SIMULATIONS OF HEAT TRANSPORT PHENOMENA IN A THREE-DIMENSIONAL MODEL OF KNITTED FABRIC

A.K. Puszkarz ^a, R. Korycki ^b, I. Krucinska ^a

^a Department of Material and Commodity Sciences and Textile Metrology, Faculty of Material Technologies and Textile Design, Lodz University of Technology, Zeromskiego St 116, 90-924 Lodz, Poland.

^b Department of Technical Mechanics and Informatics, Faculty of Material Technologies and Textile Design, Lodz University of Technology, Zeromskiego St 116, 90-924 Lodz, Poland.

Corresponding author: Izabella Krucinska; email: izabella.krucinska@p.lodz.pl

Abstract:

The main goal of the current work is to analyse the three-dimensional approach for modelling knitted fabric structures for future analysis of physical properties and thermal phenomena. The introduced model assumes some simplification of morphology. First, fibres in knitted fabrics are described as monofilaments characterized by isotropic thermal properties. The current form of the considered knitted fabric is determined by morphological properties of the used monofilament and simplification of the stitch shape. This simplification was based on a particular technology for the knitting process that introduces both geometric parameters and physical material properties. Detailed descriptions of heat transfer phenomena can also be considered. A sensitivity analysis of the temperature field with respect to selected structural parameters was also performed.

Keywords:

Knitted fabric, simulation, heat transport phenomena, modelling

Nomenclature

A	radiative surface area, m ²
a	stitch height, m
b	stitch width, m
c	specific heat of textile material, J/(kg·°C)
c_{Cu}	specific heat of copper, J/(kg·°C)
c_{PP}	specific heat of polypropylene, J/(kg·°C)
d	diameter of semicircles in the Dalidovic's model of knitted fabric, m
e	specific internal energy, J
G	thickness of fabric, m
g	diameter of yarn in Dalidovic's model of knitted fabric, m
g_i	gravitational acceleration component along i -th coordinate direction, m/s ²
h	thermal enthalpy, J
k	turbulent kinetic energy, kg/(m ² ·s ²)
l	yarn length in single stitch, m
P_r	number of rows located in the unit of length, dimensionless
P_k	number of column located in the unit of length, dimensionless
p_{air}	air pressure, Pa
Pr	Prandtl number, dimensionless
Q_H	specific heat release (or absorption) per unit volume, J/(kg·°C·m ³)
Q_T^{out}	heat radiation leaving a radiative surface, W/m ²
Q_T^{in}	incident thermal radiation arriving at surface, W/m ²
q_i	diffusive heat flux density, W/m ²

s	shape factor of stitch, dimensionless
T	temperature of surface, °C
T_{air}	air temperature, °C
T_{Cu}	temperature of heating copper plate, °C
T_{PP}	temperature of polypropylene knitted fabric, °C
u	fluid velocity, m/s
ε	surface emissivity coefficient of thermal radiation, dimensionless
ε_{Cu}	copper emissivity coefficient of thermal radiation, dimensionless
ε_{PP}	polypropylene emissivity coefficient of thermal radiation, dimensionless
λ_i	eigenvalues of thermal conductivity tensor, W/(m·°C)
λ_{PP}	thermal conductivity of polypropylene knitted fabric, W/(m·°C)
μ	dynamic viscosity coefficient, dimensionless
μ_t	turbulent eddy viscosity coefficient, dimensionless
ρ	fluid density, kg/m ³
ρ_{air}	air density, kg/m ³
ρ_{Cu}	copper density, kg/m ³
ρ_{PP}	polypropylene knitted fabric density, kg/m ³
σ	Stefan Boltzmann constant, J/°C
τ_{ik}	viscous shear stress tensor, Pa
ϕ_{air}	relative air humidity, %

Introduction

Structural modelling of knitted fabrics is a tool supporting better understanding of the impact of morphology on their physical properties. Moreover, it could provide information on the critical

parameters of materials that make up a particular type of fabric, influencing significantly the selected physical properties of the designed product. Thermal properties are basic characteristics to consider with respect to the potential user of clothing. Thus, thermal exchange between the user and the environment should be balanced to ensure comfortable conditions and to prevent both hypo- and hyperthermia. The physical description of thermal properties of textiles classified as a discrete highly porous body is a complex task. In terms of modelling, two different approaches regarding scale of simplification of the physical and mathematical description of the state of a dynamical thermal system and scale of homogenization of the structure of the body should be considered.

