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DATA ANALYSIS METHODS FOR SOFTWARE SYSTEMS

12-th Conference **Data Analysis Methods for Software Systems**
Druskininkai, December 2 - 4, 2021. **http://www.mii.vu.lt/DAMSS**

NUMERICAL SIMULATIONS OF HEAT AND MASS EXCHANGE BETWEEN HUMAN SKIN AND TEXTILE STRUCTURES

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INTRODUCTION

The main function of clothing is to protect the human body from hazardous environments. Nowadays, the three-dimensional textile is used as a moisture and thermal regulating layer in multi-layer textile packages (e.g. protecting clothing, outdoor clothing), medical bandages [1]. One of the challenges for clothing designers is to ensure thermal comfort between human skin and fabrics. According to the literature [2], the most important properties of thermal comfort are air permeability, water-vapor resistance, and thermal resistance. Modern finite element computing technologies allow for a highly realistic representation of the physical processes and can even be used to replace experiments.

In this work, we present computational techniques and finite element models that allow predicting air permeability, water-vapor resistance, thermal resistance coefficients on a micro-scale. The models can be applied in the development of passive and active cooling systems. The numerical simulations were performed using Comsol Multiphysics and Matlab software.

COMPUTATIONAL METHODS

In this study we present 3D steady state finite element models to predict air permeability (AP), water-vapor resistance (Ret), and thermal resistance (Rct) coefficients. A representative volume element (RVE) was created according to Zupin et al. [3] experimental investigation of one-layer textile structures.

Governing equations of air permeability (AP) coefficient.

Navier-Stokes equations were applied in the free flow spaces (air domain).

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u}=\nabla\cdot\left[-p\mathbf{I}+\mu\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^{T}\right)-\frac{2}{3}\mu(\nabla\cdot\mathbf{u})\mathbf{I}\right]+\mathbf{F}$$

$$\nabla\cdot(\rho\mathbf{u})=0$$

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

Brinkman equations were used in the textile domain.

$$\frac{\rho}{\varepsilon_p}\left((\boldsymbol{u}\cdot\nabla)\frac{\boldsymbol{u}}{\varepsilon_p}\right)=\nabla\cdot\left[-p\boldsymbol{I}+\frac{\mu}{\varepsilon_p}(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^T)\right]-(\mu\boldsymbol{k}^{-1})\boldsymbol{u}$$

$\rho\nabla\cdot(\boldsymbol{u})=0$, where ε_p -constant porosity, κ- local permeability**. Boundary conditions.** The inlet pressure was set to 200 Pa according to the ISO 9237:1995(E) standard, the outlet pressure was set to 0 Pa. The no-slip condition was set on the 3D textile surface and the slip/symmetry boundary condition was applied on the free flow boundaries. More details in our previous work [4].

Governing equations of Rct coefficient

Heat transfer (energy) equation was applied in all domains.

$$\rho C_p\boldsymbol{u}\cdot\nabla T+\nabla\cdot\boldsymbol{q}=Q,\ \ \boldsymbol{q}=-k\nabla T.$$

Boundary conditions. On the inlet surface we set T=35 °C, on the outlet surface T=20 °C. The RVE is depicted in Figure 2.

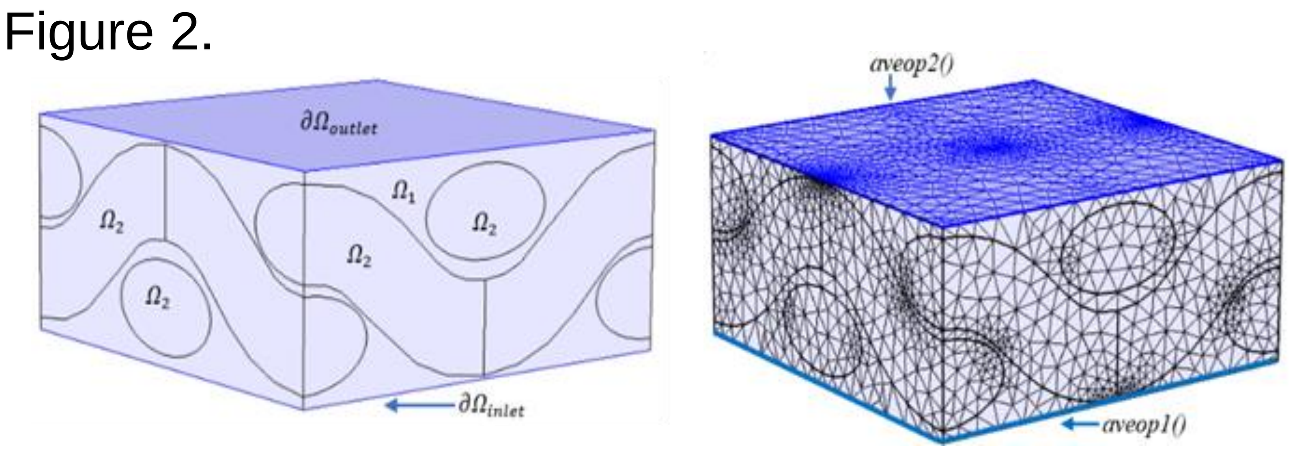

Figure 2. RVE and boundary conditions of R_{ct}.

