Computer Simulation of Heat Exchange Through 3D Fabric Layer

Aušra Gadeikytė[(✉)] and Rimantas Barauskas

Department of Applied Informatics, Kaunas University of Technology, Studentu Str. 50-407, 51368 Kaunas, Lithuania
{ausra.gadeikyte,rimantas.barauskas}@ktu.lt

Abstract. In this study the mathematical model of coupled problem of fluid flow and heat transfer through 3D polypropylene textile layer at micro-scale is presented. The purpose of the study is to investigate the influence of the fabric structural pattern on the heat resistance between human skin and the outer environment. The heat transfer mechanism includes the heat conduction of the solid fabric structure, as well as the convective heat transfer by means of the air and water vapor flow through the structure. The finite element model was created by using COMSOL Multiphysics software. The simulation results are analyzed to verify heat transfer properties, which make influence on the wearing comfort of the clothes. Simultaneously, the heat conduction, air and water vapor permeability and other important parameters used for the fabric properties characterization at macro-scale can be obtained on the base of the micro-scale analysis results.

Keywords: 3D fabric layer · Heat exchange · Finite element
COMSOL Multiphysics

1 Introduction

The aim of this work is to investigate the influence of 3D polypropylene textile layer on the heat loss between human skin and the fabric. Polypropylene is widely used in products such as plastic parts, carpeting, reusable products, paper, laboratory equipment, technology, thermoplastic fiber reinforced composites, etc. [5]. Polypropylene does not absorb moisture, has high heat resistance and is mechanically flexible. One of the important challenges for clothing designers is to ensure the wearing comfort by providing necessary thermal and moisture concentration balance at the human skin surface referred to as the microclimate layer [2].

In the recent decades various aspects of heat exchange have been investigated. Heat transfer by conduction and radiation has been well understood and documented. The heat transfer by convection through porous media layer is not straightforward as there is no exact solution to this heat transfer problem. Most of the solutions are approximate or based on empirically obtained very

simplified models [4,11]. The heat resistance of a fabric can be determined by applying the standard hot plate chamber experiment. The heat power necessary for maintaining the prescribed steady temperature value of the hot plate covered by the fabric sample is measured during the experiment [3]. Bhattacharjee et al. [4] used computational fluid dynamics (CFD) software for obtaining the equivalent heat transfer coefficient of the fabric under natural and forced heat convection by simulation. Alptekin et al. [1] numerically simulated 1D coupled transient heat transfer inside multi-layer firefighter protective clothing and skin layer. Dennis et al. [6] numerically simulated the time relationships of head and neck cooling with local tissue properties. They presented the 3D head-cooling helmet model. The surface convection boundary conditions were used in the regions where the helmet would contact the head. The tissue perfusion has been neglected in the model, and the heat transfer coefficient as h = $25\,\mathrm{W/m^2\,^\circ C}$ has been derived from real data. Verleye et al. [10] investigated the fluid flow through the woven structure, where the flow through air pores and around the yarns was considered. Generally, the flow through textiles is governed by the Navier-Stokes equations in the fluid domain and by the Brinkman equations in the porous domain. Venkataraman et al. [9] modelled the insulation behavior of nonwoven fabrics without and with aerogel. The heat transfer mechanism was simulated by using ANSYS and COMSOL Multiphysics finite element software. However, more precise theoretical investigations of heat exchange through 3D polypropylene fabric layer are not straightforward due to coupled heat and mass transfer and other physical processes, complex internal structure, unknown material properties which should be obtained from micro-scale analysis [2].

In this paper the finite element model of heat exchange through the 3D polypropylene textile layer at micro-scale was investigated including heat conduction through solid structures of the textile, heat convection due to the flow of air and water vapor. Numerical simulations were used to evaluate the heat flux and temperature distribution in the fibrous insulating material by using COMSOL Multiphysics software.