The choice of state variables depends on the problem formulation. There are a few typical variables describing the state of thermal systems, for example, temperature, entropy, pressure, internal energy etc. The heat conduction equation in textiles describes the state of structure and is a second-order differential equation with respect to temperature [1]. Thus, temperature is introduced as a state variable. Li and Li *et al.* [2-6], Fan *et al.* [7], Long *et al.* [8], Pan and Gibson [9] described the coupled heat and water vapour transport by the heat and moisture balance equations accompanied by the equation of moisture diffusion into the fibre. The state variables in this model are temperature, moisture concentration within fibres and moisture concentration in the void spaces between fibres. The alternative formulation can introduce respectively the mass balance of water vapour, the heat balance, the mass balance of liquid moisture as well as the equation of moisture diffusion into the fibre, cf. [10, 11]. The state variables are the same but the distribution of water vapour and liquid moisture should be additionally introduced. Haghi [12] introduces a theoretical model based on examination of the liquid–vapour equilibria and of the mass and energy transfer processes in porous systems. Variations in temperature and moisture content distribution are solved using the finite difference method or the finite element method. The implemented method needs the homogenized structure of the precise defined heat transfer coefficients.

In terms of homogenization of body structure there are two different approaches to effectively describe textile structure. The macro-models determine the global structure in 3-D via a two-stage homogenization process. Separate fibres are homogenized at the micro level with respect to elementary yarns and free spaces between yarns. Then, the textile structure is homogenized again with respect to void interfiber spaces filled by air or other fluids. Thus, we can optimize the structural shape as well as the material properties by introducing different optimization techniques and procedures of clear physical description (cf. variational approach of Finite Element Analysis). Some optimization options are based on local material derivatives and first-order sensitivity formulations (cf. Korycki) [13, 14].

To solve the model, a homogeneous fibre structure must be introduced. There are multiple homogenization methods available. The thermal conductivity of porous-duct-capillary materials was discussed by Wawszczak [15] as a function of the thermal conductivities of textile materials and the filling between

fibres, that is, the air within void spaces. The correlations are determined in two directions: parallel and perpendicular to the capillaries. Golański, Terada and Kikuchi [16] introduced the classic 'rule of mixtures' of the substitute thermal conductivity. The same authors described Turner's model, formulated in view of a hydrostatic analogy. The existence of homogenous fibres allows for determining the model of the spatial structure of knitted fabrics.

Since 1951 research on the description of spatial structure of knitted fabrics has been conducted [17-25] and a comprehensive literature revision of papers published till the early eighties was given by Zurek and Kopias [26]. That time the first interest of researchers was to find some relationships between fabric parameters and fabric dimensions. Nowadays from the computer modelling perspective new methods based on CAD systems are developed for simulating the shape of knitted fabrics first in 2D domain [27] and next in 3D [28] mostly using Non-Uniform Rational B-Spline (NURBS) [29-34]. Goktepe *et al.* [28] and Renkens *et al.* [29] in their works reported a method specially developed to obtain a three-dimensional loop model that was suitable for visual computer representation of warp-knitted structures. A general loop model based on the data obtained from the analysis of real loops in fabrics was then developed. Honglian *et al.* [30] used the NURBS curves for description of the warp-knitted fabric structure. Jiang *et al.* [31] designed 3D solid models of the loop yarns, insertion yarns and chopped strand mat in modern multi-axial warp-knitted fabrics to reflect the geometric structures of the three items also by using NURBS curves and the principle of curved surfaces. Göktepe [34] in his work developed a method for 3D solid computer representation of warp knitted structures using a similar technique. For this purpose, a three-dimensional cylindrical uniform solid yarn model was applied, such that the central axis is a space curve, by using NURBS surfaces.

The main goal of the current work is to conduct the modelling of heat transfer through the 3D weft knitted PP fabric. The novel element of this work is the physical and local description that is made within SolidWorks software, which was not previously available for use with reference to textile structures. Additionally the original sensitivity analysis of the temperature field on the knitting structure was conducted, which could provide instructive tools for its future application.

The modelling was realized using the following simplification of the physical and mathematical description of the state of a dynamical thermal system:

- the heat flow under steady conditions was assumed,
- the yarns are assumed as a solid, continuous structure in a form of monofilaments characterized by isotropic thermal properties,
- the spatial distribution of yarns in knitted fabrics was described using the NURBS method,
- heat transport phenomena are modelled by means of the finite volume method.