Governing equations of Ret coefficient

We use Navier-Stokes equations with diluted species formulation. $M_v\boldsymbol{u}\cdot\nabla c_v+\nabla\cdot\boldsymbol{g_w}=G$.
Here $\boldsymbol{g_w}=-M_vD\nabla c_v$, $c_v=\varphi c_{sat}$. c_{sat} denotes the saturation concentration $c_{sat}=\frac{p_{sat}}{RT}$.

Boundary conditions. On the inlet/inflow surface we set velocity 1 m/s and relative humidity 0.4. On the outflow surface we applied $-\mathbf{n}\cdot\boldsymbol{g_w}=\mathbf{0}$ (zero diffusive flux) and outlet pressure was set to 0 Pa.

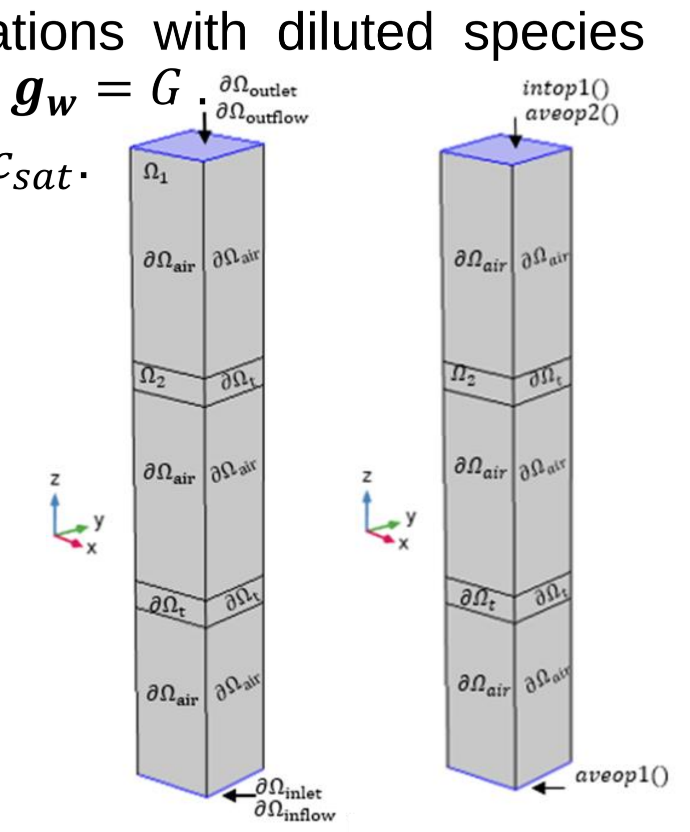

Figure 3. Boundary conditions of R_{et}.

