

Numerical modelling of transient heat and moisture transport in protective clothing

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Abstract. The paper presents a complex model of heat and mass transfer in a multi-layer protective clothing exposed to a flash fire and interacting with the human skin. The clothing was made of porous fabric layers separated by air gaps. The fabrics contained bound water in the fibres and moist air in the pores. The moist air was also present in the gaps between fabric layers or internal fabric layer and the skin. Three skin sublayers were considered. The model accounted for coupled heat transfer by conduction, thermal radiation and associated with diffusion of water vapour in the clothing layers and air gaps. Heat exchange due to phase transition of the bound water were also included in the model. Complex thermal and mass transfer conditions at internal or external boundaries between fabric layers and air gaps as well as air gap and skin were assumed. Special attention was paid to modelling of thermal radiation which was coming from the fire, penetrated through protective clothing and absorbed by the skin. For the first time non-grey properties as well as optical phenomena at internal or external boundaries between fabric layers and air gaps as well as air gap and skin were accounted for. A series of numerical simulations were carried out and the risk of heat injures was estimated.

1. Introduction

In firefighting and many industries people are exposed to high temperature of environment leading to a risk of serious thermal skin burns. For example in a case of a flash fire, e.g. sudden explosion, the firefighters may be in contact with hot gases or even with flame. Therefore, to prevent thermal injuries they wear the special protective clothing allowing them to safety escape to a secure location. The typical protective clothing is made of several layers of fabric material e.g. outer shell, moisture barrier, thermal insulation and inner layer separated by thin air gaps. Protective performance of garments are directly related to the heat and moisture transfer through such multilayer clothing as well as to heat transfer in the human skin.

Many models for studying heat and moisture transport in multi-layer protective clothing exposed to the flash fire conditions and for assessing possibility of heat injuries are available in a literature. Heat transfer model in a flame resistant single-layer fabric subjected to high heat flux was developed by Torvi and Dale [1]. Their model included thermochemical reaction in the materials as well as absorption of thermal radiation, variable thermal properties and heat transfer across an air space separating the fabric from a test sensor. Their predictions of temperature distributions and times to reach the second-degree burn criterion were in good agreement with experimental measurements. Chitrphiomsri and Kuznetsov [2] presented a complete model of a multilayer clothing, air gap, and skin system exposed to a fire which accounted for heat conduction and thermal radiation as well as



moisture transport. Subsequently they analyzed duration of the flash fire exposure on the time after which the second and third degree burns were caused. The model was also used to simulate behavior of different fabric systems and their configurations [3]. Ghazy and Bergstrom [4] developed a model to simulate transient conductive and radiative heat transfer in a protective clothing system consisting of the fire-resistant fabric, the human skin, and the air gap between the fabric and the skin. In next paper [5] they extended the previous model to a system that consisted of three layers of fabric separated by two air gaps, the human skin, and the air gap between the clothing and the skin. In both works they predicted transient heat flux and temperature distribution in the protective clothing, skin and air gap as well as the time to receive skin burn injuries during flash fire heating and subsequent cooling down processes. Zhu and Li [6] developed an interesting numerical model of heat and moisture transfer in a fabric which underwent drying and pyrolysis. The latter was modelled by one-step chemical reaction and lead to changes in fabric thermophysical properties. Their model was validated by experimental data.