Characteristics of material

The subject of the analysis presented in this paper is the simulation of thermal properties of single jersey knitted fabrics as shown in Figure 1. The basic weave morphology of this type of knitted fabrics can be determined using the shape of a single stitch that makes up the textile structure. The stitch sizes may vary due to the different characteristics of yarn, selection of different knitting parameters and impact of external forces during the production process. The structure of knitted fabrics is characterized by basic geometric parameters, that is the number of rows located in the unit of length, P_r , the number of columns located in the unit of length, P_k , the yarn length in a single stitch, l , the fabric thickness, G , and the stitch shape factor, $s = P_k / P_r$. Moreover, the geometry of knitted structures can be described by the stitch height, a , and stitch width, b , Figure 1. These fabrics are typically very susceptible to stretching and easily deformed. The best parameter to use in accurately determining material characteristics is yarn length in a single stitch, which is independent of sample dimensions.

Studies on knitted fabric geometry began in the 1940s. One of the models developed from these studies, according to Dalidovic [26], describes knitted fabric as a geometric system of semicircles and straight sections arranged on a plane, Figure 2.

Assuming that the arms of the stitch (i.e., the lengths of AC and BD) are approximately equal to the stitch height, a , the yarn length within a single stitch, l , can be described as follows:

$$l = \pi d + 2a \quad (1)$$

The diameter of semicircle, d , can be determined from the stitch width, b , by:

$$d = \frac{b}{2} + g, \quad (2)$$

and Equation (1) can be rewritten as follows:

Figure 1. Schematic of knitted fabric structure (top view and side view), illustrating basic geometric parameters.

$$l = \frac{\pi}{2}b + \pi g + 2a. \quad (3)$$

Introducing AC and BD as a hypotenuse of a right triangle (with legs a and g), Equation (3) is modified to be:

$$l = \frac{\pi}{2}b + \pi g + 2\sqrt{a^2 + g^2}. \quad (4)$$

The applied model is only an approximation of the real structure, that is knitted fabric of the prescribed geometric and material parameters. The verification of Dalidovic model with the real fabric was conducted using image analysis.

Let us assume a simple monolayer knitted fabric (single jersey) made of polypropylene with the following physical parameters: mass per unit area – 176.26 g/m², thickness – 0.781 mm, number of columns per unit length – 12.5, number of rows per unit length – 25 (Figure 3).

The three-dimensional model was determined using SolidWorks software. Stitch and weave shapes were mapped on the basis of electron micrographs. As shown in the images, the shape of the stitch is not a perfect semicircle, as described by Dalidovic [26]. Moreover, the cross-sectional shape of real knitted fabric is not a perfect circle and varies along a stitch line. These scanning electron microscope (SEM) images were imported into SolidWorks software to sketch the stitch in two planes: a projection on the horizontal plane and a variable plane of cross-sectional shape. The first stage of model construction was to create a two-dimensional sketch of axis of a single stitch on the plane using NURBS curves. The shape of the curve was determined by average sizes of the stitch of real material: height – 0.59 mm, width – 0.77 mm (Figure 4a). The next step was to construct a sketch describing the profile of the stitch in a plane perpendicular to the previous one. Using the projection operation of the first sketch to the profile a three-dimensional axis of the mesh was obtained (Figure 4b). The next step of the design was preparation of cross-sectional sketch of yarn (Figure 4c). The final shape of the stitch was obtained by means of *Swept Boss/Base* operation performed on objects created in the last two steps (Figure 4d).

Figure 2. Stitch model of knitted fabrics by Dalidovic [26].

The advantages of the applied procedure include shape approximate to the real stitch shape, average diameter yarn cross-section and average knitted fabric thickness. The obtained model is a simple multiplication of the basic stitch made of homogenized yarns in a form of monofilaments characterized by isotropic thermal properties. The void spaces between monofilaments can be filled by a substance/fluid of prescribed characteristics. Additionally, the point-wise contact between monofilaments in knitted fabric can cause extreme temperature values and consequently influence the heat transport.

Physical basis of simulation of heat transfer

Knitted fabric is a complex structure of fibres and free spaces between fibres filled by a substance or fluid, such as air or liquid. Heat is transported through the textile structure through both monofilaments (solid body) and fluids (fluid media) with simultaneous exchange between these environments. Heat transfer in fluids is expressed by the following conservation equation [35]:

Figure 3. (a) Photo of monolayer polypropylene knitted fabric and (b and c) scanning electron microscope (SEM) images (b – top view, c – bottom view, d – cross section).