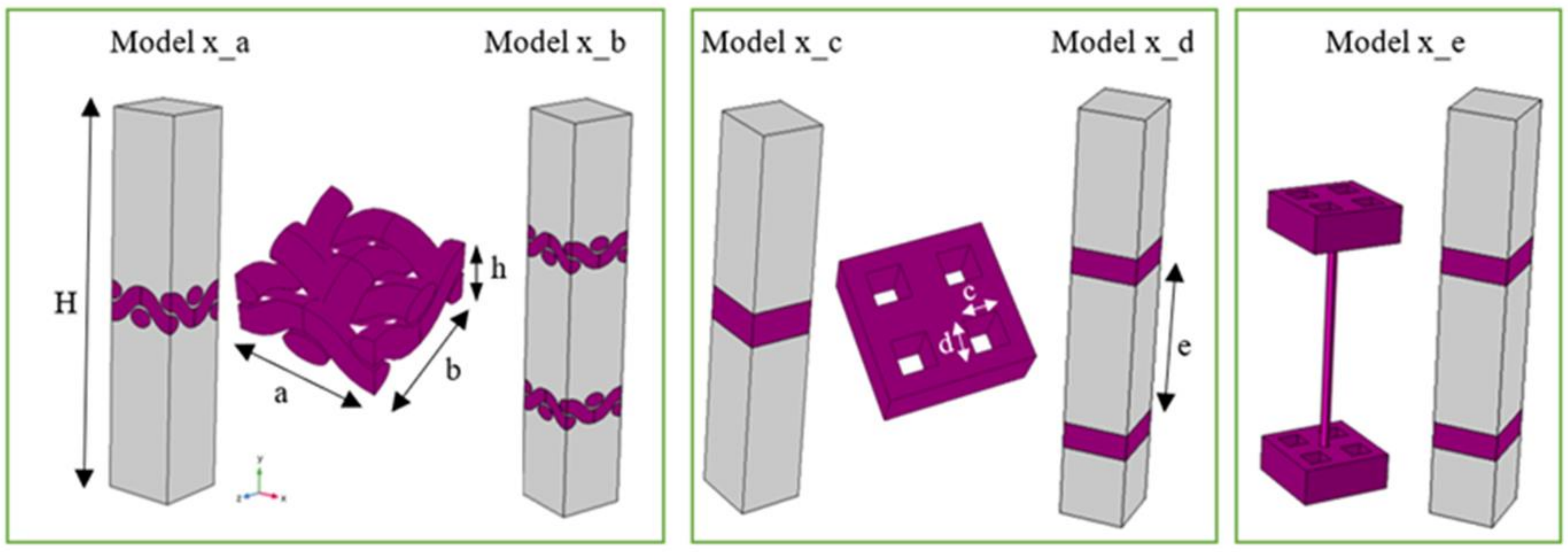

Figure 1. Different RVE of one-layer, two-layer and 3D textile.

NUMERICAL RESULTS

The outcomes of finite element simulations are average AP, Ret, and Rct coefficients in micro scale. Furthermore, distributions of air velocity and temperature flow through textile structures. The AP coefficients through 3D textile are depicted in Figure 4 and Figure 5. Temperature distribution of Model 3_e (polypropylene) is depicted in Figure 6. It was found that Rct of polypropylene is 0.11592 K·m²/W. It can be evaluated from expression $R_{ct}=\frac{\Delta T}{Q/A}$. However, Ret coeff. demonstrated sensitivity to geometry changes.

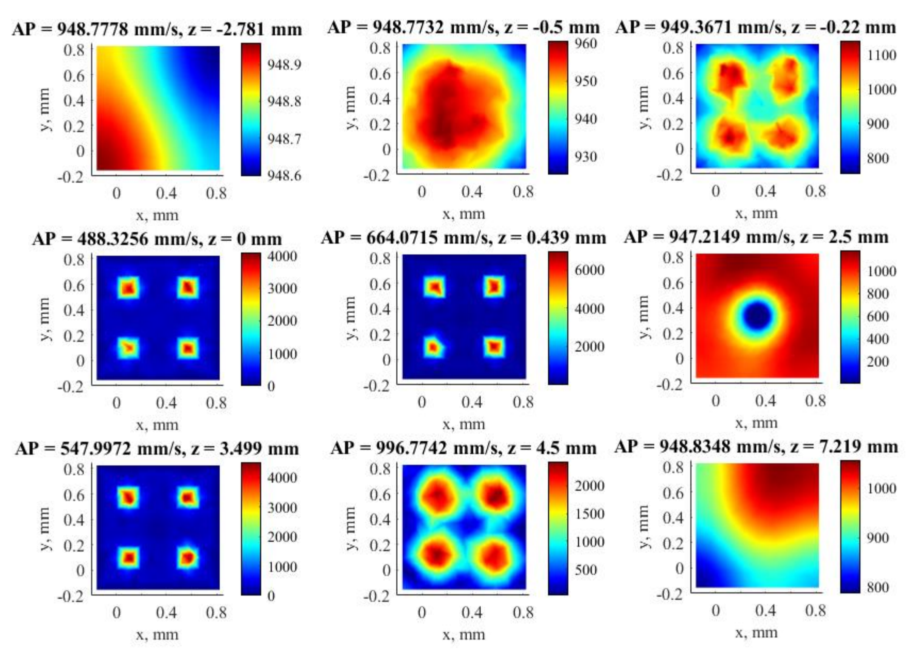

Figure 5. The air velocity distribution of *Model 2_e*.

