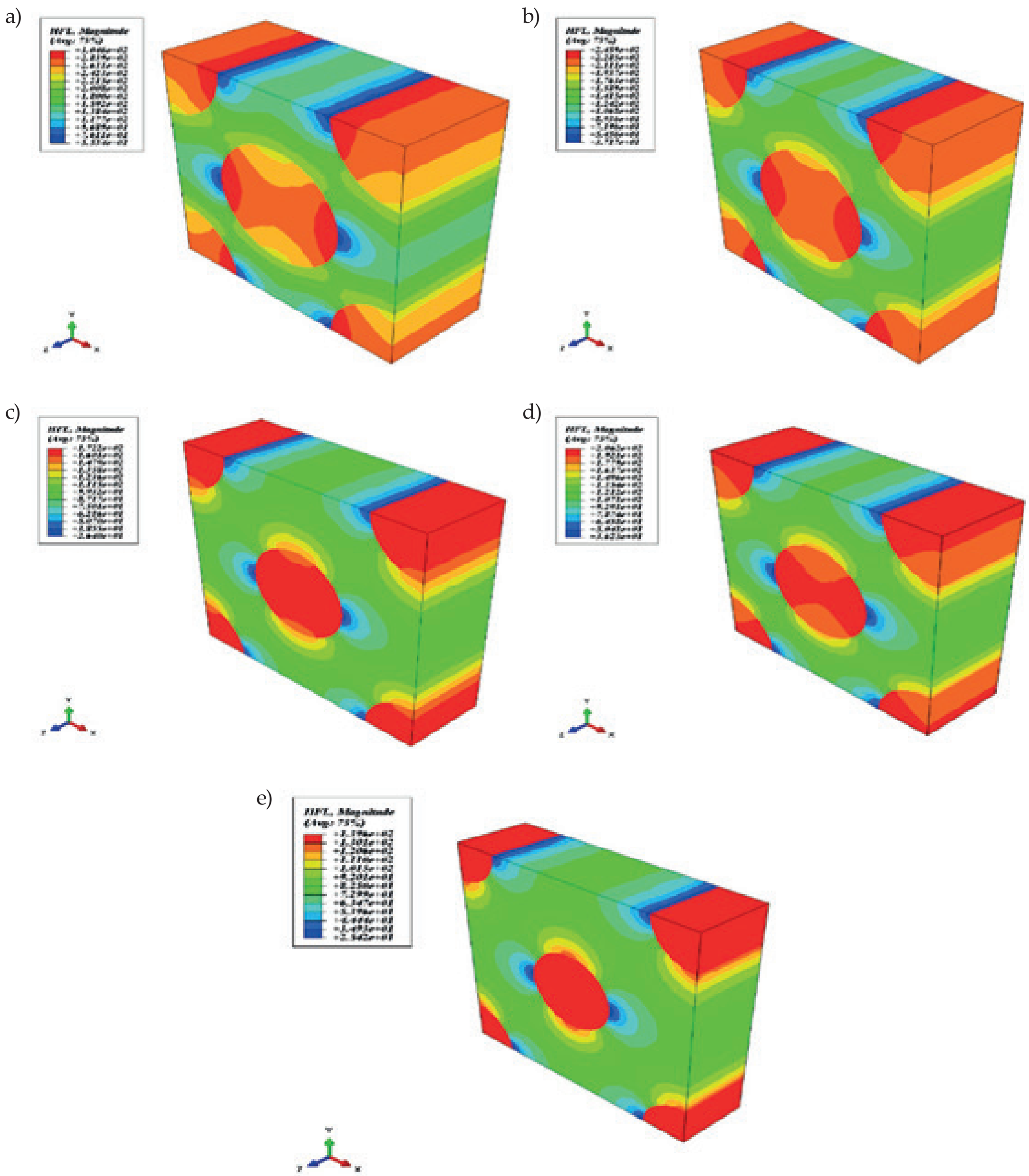

Fig. 13. Diagram of the heat flux contour of the unit cell of polyester fibers: a) 72 fibers, b) 62 fibers, c) 52 fibers, d) 42 fibers, and e) 32 fibers

0.0009, representing fine mesh geometry, and then the element size was set to normal, representing the standard mesh geometry.