2   Methodology

2.1   Governing Equations

The air flow was modelled by Navier-Stokes equations in the free flow spaces of the textile structure and by Brinkman equations in the porous parts of the structure. The Navier-Stokes momentum equation reads as

$$0 = \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)],$$

and is solved together with the continuity equation as

$$\rho \nabla \cdot \mathbf{u} = 0, \tag{1}$$

where ∇ is the gradient operator, $\mathbf{u}$ is the fluid flow velocity, ρ is the fluid mass density, p is the fluid pressure, μ is the fluid dynamic viscosity, $\mathbf{I}$ is the identity matrix.

The Brinkman equation for steady-state in the porous media flow reads as

$$0 = \nabla \cdot [-p\mathbf{I} + \frac{\mu}{\epsilon_p}(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] - (\mu\kappa^{-1} + \frac{Q_{br}}{\epsilon_p^2})\mathbf{u},$$

$$\rho\nabla \cdot \mathbf{u} = Q_{br}, \tag{2}$$

where ϵ_p- constant porosity, κ- permeability. For zero mass source ($Q_{br} = 0$) the equation of continuity, Eq. 2 reduces to Eq. 1.

For a homogeneous fluid region, the governing heat transfer equation is expressed as

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q,$$

$$\mathbf{q} = -k\nabla T,$$

where C_p- specific heat capacity, Q- overall heat transfer, k- thermal conductivity of fluid. In porous media

$$\mathbf{q} = -k_{eff}\nabla T$$

where $k_{eff} = \theta_p k_p + (1 - \theta_p)k$ is effective thermal conductivity of the fluid-solid mixture, k_p is the thermal conductivity of the porous medium and θ_p is the volume fraction.

2.2   Finite Element Model

We developed three finite element models to analyze heat exchange mechanism in 3D textile layer at micro-scale. All models include two porous media domains which are 1.4 mm × 1.4 mm × 1 mm in length (x direction), width (y direction) and height (z direction) (see Fig. 1). In model 1 air domain is 1.4 mm × 1.4 mm × 6.3 mm in length, width, and height. In model 2 and model 3 the air domain is 1.4 mm × 1.4 mm × 5.3 mm in length, width, and height. The initial material properties of air and polypropylene are given in Table 1. The boundary conditions of heat transfer in porous media and the boundary conditions of free and porous media flow used in the three models are shown in Fig. 1. Model 1 simulates the heat transfer in porous media driven by the change of temperature from T = 37 °C at the human skin to the ambient temperature T = 20 °C at the opposite surface of the model. Model 2 presents the situation when convective heat flux from the human skin is given as a boundary condition. In Model 3 the heat source boundary condition at the human skin was employed.

Table 1. The characteristics of air and polypropylene at T = 20 °C [7,8]

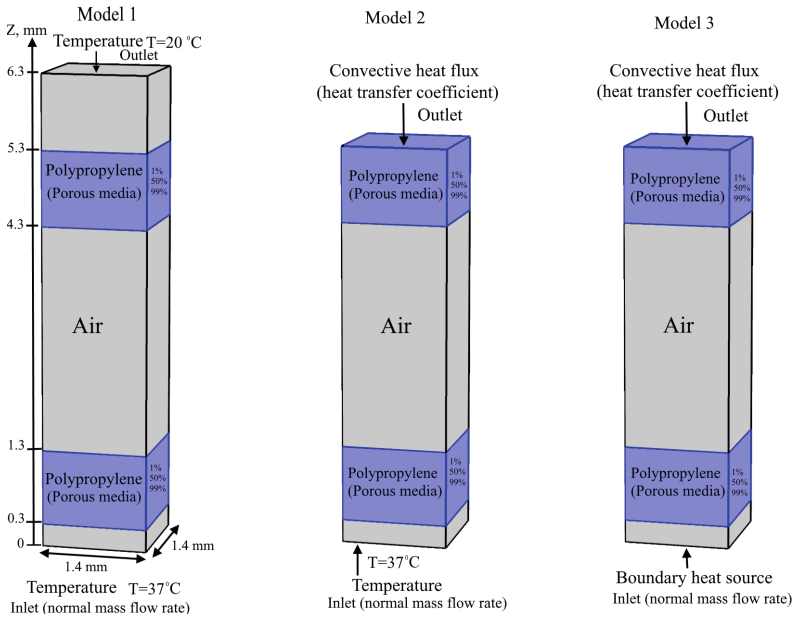| Material	Density kg · m^{-3}	Thermal conductivity W/(m · K)	Dynamic viscosity kg/(m · s)	Specific heat J/(kg · K)
Air	1.2047	0.0256	$1.8205 \cdot 10^{-5}$	1006.1
Polypropylene	900	0.22	–	1700