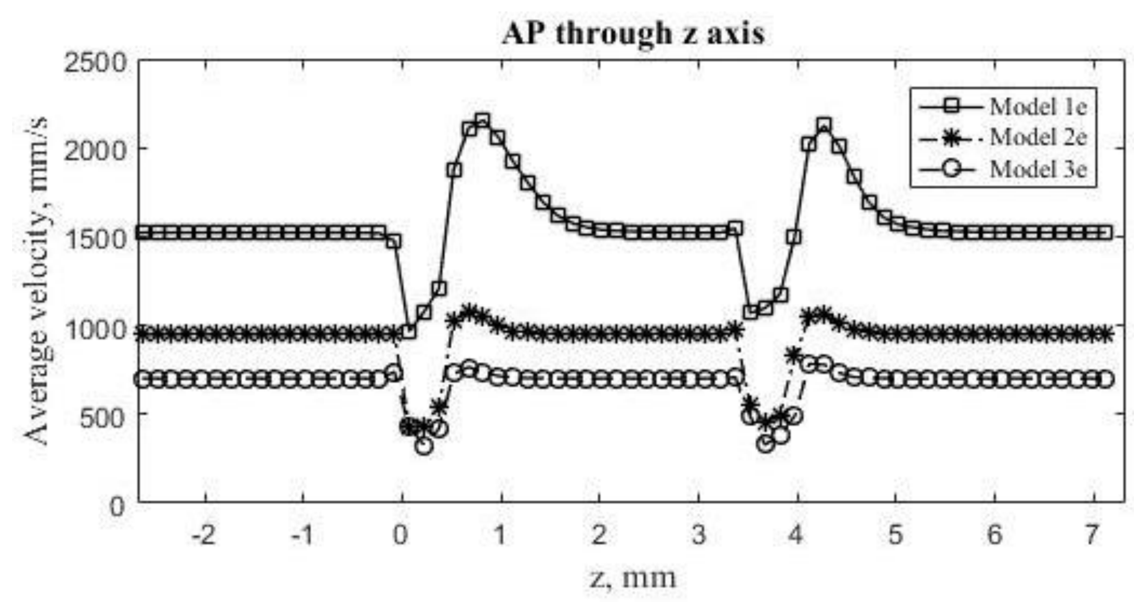

Figure 4. The AP coeff. of 3D textile models.

CONCLUSIONS

The proposed methodology allows to predict the air permeability (AP), water-vapor resistance (Ret), and thermal resistance (Rct) coefficients in micro scale. The effective coefficients can be applied in the development of passive and active cooling systems in macro scale.

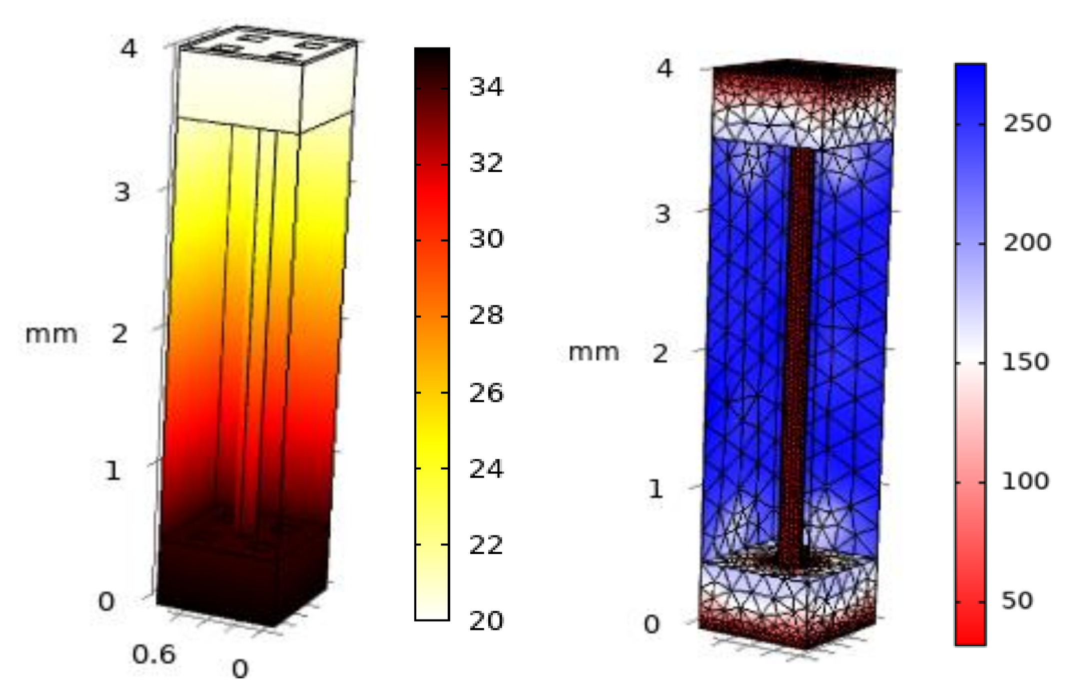

Figure 6. Temperature distribution of Model 3_e and distribution of element size, µm.

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