TEKSTİL VE KONFEKSİYON

VOL: 34, NO. 3
DOI: 10.32710/tekstilvekonfeksiyon.1299755

Dynamic Heat Transfer Simulation in Textile for Practical Application: A Comparative Analysis of Microscopic and Macroscopic Approaches

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ABSTRACT

Heat transfer simulation in textile materials has many practical applications, such as in the design of protective clothing for firefighters, the development of thermal insulation materials, and the optimization of temperature control in textiles for comfort and performance. This paper presents a study on heat transfer simulation in woven fabrics using the Comsol Multiphysics® application. The simulations were carried out for both microscopic (3D) and macroscopic (1D) scales and the heat flux variation was compared with experimental results. The steady-state average heat flow through the textile was determined, and this value was used to calculate the thermal resistance of the woven fabrics. The thermal resistance values obtained were within a deviation range of 4.2% to 6.3% from the values determined according to ISO 11092/1016, thus validating the proposed model. For the transient regime, the microscopic approach proved to be more accurate, the estimated time for the heat flow to reach a certain value depending essentially on the scale approached in the modeling. This finding has particular significance in the field of protective clothing, especially for firefighters exposed to radiant heat sources, where estimating the time for burns to occur is crucial.

ARTICLE HISTORY
Received: 20.05.2023
Accepted: 18.01.2024

KEYWORDS
Textiles, simulation, heat transfer, thermal resistance

1. INTRODUCTION

Clothing is the interface between the human body and the environment, with the main role of ensuring the thermal protection of the wearer. The heat-related characteristics of textiles play a crucial role in determining the level of thermal comfort they provide, and, over time, many standard properties have been defined to characterize the heat transfer capacity of textiles. Heat exchange between the human body and environment throughout the clothing system takes place under dynamic conditions and these standardized properties are not sufficient for the characterization of textiles in terms of heat transfer, especially in thermal protective clothing and sportswear during intense physical activity and/or special environmental conditions (e.g., high temperature and thermal radiation). Modeling and simulation are methods that can cover this dynamic behavior issue [1].

Heat transfer simulation in textile materials is an active area of research that aims to understand and optimize the thermal performance of textiles [2]. Overall, heat transfer simulation in textiles is advancing rapidly, providing valuable insights into the thermal performance of textiles and leading to the development of more efficient products [3].

Torvi [4] was the first to develop and validate a significant model for textile heat transfer, specifically for testing fabrics at high temperatures and open flame. The one-dimensional physical model considered the textile material homogeneous and the mathematical equations accounted for heat transfer through conduction and radiation. Mell and Lawson [5] then used the Torvi model but incorporated multilayer textile structures for protective clothing for firefighters. Gibson [6] proposed a model in which the textile material was treated as a hygroscopic porous medium, coupling mass, and heat transfer according to

To cite this article: Codau E, Codau T C, Chivu R M. 2024. Dynamic heat transfer simulation in textile for practical application: a comparative analysis of microscopic and macroscopic approaches. *Tekstil ve Konfeksiyon*, 34(3), 275-282.

Whitaker's theory. The proposed mathematical model accounted or the conservation of momentum and energy as well as the continuity equation. Prasad [7] developed a detailed mathematical model for studying non-stationary heat and moisture transfer through multilayer fabric assemblies, considering the presence of air gaps and the changes in thermodynamic and transport properties due to the presence of water. The model was solved using the Runge-Kutta approximation method and compared favorably to experimental measurements. More recently, Łapka [8] presented a complex mathematical model that accounted for the interaction between protective clothing for firefighters and human skin, incorporating heat transfer through conduction and radiation, as well as the diffusion of water vapor through porous media.

The mathematical models outlined earlier describe the system using global equations that do not consider the thermal interaction between the fluid and solid components within the textile structure. Over the last decade, recent advancements in simulation software have made it possible to reduce the computational resources required for these simulations. Currently, two approaches are highlighted in the simulation of heat and mass through porous materials, depending on the model scale: microscopic or macroscopic. Each of these two model types comes with its working assumptions that directly influence the accuracy of the results and the costs of simulation. However, the comparisons between the values from the macroscopic scale simulation and the experimental results revealed substantial differences in the transitory area (dynamic regime) for temperature, heat flow, etc. [9]. These differences are of particular importance in critical applications such as firefighting interventions, for steel workers exposed to fire and very high temperatures, etc.