Fig. 1. Model 1, Model 2, Model 3 geometry and boundary conditions

3   Numerical Results

All three Models were constructed using the laminar flow mode combined with heat transfer in porous media flow mode. Model 1 presents the heat exchange process at constant temperature of skin (heating plate). Figure 2 shows the temperature distribution along Oz when porosity is 1%, 50% and 99% correspondingly. Figure 3 presents the dependencies of the temperature distribution along Oz where the heat transfer coefficient was varied from $h = 20$ W/m^{2}K to $h = 25$ W/m^{2}K at porosity 99%.

Model 1 and Model 2 are comparable when $h = 25$ W/m^{2}K (without normal mass flow rate m $= 0$ kg/s) and $h = 22$ W/m^{2}K (with normal mass flow rate m $= 1.5092 \cdot 10^{-8}$ kg/s). In our opinion, the assumed value $h = 25$(W/m^{2}K) of the surface convection coefficient could be regarded as realistic basing on previous works of several researchers [6]. At porosity value 50% the same heat transfer coefficient values ($h = 25$ W/m^{2}K and $h = 22$ W/m^{2}K) were obtained (Fig. 4).

In model 3 we applied the surface convection coefficient value 22 W/m^{2}K at normal mass flow rate m $= 1.5092 \cdot 10^{-8}$ kg/s. Figure 5 demonstrates temperature distribution and z position dependencies on general source Q. Model 1 and Model 3 are comparable when general source Q varies from 41 W/m^2 to 42 W/m^2.
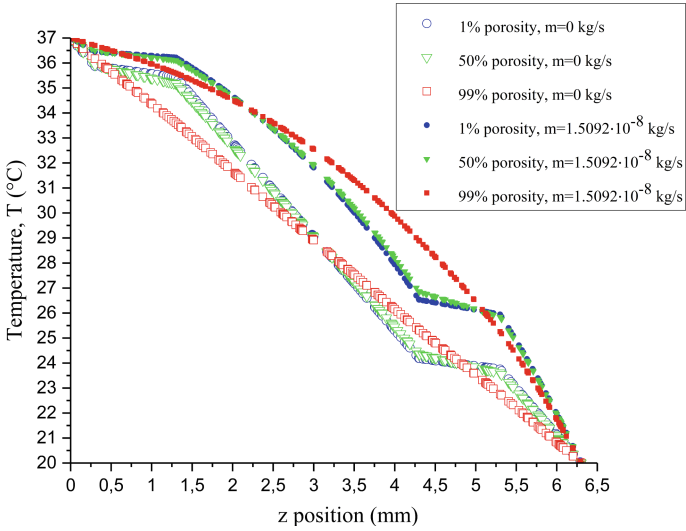
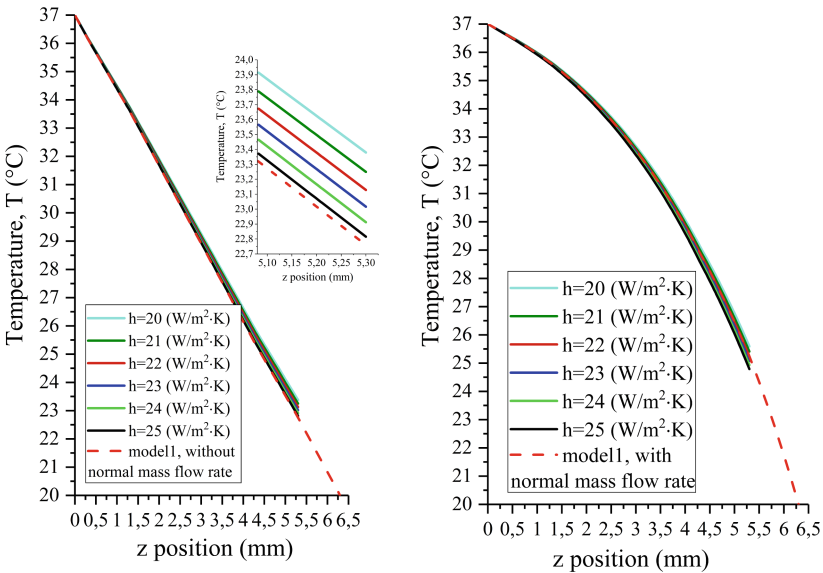**Fig. 2.** Temperature distribution along Oz in Model 1, normal mass flow rate m = 0 kg/s, m = $1.5092 \cdot 10^{-8}$ kg/s