Figure 4. Stages of design of three-dimensional model of polypropylene knitted fabric designed on the basis of SEM images.

Figure 5. Three-dimensional model of polypropylene knitted fabric designed on the basis of SEM images.

$$\frac{\partial}{\partial t} \left[\rho \left(h + \frac{u^2}{2} \right) \right] + \frac{\partial}{\partial x_i} \left[\rho u_i \left(h + \frac{u^2}{2} \right) \right] = \frac{\partial}{\partial x_i} \left[u_i (\tau_{ij} + \tau_{ij}^R) + q_i \right] + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho \varepsilon + S_i u_i + Q_H ; \quad (4)$$

where $S_i = S_i^{\text{porous}} + S_i^{\text{gravity}} + S_i^{\text{rotation}}$ is the mass-distributed external force per unit mass due to porous media resistance (S_i^{porous}), buoyancy ($S_i^{\text{gravity}} = -\rho g_i$) and the coordinate system rotation (S_i^{rotation}). The subscripts are used to denote summation over the three coordinate directions.

The heat flux density is defined by the following equation:

$$q_i = \left(\frac{\mu}{Pr} + \frac{\mu_i}{\sigma_c} \right) \frac{\partial h}{\partial x_i}; \quad i = 1, 2, 3; \quad (5)$$

where

$$\mu_i = \frac{C_\mu \rho k^2}{\varepsilon} \quad (6)$$

The constant C_μ is determined according to [35] as equal to $C_\mu = 0.09$; whereas $\sigma_c = 0.9$. The equations describe both laminar and turbulent flows. Moreover, transitions from one case to another and back are possible. The parameters k and μ_i are zero for pure laminar flows. The phenomenon of anisotropic heat conductivity in solid media is described by the following correlation:

$$\frac{\partial(\rho e)}{\partial t} = \frac{\partial}{\partial x_i} \left(\lambda_i \frac{\partial T}{\partial x_i} \right) + Q_H ; \quad (7)$$

where $e = cT$. It is assumed that the heat conductivity tensor is diagonal to the considered coordinate system and that the heat transport within polypropylene is direction-independent, that is, we introduce isotropic medium and can denote $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$.

The surfaces that lose heat by radiation can emit, absorb and reflect solar or thermal radiation. The thermal radiation determined by the surface or radiation source is expressed as a sum of material radiation (described by the surface emissivity and a prescribed area of radiation) and incoming radiative transfer. This problem is defined by the following equation [35]:

$$Q_T^{\text{out}} = \varepsilon \cdot \sigma \cdot T^4 \cdot A + (1 - \varepsilon) \cdot Q_T^{\text{in}} \quad (8)$$

Heat flow phenomena simulation

The steady problem was assumed, and some simulations were determined with the SolidWorks Flow Simulation module. The knitted fabric was introduced as monolayer 1 made of solid monofilaments and fluid in void spaces. The polypropylene knitted structure was situated on the upper surface of a rectangular copper plate that served as a heater. Both elements were positioned on the bottom of a rectangular computational domain with volume equal to $52.8 \cdot 10^{-9} \text{ m}^3$ ($10 \times 2.4 \times 2.2$) $\cdot 10^{-3} \text{ m}$, filled with air, Figure 6.

To eliminate the effects of asymmetric boundary conditions, settings were applied to imitate an infinite layer of fabric propagating outside of the domain in all three directions. The initial conditions of the model were assumed as follows: $T_{\text{Cu}} = 30^\circ\text{C}$, $T_{\text{PP}} = 20^\circ\text{C}$, $T_{\text{air}} = 20^\circ\text{C}$, $p_{\text{air}} = 1013.25 \text{ hPa}$ and $\varphi_{\text{air}} = 60\%$.

The computational domain was divided into 29,346 cells (12,954 fluid cells, 2,950 solid cells and 13,442 partial cells). The fluid cells were filled with air, and the solid cells had the material characteristics of knitted fabric, the copper heating plate or both the knitted fabric and heating plate. The partial cells contained both solid material and air. In the 3-D geometric model of knitted fabric, the following physical parameters of polypropylene were applied: $\rho_{\text{PP}} = 890 \text{ kg/m}^3$, $\lambda_{\text{PP}} = 0.26 \text{ W/m} \cdot ^\circ\text{C}$, $c_{\text{PP}} = 1881 \text{ J/kg} \cdot ^\circ\text{C}$, and $\varepsilon_{\text{PP}} = 0.8$. The copper plate had the following characteristics: $\rho_{\text{Cu}} = 8900 \text{ kg/m}^3$, $\lambda_{\text{Cu}} = 390 \text{ W/m} \cdot ^\circ\text{C}$, $c_{\text{Cu}} = 380 \text{ J/kg} \cdot ^\circ\text{C}$, and $\varepsilon_{\text{Cu}} = 0.02$.