In this paper, the Finite Element Method (FEM) has been used to simulate the heat transfer over textiles at the microscopic and macroscopic scales.

2. THEORETICAL CONSIDERATION

Porous materials facilitate heat transfer through two mechanisms: the solid matrix and the fluid in the voids. Heat is transferred through the solid matrix via conduction, while the transfer through the fluid occurs through conduction, convection, and radiation.

Thermal conduction is a process of transferring heat within a thermodynamic system or between systems that are in thermal contact, and it occurs due to direct molecular interactions without involving mass transfer. The equation for conduction heat transfer was derived by Fourier in 1882 and can be expressed as [10]:

$$\frac{\partial T}{\partial t} = \frac{1}{C_p \cdot \rho} \cdot k \cdot \nabla^2 T \qquad (1)$$

where: k is thermal conductivity, ρ - density, C_p - thermal capacity, T - temperature, t - time variable, and $\Delta^2 T$ - divergence of gradient temperature (Laplace operator).

Radiation heat transfer occurs through electromagnetic waves and involves wavelengths ranging from 0.1 µm (ultraviolet) to 100 µm (infrared). The relationship between emitted energy and the temperature was established experimentally by Jozef Stefan and theoretically by Ludwig Boltzmann, utilizing the abstract concept of the black body [11]:

$$E_b = \varepsilon \cdot \sigma \cdot T^4 \qquad (2)$$

where: E_b is the energy emitted in unit time, per unit area, T - the temperature, σ - Stefan-Boltzmann constant, and ε - the emissivity coefficient.

Radiative heat transfer is a property of the surface that is influenced by temperature, optical properties, and surface orientation. To determine the effect of surface orientation, a *shape factor* was introduced. Although it is impossible to calculate shape factors within the voids of natural porous materials, Song [12] concluded that radiative heat transfer can be disregarded in textiles due to the very small dimensions of the voids between structural components (yarns/fibers).

Convection is the mechanism of heat transfer associated with fluid mass transport. When the flow lines are parallel there is a laminar flow, otherwise, it is a turbulent flow. The law of thermal convection was deduced by Newton and has the form:

$$\frac{\dot{Q}}{S} = h_t \cdot (T_s - T_\infty) \qquad (3)$$

where: ${}^{\dot{Q}}/_{S}$ is heat flow, h_t - the thermal convection coefficient, T_∞ - the bulk fluid temperature, and T_s - the border temperature.

The convection coefficient includes all the factors on which the heat transfer depends on the fluid properties, surface geometry, and flow type [13]. In most cases, this coefficient is impossible to be calculated or experimental determined. For that reason, the similarity and boundary layer theory is necessary.

Free convection is governed by a non-dimensional number called the *Rayleigh number, Ra*:

$$Ra = \frac{\rho^2 \cdot g \cdot \beta \cdot C_{p,a}}{\mu_a \cdot k_a} \cdot L_{ch}^3 \cdot \Delta T \qquad (4)$$

where: g is gravitational acceleration, β - the coefficient of thermal expansion, ΔT - the difference between surface temperature T_s and bulk temperature T_∞, L_{Ch} - the characteristic length, v - the kinematic viscosity, μ_a - the dynamic viscosity of air, $C_{p,a}$ - the specific heat, and k_a - the thermal conductivity.

In the case of textile structures, calculating the characteristic length can be challenging, but considering a channel that is tangentially confined by the warp and weft yarns, the characteristic length can be substituted with the equivalent hydraulic diameter, dh [14]:

$$d_h = \frac{4 \cdot A}{C_s} \tag{5}$$

where A is the area of the channel section and C_s is the perimeter of the section.

3. MATERIAL AND METHOD

3.1 Material

All textile materials used in this study are woven fabrics, each with the same composition in the warp and weft systems. The woven fabrics were selected taking into account the importance of these materials in applications such as fire protection clothing.