Boundary conditions

The boundary conditions across the thickness of the fabric were established according to the specified temperature and pressure values for the upper and lower sides of the fabric, assuming unidirectional constant flow:

T_{upward} = 100°C and $T_{downward}$ = 0°C
P_{inlet} = 10 Pa and P_{outlet} = 0 Pa respectively.

In addition, the properties of the materials were set appropriately as specified for the air and fiber regions. Overall air permeability, heat flux and effective thermal conductivity are calculated by the software itself.

Material orientation

The orientation for the material is assigned in such an order that the *z*-axis is taken as the axial axis parallel to the yarn direction also called longitudinal, *x* and *y* axes are considered as perpendicular (transverse) to the yarn direction also called lateral. The yarn is assumed to be orthotropic and solid. A transversely isotropic nature is found in textile fibers in which the properties remain consistent in one plane and vary in the perpendicular plane, hence it is essential to assign orientation when using the finite element analysis (FEA) modeling technique. The orientations that have

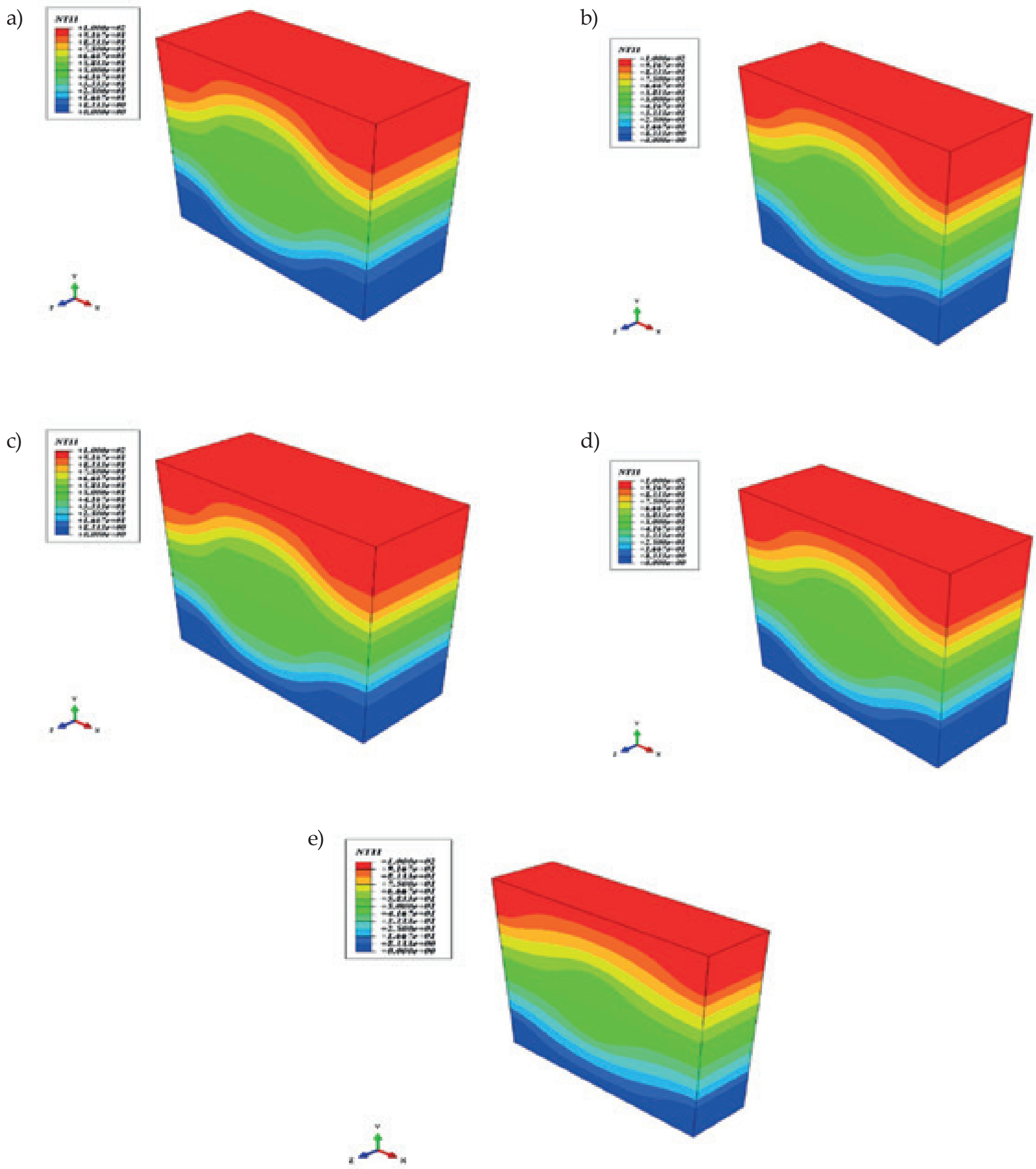

Fig. 14. Unit cell temperature contour diagram of polyester fibers: a) 72 fibers, b) 62 fibers, c) 52 fibers, d) 42 fibers and e) 32 fibers

been assigned along their respective axis are mentioned below:

For lateral axes (transverse): k_{11} = (0.157) x-axis, k_{22} = (0.157) y-axis

For longitudinal axis (axial): k_{33} = (1.26) z-axis.

RESULTS AND DISCUSSION

To facilitate model processing, multi-yarn models were developed by gradually reducing the fibers number and adapting unit cell models to parametric dimensions to calculate the effective thermal conductivity and air permeability of the yarn from the parametric dimensional image obtained from SEM analysis.

The portion of fiber and air present in each of the models and their contour plot of heat flux and temperature are shown in Figs 13 and 14. After obtaining results from simulation modeling, graphs are plotted between effective thermal conductivity and the number of fibers in the yarn as shown in Fig. 15, and between yarn porosity and the number of fibers in the yarn as shown in Fig. 16. It was found that as the number of fibers in the yarn increase, the effective thermal conductivity of the yarn increases, and the porosity of the yarn decreases linearly.

A similar trend was observed between the air permeability and the number of fibers as shown in Fig. 17. Another graph is plotted between the yarn air permeability and the porosity values, the exponential increase is observed when number of fibers changes in each yarn cross-section as shown in Fig. 18.

The porosity of the yarn can be written as:

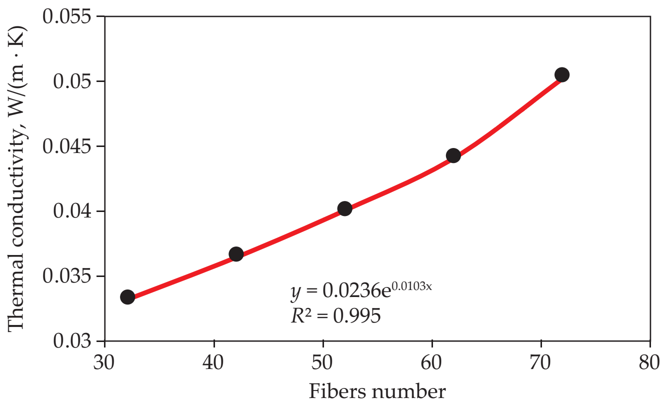

Fig. 15. Thermal conductivity as a function of fibers number

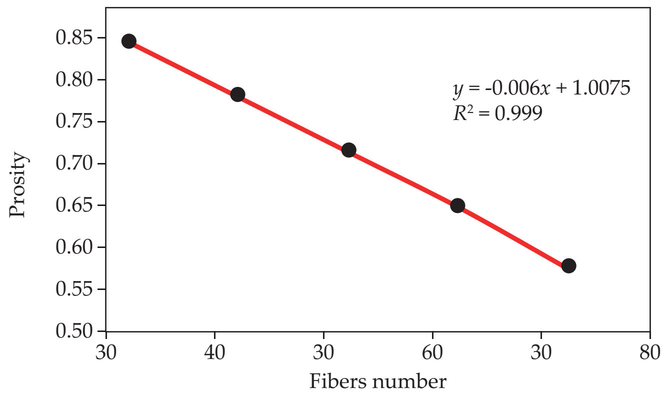

Fig. 16. Yarn porosity as a function of fibers number

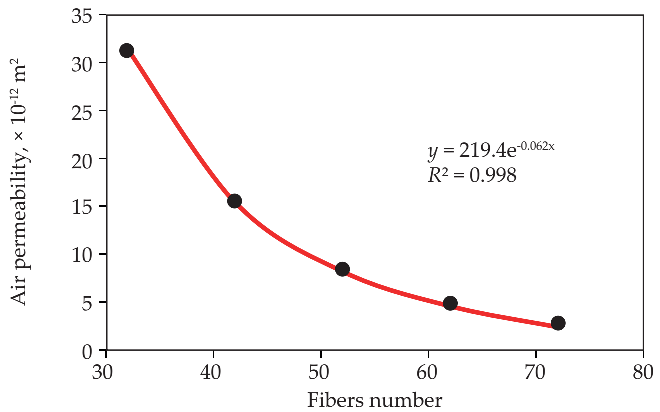

Fig. 17. Air permeability as a function of fibers number

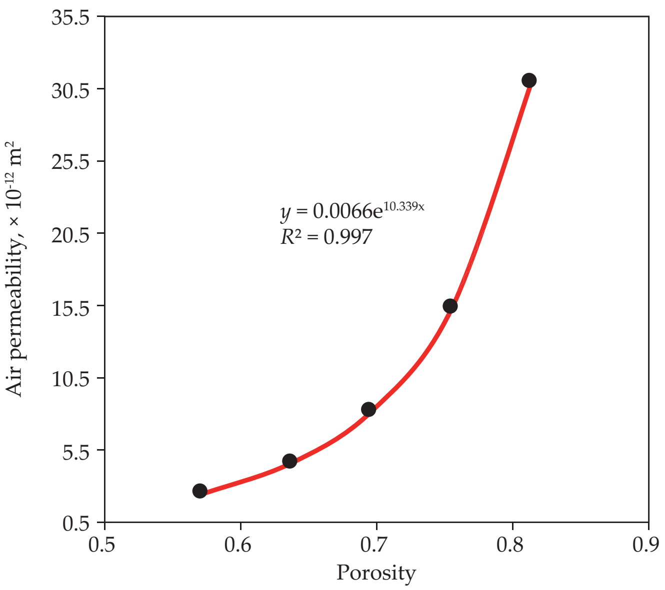

Fig. 18. Air permeability as a function of yarn porosity

$$\varnothing = 1 - V_f \tag{17}$$

where: $\varnothing$ is the yarn porosity and V_f is the fiber volume fraction.

Similarly, the radius of fibers with respect to fiber volume fraction can be calculated from equation 18 while the radius and lateral dimensions of polyester fiber is shown in Table 3.

$$R = \sqrt[3]{\frac{3V_f \cdot L^3}{4\pi}} \tag{18}$$

where: L is the fiber length.

The values computed through software for air permeability and the porosity of unit cell models with 72, 62, 52, 42, 32 fibers are shown in Table 4.

Creeping and Darcy's flow velocity, and pressure unit cell model of yarn with 72 fibers are shown in Fig. 19.

Simulation models

Validation of predicted thermal conductivity and air permeability

Unit cell models have been developed with the analysis of the yarn parametric specifications to predict the effective thermal conductivity of the yarn at different fiber numbers and fiber volume fractions. The effective thermal conductivity was also calculated using the Clayton formula and the predicted values obtained from the simulation modeling in ABAQUS/CAE were verified using the Clayton model formula as shown in Table 5 and Fig. 20. Similarly, the predicted air permeability values obtained using the simulation modeling in COMSOL were verified using the Gebart model formula as shown in Table 6 and Fig. 21. The predicted values are almost identical. Thanks to this, the generated unit cell models can be used for finite element analysis. In addition, the absolute error was calculated and the absolute error percentages were within tolerance as shown in Table 5. Using the Clayton model the absolute error is:

$$\text{Absolute error} = \frac{\text{Actual value} - \text{Predicted value}}{\text{Actual value}} \cdot 100\% \tag{19}$$

CONCLUSIONS

The effective thermal conductivity and air permeability of a multifilament yarn were predicted by generating finite element models in the COMSOL system.