Fig. 3. Temperature distribution along Oz in Model 2, normal mass flow rate m = 0 kg/s, m = $1.5092 \cdot 10^{-8}$ kg/s, porosity 99%
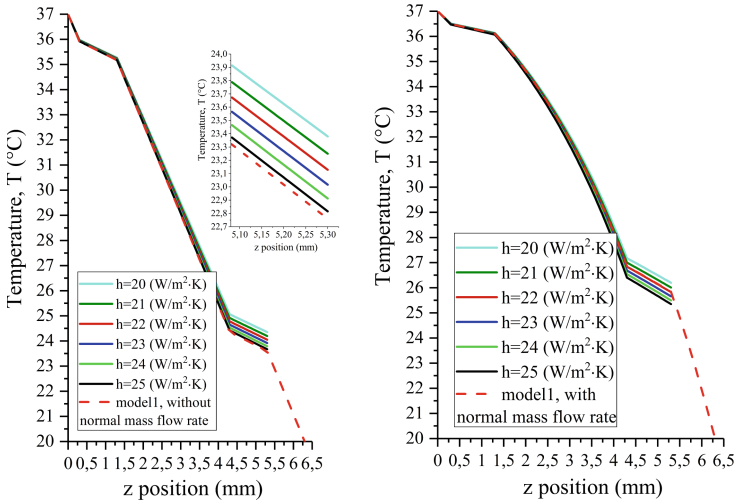
Fig. 4. Temperature distribution along Oz in Model 2, normal mass flow rate m = 0 kg/s, m = 1.5092 · 10^{-8} kg/s, porosity 50%

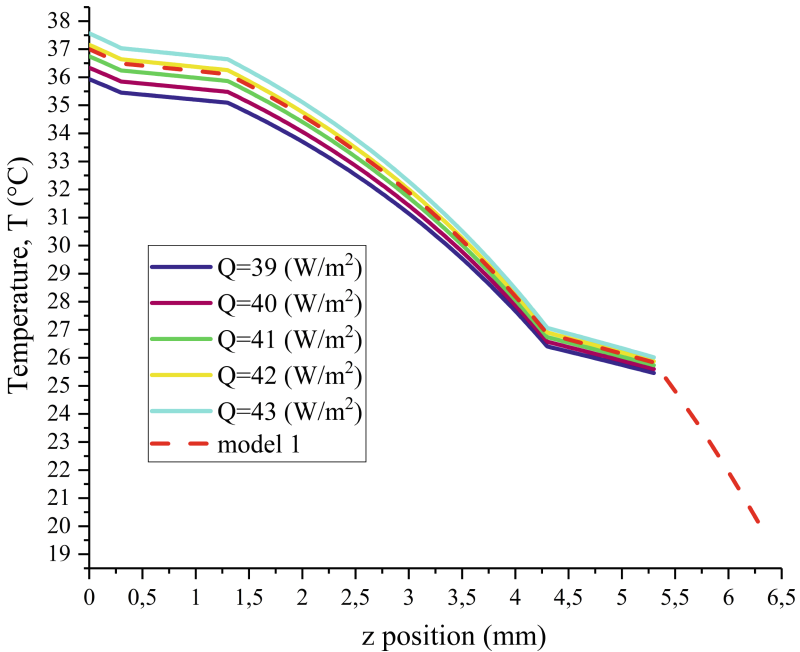**Fig. 5.** Temperature distribution along Oz in Model 3, normal mass flow rate m = 1.5092 · 10^{-8} kg/s, porosity 50%, heat transfer coefficient h = 22(W/m^{2}K)