The thermal conductivity and specific heat capacity were measured with the *Hot disc* technique in compliance with the standard ISO 22007-2/2008. The thermal resistance of the fabrics was determined using the *Sweating guarded hot plate*, in compliance with the standard ISO 11092/2016. Fabric thickness was tested with a *Digital Thickness Gauge* SDL Atlas according to ISO 5084/1996 and for surface weight, an electronic balance was used. The thermal properties of the fabrics determined according to these standards are shown in the first table from the *Results and Discussion* section and are used in the 1D (macroscopic) simulation of heat transfer.

To simulate the heat transfer through textile materials at the microscopic level, the properties of the yarns were performed directly in Comsol® starting from those of the fibers (listed in Table 1) and their composition. The equivalent thermal conductivity of the yarns, k_{ech}, was calculated with the following relation [15]:

$$k_{ech} = \sum \theta_i \cdot k_i + \varepsilon_y \cdot k_{fluid} \tag{6}$$

where k_i, are the thermal conductivity of fibers, Θ_i the volume fraction of fibers, ε_y - the yarn porosity and k_{fluid} - the thermal conductivity of the fluid.

The volume fraction of fibers can be written as:

$$\Theta_i = \frac{\rho_y}{\rho_i} \alpha_i \tag{7}$$

where ρ_i is the density of the fibers, α_i – the mass fraction of fibers (from Table 1), and ρ_y – the density of the yarn.

The density of the yarn was determined from the following equation:

$$\rho_y = \frac{Yarn\ linear\ density}{Yarn\ cross-section\ surface} \tag{8}$$

The porosity of the yarn can be found from the following relation:

$$\sum \theta_i + \varepsilon_y = 1 \tag{9}$$

Table. 1. Fiber properties [16] [17]

Fibers	Density	Thermal conductivity	Heat capacity
	g/m^3	W/(m·K)	J/(kg·K)
Nomex®	1380	0.25	1256
Kevlar®	1440	0.04	1420
PBI	1300	0.41	1130
Viscose	1530	0.289	1590
PA-antistatic	1070	0.21	1700

3.2 Method

3.2.1. Heat transfer simulation

The software used in the simulation is Comsol Multiphysics®, which is a cross-platform software that allows the modeling and simulation of physical processes based on FEM [18]. FEM is the most widely used method of solving engineering problems including structural analysis, heat transfer, fluid flow, or mass transport [19]. Comsol Multiphysics® has a large number of modules that allow solving engineering or scientific problems, with the possibility of coupling these modules. Due to the predefined models, the simulation is much easier. The emphasis is on the physical quantities and there is no need to define new equations.

In this paper, Comsol Multiphysics® has been used to simulate the heat transfer in textile structures at the macroscopic and microscopic scales. The macro-scale simulation was performed under the assumption that the fabrics are homogeneous and isotropic materials for which the global properties are obtained by standard methods (Table 2). For the microscopic level simulation, the 3D geometric models and the yarns property were considered. The heat transfer mechanism through the woven fabrics takes place mainly by conduction. A very small order of magnitude of the Rayleigh number obtained directly in Comsol® for fabrics from Table 2 under ISO 11092/2016 conditions, confirms that the thermal convection can be neglected. To estimate *Ra*, Equation 4 and the air properties stored in the material library were used.

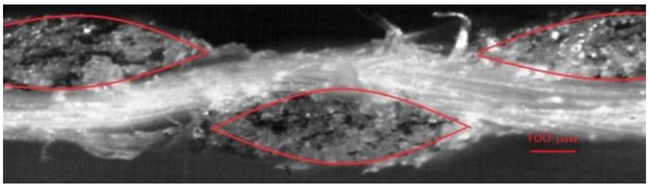
3.2.2. 3D model of the textile structure

To accurately simulate the heat transfer through textiles, a geometric model close to the actual fabric structure is necessary. Ideal yarn is assumed to have a circular cross-sectional shape, but due to the mechanical stress in the weaving process and the interlacing of the yarns, the shape of the cross-section of yarn is flattening. To take into account this effect, Pierce [20] modified his circular model, introducing an elliptical shape. Later, Kemp [21] proposed a new cross-section model, a rectangular geometry with two circular shapes at the ends that is more suitable for jammed configuration. A lenticular geometric cross-section shape was proposed by Hearle, in 1978 [22].