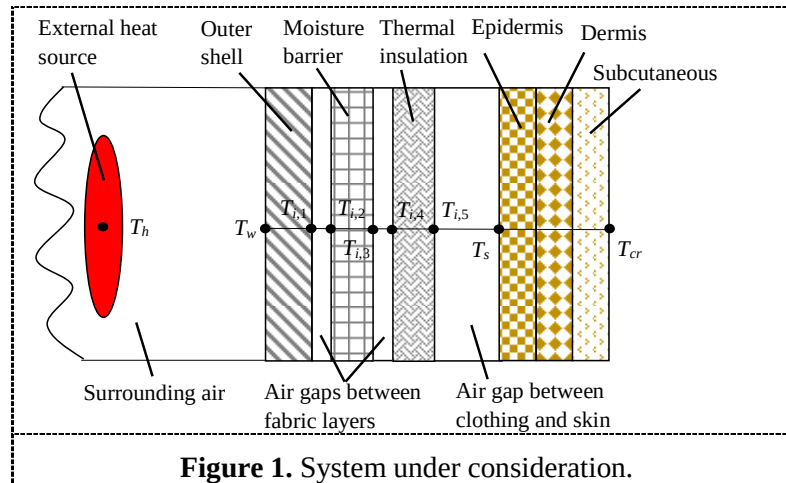
New concepts of protecting clothing to improve workers safety were also designed and the respective models describing their thermal behavior were developed. For example Chitrphiomsri et al. [7] proposed an intelligent multi-layer firefighter protective clothing, which during the flash fire exposure absorbed a significant amount of incident heat flux due to evaporation of the injected water and thus limited temperature increase on firefighter's skin. A comprehensive mathematical model of heat and moisture transport was also developed. In turn Hu et al. [8] performed numerical and experimental studies on heat transport through firefighting protective clothing with embedded phase change material (PCM). They simulated different thicknesses and location of PCM in the garment and analyzed possibility of burns occurrence.

In a high temperature environment the main heat transfer mode is thermal radiation which transfers energy from the fire or hot surfaces to the firefighter's clothing and then in conjunction with heat conduction through its textile layers and air gaps to the human skin. The heat exchange process is accompanied by moisture transfer in the fabrics and air gaps which affects thermophysical properties of the clothing system. Therefore, an advanced model describing thermal interaction of a fire with the protecting multi-layer clothing and the conjugated heat and mass transfer across textile layers, air gaps between them and the skin as well as through sublayers of the human skin was developed in this paper. The single fabric layer was assumed to be a hygroscopic porous medium that contained bound water. Additionally the water vapor mixed with the air filled pores in fabric and air gaps. Complex thermal and mass transfer conditions on the internal or external boundaries between fabric layers and air gaps as well as the air gap and the skin were taken into account. Special attention was paid to modeling of thermal radiation coming from the fire, penetrating through the protective clothing and then being absorbed by the skin. For the first time non-grey properties as well as optical phenomena at the internal or external boundaries between fabric layers and air gaps as well as air gap and the skin were considered. Three sublayers skin model was introduced and possibility of heat injures occurrence were also evaluated. A series of numerical simulations for different exposition (heating) times were carried out.

2. Statement of the problem

A schematic diagram of the system under consideration is presented in figure 1. The protective clothing was composed of three fabric layers: outer shell, moist barrier and thermal insulation separated by two narrow air gaps. The external heat source was located on the left hand side while the wide air gap and three sublayers of skin: epidermis, dermis and subcutaneous were on the right hand side. All fabric layers and the skin were assumed to absorb, scatter or reflect and emit thermal radiation and additionally had the same value of refractive index equal to 1.0. All other optical properties were dependent on wavelength and the air was assumed transparent to the thermal radiation. The internal and external boundaries (interfaces) were semitransparent i.e. absorbing and diffusively emitting, reflecting and transmitting thermal radiation except the interfaces between skin sublayers which were assumed transparent. Blood perfusion was included in the skin model. Convection in the

clothing and air gaps was neglected. The model assumed one dimensional heat and moisture transfer due to the small thickness of the considered system in comparison to its dimension along the protective clothing and assumed no variation of external thermal conditions in this direction.



3. Modelling of the heat transfer in the skin and estimation of degree of burning injuries

The heat transfer model in the skin was based on Pennes model [9] and account for heat transfer between tissue and blood and radiative heat transfer in all skin sublayers [10]. The governing equations in three sublayers were following:

$$(\rho c)_{ep} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_{ep} \frac{\partial T}{\partial x} \right) - \frac{\partial q_{r,ep}}{\partial x} \quad (1)$$

$$(\rho c)_d \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_d \frac{\partial T}{\partial x} \right) + (\rho c)_b \omega_b (T_{cr} - T) + q_m - \frac{\partial q_{r,d}}{\partial x} \quad (2)$$

$$(\rho c)_{sc} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_{sc} \frac{\partial T}{\partial x} \right) + (\rho c)_b \omega_b (T_{cr} - T) + q_m - \frac{\partial q_{r,sc}}{\partial x} \quad (3)$$

where: subscripts ep , d , sc and b denotes epidermis, dermis, subcutaneous and blood, respectively. The symbol ρ describes the density, c is the specific heat, k is the thermal conductivity, ω_b stands for the blood perfusion, q_m is the metabolic heat rate, $T_{cr} = 37^\circ\text{C}$ is assumed to be the inner body (core) temperature while q_r denotes radiative heat flux vector. Boundary conditions for these equations were following:

- At the interface between the epidermis and dermis as well as the dermis and subcutaneous continuity of temperature and heat flux were assumed.
- At the right boundary of the system (body interior), see figure 1, fixed body temperature T_{cr} was assumed.
- At left boundary (skin surface), see figure 1, temperature was found from the energy balance in the form:

$$\begin{aligned} & -k_a \frac{\partial T}{\partial x} \Big|_a + \int_0^\infty (q_{r,\lambda,in,a} - \varepsilon_{\lambda,s} E_{b,\lambda}(T_s) - r_{\lambda,s} q_{r,\lambda,in,a} - t_{\lambda,s} q_{r,\lambda,in,ep}) d\lambda + \\ & -k_{ep} \frac{\partial T}{\partial x} \Big|_s + \int_0^\infty (q_{r,\lambda,in,ep} - \varepsilon_{\lambda,s} E_{b,\lambda}(T_s) - r_{\lambda,s} q_{r,\lambda,in,ep} - t_{\lambda,s} q_{r,\lambda,in,a}) d\lambda = 0 \end{aligned} \quad (4)$$

where: the subscripts s and a denote the skin surface and air, respectively, $q_{r,\lambda,in}$ is monochromatic incident radiative heat flux, $E_{b,\lambda}$ is spectral blackbody emissive power, ε , r and t stand for the surface emissivity, reflectivity and transmissivity, respectively and λ denotes the wavelength.

Henriques and Moritz model [11] was applied to estimate a degree of thermal injuries. According to their model the burns occur when temperature at the interface between the epidermis and dermis exceeds $T_{ep/d} = 44^\circ\text{C}$. The degree of thermal injury can then be estimated by finding the value of the following integral (Henriques and Moritz integral):

$$\Omega_i = \int_0^t P e^{-\Delta E/BT_i} dt \quad \text{for } T_{ep/d} \geq 44^\circ\text{C} \quad (5)$$

where: t is time, P denotes frequency factor, B describes universal gas constant, ΔE is skin activation energy and T_i stands for interface temperature either between the epidermis and dermis (ep/d) for the first and second degree burns or between the dermis and subcutaneous (d/sc) for the third degree burns. The first degree burns occur for $\Omega_{ep/d} = 0.53$, the second ones for $\Omega_{ep/d} = 1.0$ and the third ones for $\Omega_{d/sc} = 1.0$.

4. Heat transfer in fabric layers and gaps

Heat transfer in the porous fabric layer or in air gap was modeled by the following energy equation which included heat flow by conduction, associated with water vapor diffusion, thermal radiation as well as heat absorbed or released due to phase transition of the bound water to its gaseous (vapor) state:

$$(\rho c)_{ef} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_{ef} \frac{\partial T}{\partial x} + D_{v-a,ef} \frac{\partial \rho_v}{\partial x} c_{p,v} T \right) + \dot{m}_{vbw} (\Delta h_{vap} + \Delta h_{abs}) - \frac{\partial q_r}{\partial x} \quad (6)$$

The above equation were complemented with additional relations for:

- *Effective heat capacity:*

$$(\rho c)_{ef} = \varepsilon_{bw} \rho_w c_w + \varepsilon_f \rho_f c_f + \varepsilon_g (\rho_v c_{p,v} + \rho_a c_{p,a}) \quad (7)$$

where dry gas and water vapor densities can be found from formulae:

$$\rho_a = p_a M_a / BT = \varepsilon_a p M_a / BT \quad (8)$$

$$\rho_v = p_v M_v / BT = \varepsilon_v p M_v / BT \quad (9)$$

Here B is the universal gas constant, p , p_a and p_v are total, dry air and water vapor pressures, respectively and M_a and M_v are molecular masses of the dry air and water vapor.