4   Conclusions and Future Work

Computer simulations of heat exchange were carried out through 3D polypropylene textile layer by COMSOL Multiphysics software. The simulation results showed that Model 1, Model 2 and Model 3 can provide similar results when using appropriate boundary conditions.

The comparison of the results among the three models provided a certain background for obtaining the reasonable types of the boundary conditions and the values of the heat transfer coefficients. Skin (heating plate) temperature $T = 37$ °C (Model 1) approximately corresponds to the surface heat generation power density as 41–42 W/m^2 (Model 3). From the results provided by Model 2 we obtained that the value of the surface convection coefficient h $= 22$ W/m^{2}K could be regarded as reasonable. As a structure, Model 3 is the most realistic model which presents heat exchange between human skin and 3D textile layer at micro-scale.

Further research is to investigate convective heat transfer and the effect of polypropylene geometry structure (pore sizes) in Model 3.

References

1. Alptekin, E., Ezan, M.A., Gül, B.M., Kurt, H., Ezan, A.C.: Numerical investigation of thermal regulation inside firefighter protective clothing. Tekstil ve Mühendis **24**(106), 94–100 (2017). https://doi.org/10.7216/1300759920172410606
2. Barauskas, R., Abraitiene, A.: A model for numerical simulation of heat and water vapor exchange in multilayer textile packages with three-dimensional spacer fabric ventilation layer. Text. Res. J. **0**(00), 1–21 (2010). https://doi.org/10.1177/0040517510392468
3. Barauskas, R., Sankauskaite, A., Abraitiene, A.: Investigation of the thermal properties of spacer fabrics with bio-ceramic additives using the finite element model and experiment. Text. Res. J. **88**(3), 293–311 (2018). https://doi.org/10.1177/0040517516677228
4. Bhattacharjee, D., Kothari, V.K.: Prediction of thermal resistance of woven fabrics. Part II: heat transfer in natural and forced convective environments. J. Text. Inst. **99**(5), 433–449 (2008). https://doi.org/10.1080/00405000701582596
5. Creative Mechanisms Homepage. https://www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic. Accessed 30 Apr 2018
6. Dennis, B.H., Eberhart, R.C., Dulikravich, G.S., Radons, W.: Finite-element simulation of cooling of realistic 3-D human head and neck. J. Biomech. Eng. **125**(6), 832–840 (2003). https://doi.org/10.1115/1.1634991
7. Global Supplier for Materials Homepage. http://www.goodfellow.com/E/Polypropylene.html. Accessed 1 June 2018
8. University of Waterloo Homepage. http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html. Accessed 1 June 2018
9. Venkataraman, M., Mishra, R., Militky, J., Behera, B.K.: Modelling and simulation of heat transfer by convection in aerogel treated nonwovens. J. Text. Inst. **108**(8), 1442–1453 (2017). https://doi.org/10.1080/00405000.2016.1255124

10. Verleye, B., Klitz, M., Crose, R., Roose, D., Lomov, S., Verpoest, I.: Computation of permeability of textile reinforcements. In: Proceedings, Scientific Computation IMACS, Paris, 11–15 July 2005
11. Zhu, G., Kremenakova, D., Wang, Y., Militky, J., Mishra, R., Wiener, J.: 3D Numerical simulation of laminar flow and conjugate heat transfer through fabric. AUTEX Res. J. **17**(1), 53–60 (2017). https://doi.org/10.1515/aut-2015-0052