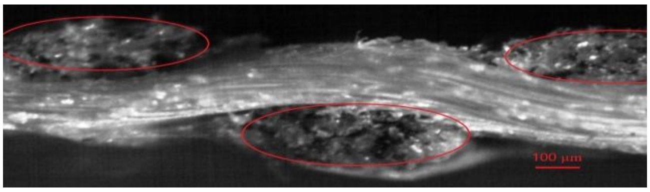
Another aspect to be considered in the geometric model is the yarn path of both the weft and warp systems. The path of the yarns is related to the yarn density (yarns/cm) and cross sections of the yarns from the other system and was described by the same researchers who developed the cross-sectional models. Even if the lenticular geometry is the most widespread cross-section of the yarn in woven fabrics, the path and the cross-section shape depend on many technological factors such as yarn twist, mechanical stress, yarn density, etc.

In order to have a higher accuracy of the 3D model, microscopic analysis was used. Thus, the geometrical parameters of yarns in the fabrics were acquired by using a Magnum Ceti Binocular microscope.

A very clear cross-sectional image of the woven fabric is difficult to obtain. When the fabric is cut, the fibers are withdrawn from the yarn which makes it difficult to obtain a clear and real cross-section. To avoid this problem the fabrics were coated before cutting with an acrylic binder without applying pressure. For example, Figure 1 shows the cross-sectional image of S1 and S2 fabrics. The yarns of the S1 structure (Figure 1a) have a lenticular cross-section, while S2 (Figure 1b) have elliptical cross-section yarns.



a) S1-lenticular cross-section yarns



b) S2- elliptical cross-section yarns

Figure 1. Micrograph cross-section of woven fabrics

The geometric parameters were obtained by processing the images by ImageJ software [23]. The parameters have been used to design the geometric model of the textile structure for each woven fabric in TexGen®.

TexGen® is an open-source software under the General Public License developed at the University of Nottingham for modeling textile structures [24]. To generate each yarn in TexGen® it was used a two-dimensional shape that swept along a path. The cross-section of yarns can be defined as an ellipse, lenticular, rectangle, or hybrid shape and can be constant along the path or different for each node. After creating the geometric model, TexGen® allows exporting it as an IGES file to Comsol Multiphysics®. Figure 2 shows the image of the S1 fabric and the corresponding geometrical model.

Figure 2. S1 woven fabric structure and 3D geometrical model

3.3. Experimental devices

To find out the experimental values of the heat flow through fabrics the device from Figure 3 was used.

The constant temperature of the lower border is provided by a calorimeter connected to a *Julabo* thermostatic bath while at the upper border, there is a radiator with a high dissipation power. The heat flux is monitored with a Captec flow sensor and the temperature is measured by the Omega type E thermocouples. Professional precision spacers are used to avoid changing the thickness of the textile material. The data obtained from the sensors are collected by the Data Acquisition System, DAQ Keithley 2700, taken over by a computer, and processed in Excel.