T a b l e 3. Radius and lateral dimensions of polyester yarn

No. of fibers	Radius mm	Lateral dimension mm
72	0.0109	0.02332
62	0.01139	0.02565
52	0.01173	0.02801
42	0.01216	0.03117
32	0.012721	0.03571

T a b l e 4. Air permeability and porosity of the unit cell

No. of fibers	Air permeability m^2	Porosity	
	Computational modeling	Calculation	Computational modeling
72	$2.4773 \cdot 10^{-12}$	0.55621	0.56979
62	$4.6382 \cdot 10^{-12}$	0.63320	0.63598
52	$8.2016 \cdot 10^{-12}$	0.69230	0.69498
42	$1.5284 \cdot 10^{-11}$	0.75150	0.75384
32	$3.104 \cdot 10^{-11}$	0.81066	0.81279

T a b l e 5. Thermal conductivity of polyester yarn

No. of fibers	Fiber volume fraction	Effective thermal conductivity W/(m · K)		Absolute error %
		Actual	Predicted	
72	0.44379	0.050110	0.050480	0.74
62	0.36680	0.043869	0.044237	0.84
52	0.30770	0.039250	0.040137	2.26
42	0.24850	0.035480	0.036455	2.75
32	0.18934	0.032171	0.033155	3.06

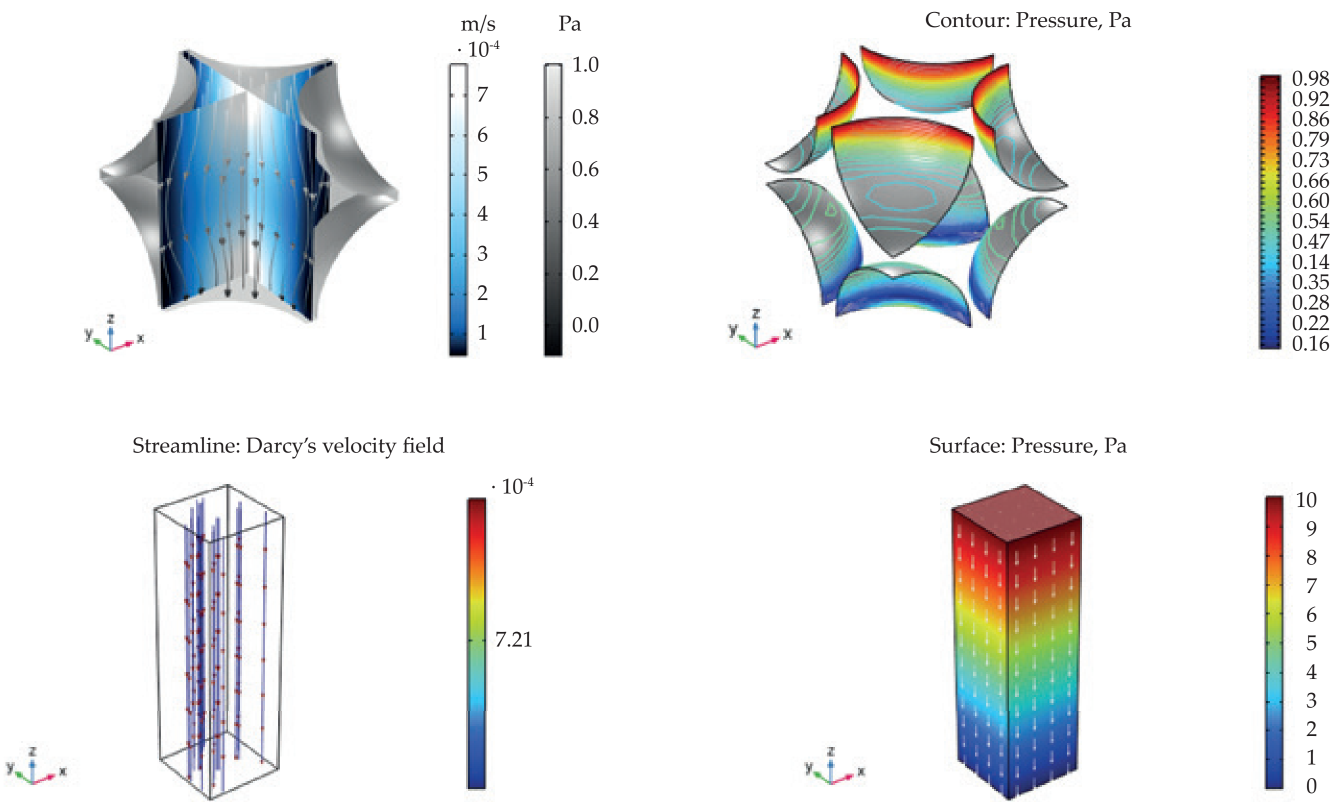

Fig. 19. Creeping and Darcy's flow velocity and pressure unit cell model of polyester yarn having 72 filaments