Figure 6. Three-dimensional model of polypropylene knitted fabric positioned on a heating plate located on the bottom of a computational domain of size $(10 \times 2.4 \times 2.2) \cdot 10^{-3} \text{ m}$.

Physical simulation using SolidWorks software allows for introduction of the following five physical phenomena: (1) heat conduction in a solid material (i.e., copper heating plate and fibres of the knitted structure), (2) convection and (3) radiation heat transfer from solid surfaces, (4) gravitational effects influencing air molecule transport within free spaces, and (5) laminar and turbulent fluid flow within void spaces.

Simulation results and discussion

The SolidWorks Flow Simulation module simultaneously calculates the parameters of all selected thermodynamic processes within the assumed structural domain. Based on the output results, the software creates three-dimensional colour visualizations in the form of cut plots (plots of cross-sections of selected objects). For the mentioned 3D model of monolayer polypropylene knitted fabric, the distribution of heat conductivity and heat radiation (as the most effective method of heat loss) were determined. Moreover, the distribution of temperature and air density can be visualized within the entire computational domain.

The temperature distribution in the knitted fabric, presented in Figure 7a, showed that the temperature difference in a propylene monolayer (as a thermal insulator) is approximately 0.35°C . The surface of the textile structure adjacent to the heating plate was in thermal equilibrium with the copper plate (30°C), while the upper surface was approximately 29.65°C .

According to the heat flux distribution presented in Figure 7b, the greater part of thermal energy was propagated in the stitch sections that have the most vertical direction. These sections are the best channels for the heat flow propagated from the plate to the environment because the ends of these segments are the link points of the greatest temperature difference in the knitted fabric. Inside of the heating plate, the heat flux is equal to zero, that is, thermal equilibrium is obtained in the entire volume. For the leaving radiant flux (described by Figure 7c), the largest portion of thermal energy was emitted from

the warmest part of the knitted fabric, in particular, parts in contact with the heating plate. According to Equation 8, which describes the heat radiation phenomenon, cooler parts of the knitted structure emit significantly less thermal radiation.

The distributions of air temperature and air density, presented, respectively, in Figure 7d and e, were characterized by a linear gradient of change. The air temperature decreases with height above the heating plate, and on the level of $10 \cdot 10^{-3}$ m (computational domain top), it achieves the value of 23.75°C .

Figure 7. Distributions of (a) temperature, (b) heat flux, and (c) leaving radiant flux in the knitted fabric, and two cut plots illustrating the (d) temperature distributions and (e) density of air contained in the computational domain.

Figure 8. Distribution of air temperature in computational domains with different heights: (a) $10 \cdot 10^{-3}$ m, (b) $20 \cdot 10^{-3}$ m, (c) $100 \cdot 10^{-3}$ m.

The air density increases linearly (from 1.16 kg/m^3 to 1.19 kg/m^3) above the heating plate. All obtained values were calculated using mesh guaranteed high accuracy level. Unreliability of computed parameters is as follows, temperatures of the knitted fabric and air: 0.5 %, air density: 1.5 %, heat flux density: 3.5 %, leaving radiant flux density: 0.2 %.

The main difficulty is in determining the proper height of the computational domain. To assess this parameter, we analysed the impact of three height values: $10 \cdot 10^{-3} \text{ m}$, $20 \cdot 10^{-3} \text{ m}$ and $100 \cdot 10^{-3} \text{ m}$ on the thermal parameters. The height of computational domain of knitted polypropylene fabric is not sensitive to temperature, heat flux density or leaving radiant heat flux. The obtained distributions were identical to those shown in Figure 7a, b, and c. This result is likely due to the significant differences between the knitted fabric thicknesses: height of computational domain ratios for the three cases, which are, respectively, 0.05, 0.025 and 0.005.

The impact of the three height values ($10 \cdot 10^{-3} \text{ m}$, $20 \cdot 10^{-3} \text{ m}$ and $100 \cdot 10^{-3} \text{ m}$) on temperature (Figure 8) and density distribution (Figure 9) was also analysed. According to Figure 8b, the initial air temperature (20°C) was determined at the height $20 \cdot 10^{-3} \text{ m}$,

while the minimum air temperature in the lowest computational domain ($10 \cdot 10^{-3} \text{ m}$, Figure 8a) was equal to 23.75°C .