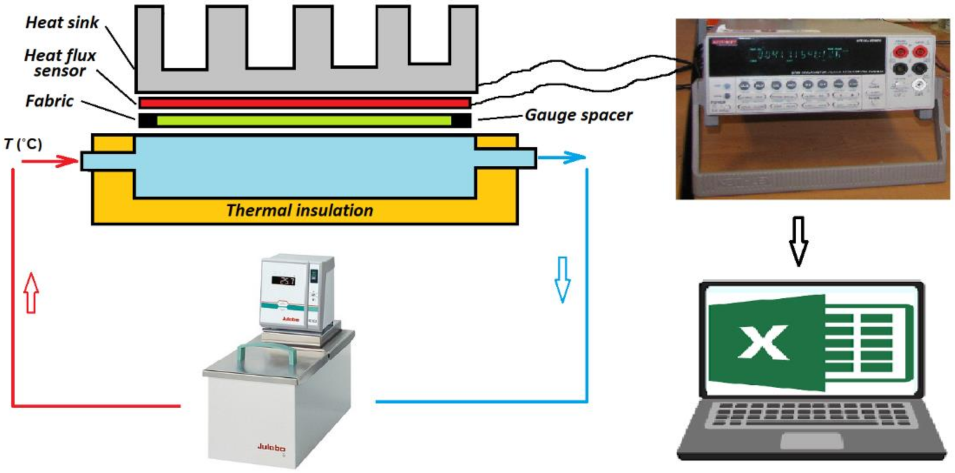


Figure 3. Experimental device to measure heat transfer through textile materials

4. RESULTS AND DISCUSSION

Table 2. gives the characteristics and thermal properties of the fabrics used in this study.

Table 2. The characteristics and thermal properties of woven fabrics

	Symbol	S1	S2	S3	S4	S5
Properties		93% Nomex® 5% Kevlar® 2% PA (antistatic)	40% PBI 58% Kevlar® 2% PA (antistatic)	95% Nomex® 5% Kevlar®	93% Nomex® 5% Kevlar® 2% PA (antistatic)	50% Viscose 47% Nomex® 2% Kevlar® 1% PA (antistatic)
	Units	Plain-weave	Plain-weave	Plain-weave	Plain-weave	Plain-weave
Yarn-linear density, T_t	tex	55	45	20	20	20
Warp/Weft density	yarns/cm	21/21	19/19	38/38	32/29	26/23
Warp/Weft yarn spacing	mm/mm	0.476/0.476	0.526/0.526	0.263/0.263	0.312/0.344	0.384/0.434
Surface weight	g/m^2	242	211	150	110	130
Density	kg/m^3	562	527	441	423	433
Thickness	mm	0.43	0.40	0.34	0.26	0.30
Thermal conductivity	W/(m·K)	0.1154	0.2122	0.1074	0.1073	0.1142
Specific heat capacity	J/(kg·K)	951	655	1026	964	1184
Thermal resistance	(m^2·K)/W	0.0129	0.0115	0.0105	0.0085	0.0097

To validate the 3D model of each fabric from Table 2, the thermal resistance, Rct, determined according to ISO 11092/2016 was compared with the value obtained by simulation at steady-state. The results are shown in Figure 4. The boundary conditions used in the simulation are the same as the standard ones: the lower side temperature, Tm, is 35 °C, the upper side temperature, Ta, is 20 °C, and the relative humidity RH of 65 %.

By definition, thermal resistance is defined as the ratio of the temperature difference between the two faces of a material to the heat flow:

$$R_{ct} = \frac{\Delta T}{\Phi} \qquad (10)$$

The thermal resistance values obtained from the microscopic simulation in Comsol® are local values because they depend on the point where the calculation was performed. However, to compare with the experimental results, global values are required. These values were obtained by using averaging functions provided by Comsol® and are related to the surface integral over a 2-dimensional domain.

It is noted that the values resulting from the simulation are close to the standard measurements, proving a good agreement between the predicted and experimental data. The correlation coefficient calculated between the two data sets is 0.999, which indicates a very good correlation. However, the predicted thermal resistance is lower than the experimental values within a deviation range of 4.2% to 6.3%. The reason behind these differences is given by the assumptions taken into account when the geometric model was created. Actually, the thermal conductivity of the yarns is lower than the calculated values due to their microporous nature. There is an important factor that influences the thermal conductivity of the yarns, namely the contact surface between the fibers, and it is related to the technological parameters.

To highlight the importance of the model scale in the simulation of heat transfer, two approaches were considered: microscopic and macroscopic scales at transient conditions. The simulations were performed for the fabrics and the results were compared with experimental determinations. The boundary conditions were those stipulated in ISO 11092/2016, while the initial temperature of the sample was 20 ºC with a relative humidity R.H. of 65 %.

As can be seen in Figures 5.a. and 5.b., the intermediate values of heat flow on 3D simulation have also a non-uniform distribution, and therefore an averaging value must be calculated with the surface integral of the local heat flow divided by the total surface value.