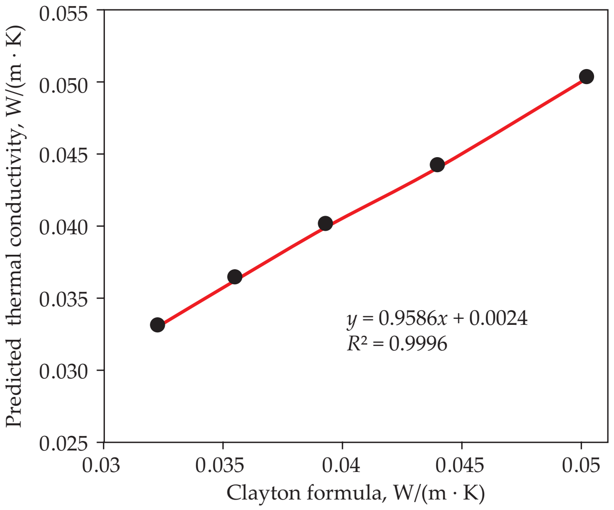

Fig. 20. Validation of the effective thermal conductivity by using Clayton model

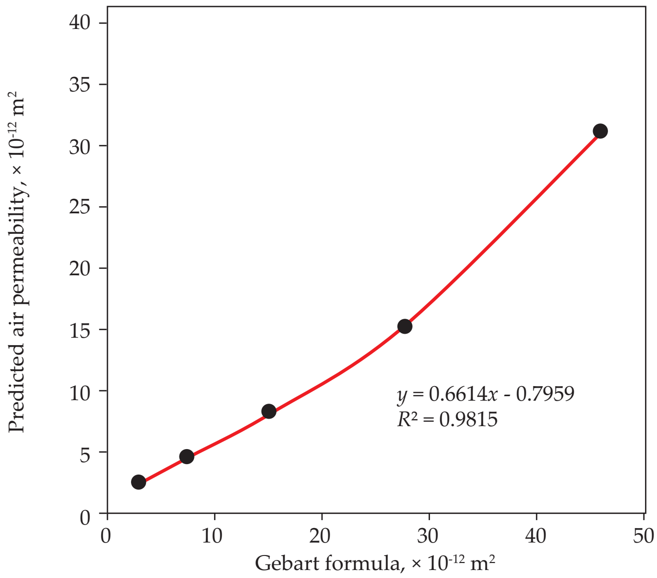

Fig. 21. Validation of air permeability by using Gebart formula

T a b l e 6. Air permeability of polyester yarn

No. of fibers	Air permeability, m^2	
	Actual	Predicted
72	$2.4773 \cdot 10^{-12}$	$2.9813 \cdot 10^{-12}$
62	$4.6382 \cdot 10^{-12}$	$7.5840 \cdot 10^{-12}$
52	$8.2016 \cdot 10^{-12}$	$15.2030 \cdot 10^{-12}$
42	$1.5284 \cdot 10^{-11}$	$2.7567 \cdot 10^{-11}$
32	$3.104 \cdot 10^{-11}$	$4.5855 \cdot 10^{-11}$

It was found that factors such as the number of fibers, their volume fraction and porosity have a direct and indirect impact on the effective thermal conductivity and air permeability of the yarn. As the number of fibers increases, the fiber volume fraction increases, and thus the effective thermal conductivity. Similarly, as the number of fibers increases, the porosity of the yarn decreases linearly, and the air permeability decreases exponentially. Air permeability was found to have an exponentially increasing relationship with porosity. Thus, ideally, according to the research results, the yarn for sports T-shirts should contain a high number of fibers for better thermal regulation and a low number of fibers for better air permeability.

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