The minimum value of air density (1.20 kg/m^3) was obtained at a height equal to $20 \cdot 10^{-3} \text{ m}$, Figure 9b.

The final goal was to analyse the sensitivity of the thermal properties of polypropylene knitted fabric to different layer numbers. Thus, models with two and three layers were created and compared for the mid-range computational domain height, $20 \cdot 10^{-3} \text{ m}$. The results were compared with the outcomes for the monolayer model, as shown in Figure 10.

The results presented in Figure 10, column (a) demonstrate that the two- and three-layer fabrics cause a temperature difference (between the upper and lower surfaces) of approximately 1.1°C and 1.7°C , respectively. The distributions presented in Figure 10, column (b) describe the heat flux density as gradually decreasing with the number of layers. This phenomenon is because thicker fabrics of this material (with a smaller number of layers) have a lower temperature difference between the lower and upper surfaces. Thus, increasing the number of layers within the textile structure reduces the heat flux density

Figure 9. Distribution of air density in computational domains with different heights: (a) $10 \cdot 10^{-3} \text{ m}$, (b) $20 \cdot 10^{-3} \text{ m}$, (c) $100 \cdot 10^{-3} \text{ m}$.

Figure 10. Distributions of thermal parameters for mono-, two- and three-layer polypropylene knitted fabric: temperature (column a), heat flux density (column b) and leaving radiant flux density (column c)

transported through the fabric. In the case of a single layer, the maximum heat flux density is approximately 200 W/m^2 . The radiation emitted by the knitted fabrics is presented in Figure 10, column (c). According to the theory of radiation, the highest radiation energy is emitted from the warmest layer of fabric (i.e., the lowest surface, radiation flux density of approximately 480 W/m^2), while the coolest top layer in three-layer knitted fabric emitted a radiation flux density equal to approximately 465 W/m^2 .

Generally speaking, multilayer knitted fabrics are heat isolators, but the basic heat transport parameters are not linearly dependent on the number of applied layers.

Conclusions

The primary goal of the current work was to describe and analyse the three-dimensional approach in SolidWorks software for modelling knitted fabric structures for future analysis of physical properties and thermal phenomena. This approach is based on detailed image analysis of a particular knitted fabric. The shape is modelled by approximating the fibre geometry by an average fibre thickness and single stitch shape. The model is consistently multiplied with respect to one stitch with smoothed connections between particular elements in horizontal and vertical planes. The advantage of this model is the ability to optimize parameters to adapt to the shape of real knitted fabric, which allows for the introduction of different forms of complex textiles. However, this model

includes a complicated structural geometry, which results in memory-consuming precise Finite Element description and time-consuming operational calculations. The results from this study demonstrate that SolidWorks software effectively describes the shape of knitted fabrics and can be applied to approximate other textile structures. The above description can also be introduced to determine the geometry of a wide variety of textiles, that is, woven fabrics of different weaves and nonwoven fabrics of repeatable structures. Additionally, the introduction of this approach into existing optimization procedures would be facile and could aid in visualization of obtained numerical results of optimal shape and material properties.

The SolidWorks approach introduces different phenomena during the heat transfer. Thus, steady heat conduction, convection and radiation can be determined within complex knitted fabrics as three basic different heat loss mechanisms. The steady-state heat transfer is relatively unique within real textiles. Thus, the existing description can be extended to transient problems that can help to solve more complicated cases with reference to commonly utilized applications. The next objective is the approximation of the SolidWorks environment within the coupled heat and mass transport within the structure. The main issue is to appropriately determine the mass diffusion.

Detailed analysis of heat transport problems can answer various questions and give instructive conclusions on future applications of analysed textiles, including material resistance to heat transfer

loading in point-wise contact between elements and inlayer structures connected by polymers. In summary, the SolidWorks approach appears to be an effective tool for determining the complex heat transfer phenomena in composite textiles.

Of course, the obtained results of temperature distribution can be verified using a set of sensors between particular layers of knitted fabrics. The next verification method can introduce the variational approach of shape optimization in order to determine the distribution of state variables. The space 3D problem can be reduced to the plane 2D cross-section by an optional plane perpendicular to the heating plate. Thus, the verification problem is beyond the scope of the paper presented and will be determined and discussed in the consecutive paper.

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