The experimental values were obtained under the same initial and boundary conditions using the device from Figure 3. The transient heat flow is similar for all studied samples. An example for the fabric S1 was provided to highlight distinctions between the micro and macro-scale approaches in dynamic simulation scenarios (Figure 6). The differences between the simulated and experimental data are shown in Figure 7.

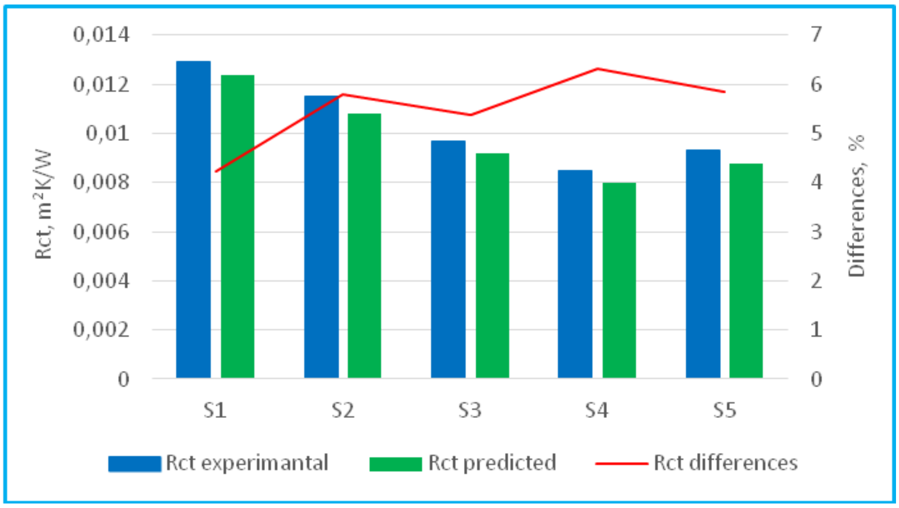


Figure 4. Comparison of predicted thermal resistance with experimental results

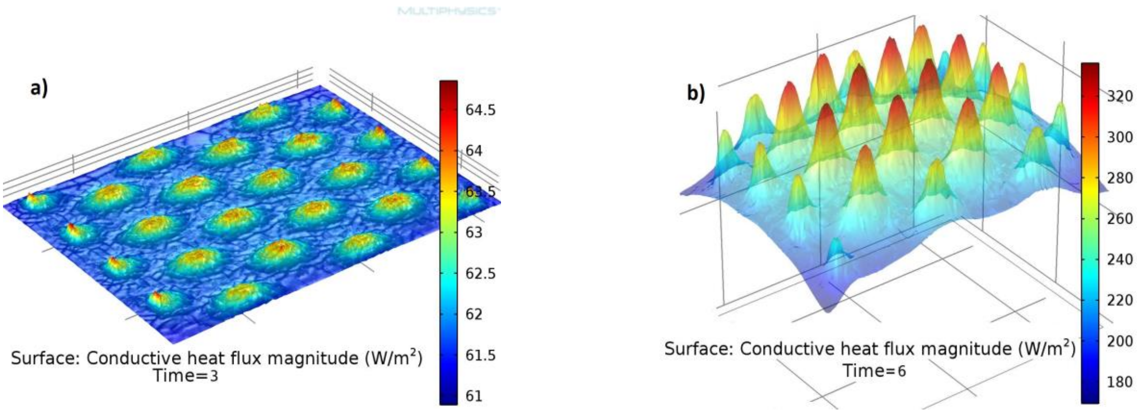


Figure 5. 3D distribution of heat flow simulated for S1 fabric after 3s (a) and 6s (b), respectively.

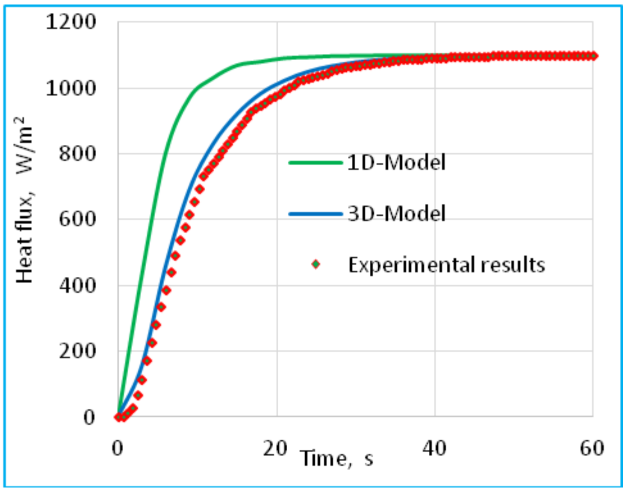


Figure 6. The experimental and simulated values of heat flow for the S1 fabric

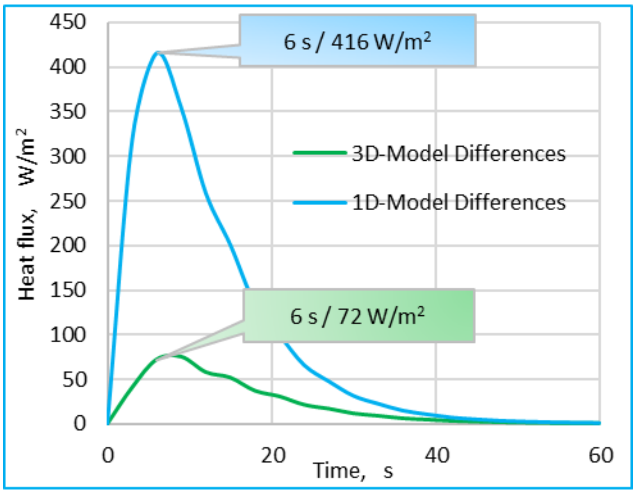


Figure 7. Heat flux differences between the experiment and simulation for the S1 fabric

The heat flux, for both simulation scales, shows values very close to the experimental data at steady-state, while in the transition area, substantial differences are observed. These differences are given by the rate of flux variation passing through the fabric reported to the time unit (the first derivative). From the 1D modeling, it can be concluded that the textile material would have a lower "thermal inertia" than in reality. For example, the 1D simulation estimates that the heat flow through the textile material reaches the value of 1000 W/m^2 in about 10 s, while the 3D modeling estimates 20 s, which is very close to the experimental value of 21.5 s. Thus, the 3D model can reproduce more faithfully the behavior of the textile material in the case of transient heat transfer because the results are much closer to the experimental data. Accurately, estimating the dynamic heat transfer performance is crucial on firefighter clothing because heat flux and exposure time are closely related to the degree of burns that the human skin can suffer. Stoll and Chianta [25] have quantified the reaction of human skin (second-degree burns) based on the thermal flux received by the human body and the time of exposure.

5. CONCLUSION

Using the Comsol Multiphysics® software, the heat transfer simulation through woven fabrics was performed for both microscopic (3D) and macroscopic (1D) scales. At steady-state, the heat flow through the 3D textile model has a relatively constant value and it was used to determine the thermal resistance of the woven fabrics. The values obtained have a deviation between 4.2 % and 6.3% from the thermal resistance of the fabrics determined according to ISO 11092/2016. Thus, the 3D model was validated with the experimental results and a good correlation was found at steady-state.

The heat flux variation for both micro and macro-scale simulations was compared also on transient conditions. Although, the microscopic and macroscopic approaches do not show significant differences in terms of heat transfer at steady-state, for the transient area the micro-scale modeling provides more accurate results. Usually, in the textile field, the microscopic approach has not been widely used due to the very large hardware resources required but is of particular interest in the design of protective clothing for firefighters, the development of thermal insulation materials, and the optimization of temperature control in textiles for comfort and performance. For such applications, the use of accurate modeling justifies the necessary software resources, especially since the current technological advance has led to a large decrease in simulation costs.

The future research will focus mainly on:

- Carrying out simulations for high and very high heat flows and comparing the results with the experimental ones carried out within the standard EN ISO 6942:06/2002.
- Performing the mass transfer simulation through textiles and coupling the mass transfer with heat transfer that occurs simultaneously.
- Parameterization of geometric models to optimize complex textile structures in terms of heat and mass transfer.

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