- *Effective thermal conductivity:*

$$k_{ef} = k_g \left\{ \left[1 + (\varepsilon_{bw} + \varepsilon_f) \right] k_\sigma + \varepsilon_g k_g \right\} / \left\{ \varepsilon_g k_\sigma + \left[1 + (\varepsilon_{bw} + \varepsilon_f) \right] k_g \right\} \quad (10)$$

where thermal conductivities of the moist air and fabric as well as dry air are given by the expressions:

$$k_g = (k_v \rho_v + k_a \rho_a) / (\rho_v + \rho_a) \quad (11)$$

$$k_\sigma = (k_w \rho_w \varepsilon_{bw} + k_f \rho_f \varepsilon_f) / (\rho_w \varepsilon_{bw} + \rho_f \varepsilon_f) \quad (12)$$

$$k_a(T) = \begin{cases} 0.026 + 0.000068(T[\text{K}] - 300) & \text{for } T \leq 700\text{K} \\ 0.053 + 0.000054(T[\text{K}] - 700) & \text{for } T > 700\text{K} \end{cases} \quad (13)$$

- *Effective diffusivity:*

$$D_{v-a,ef} = \begin{cases} D_a \varepsilon_g / \tau & \text{for fabric} \\ D_a & \text{for air gap} \end{cases} \quad (14)$$

where the diffusivity of the water vapor in the air is given by:

$$D_a = 2.23 \cdot 10^{-5} (T/273.13)^{1.75} \quad (15)$$

and τ is the tortuosity factor.

In the above formulae: ε_{bw} , ε_f , ε_g , ε_a and ε_v are volumetric fractions of the bound water, dry fabric, moist air, dry air and water vapor, respectively. The specific heats of water, dry fabric, dry air and water vapor are denoted by symbols c_w , c_f , $c_{p,a}$ and $c_{p,v}$, while their thermal conductivities given by k_w , k_f , k_a and k_v . The symbols ρ_w and ρ_f stand for densities of water and dry fabric. The heat of desorption of the bound water to its liquid state and from the liquid state to the gaseous one were assumed to satisfy the following relations:

$$\Delta h_{abs} = 1.95 \cdot 10^5 (1 - \phi) \left[(0.2 + \phi)^{-1} + (1.05 - \phi)^{-1} \right] \quad (16)$$

$$\Delta h_{vap} = 2.792 \cdot 10^6 - 160T[K] - 3.43T[K]^2 \quad (17)$$

where the relative humidity is related to the partial pressures of water vapor in the air-vapor mixture by:

$$\phi = p_v / p_s \quad (18)$$

and the water vapor pressure at saturation was calculated from the formula:

$$p_s = 614.3 \exp \left[17.06 (T[K] - 273.15/T[K] - 40.25) \right] \quad (19)$$

The volumetric mass rate of transition of the bound water, present in the fabric, to the gaseous state depends on how far the bound water content is from its equilibrium one:

$$\dot{m}_{vbw} = D_f \rho_f / d_f^2 (R_{f,eq} - R_f) \quad (20)$$

where the fiber regain and equilibrium fiber regain can be found from expressions:

$$R_f = \varepsilon_{bw} \rho_w / \varepsilon_f \rho_f \quad (21)$$

$$R_{f,eq} = 0.578 R_{f,\phi=0.65} \phi \left[(0.321 + \phi)^{-1} + (1.262 - \phi)^{-1} \right] \quad (22)$$

Here D_f is the effective diffusivity of bound water in the solid phase (fibers), d_f is the average fiber diameter, $R_{f,\phi=0.65}$ is fiber regain at $\phi = 0.65$.

The volume fractions are constrained by the following relation:

$$\varepsilon_{bw} + \varepsilon_f + \varepsilon_g = 1 \quad (23)$$

where: $\varepsilon_g = \varepsilon_a + \varepsilon_v$.

For air gaps the terms in equation (6) corresponding to the phase transition of bound water disappear and properties are calculated for the moist air for which $\varepsilon_g = \varepsilon_a + \varepsilon_v = 1.0$.

On the right hand side of computational domain the boundary condition for equation (6) (temperature of the skin surface T_s) was calculated from equation (4) while on the left hand side external wall temperature T_w (surface of the protective clothing) was found from following balance of energy:

$$\begin{aligned}
& -k_{ef} \left. \frac{\partial T}{\partial x} \right|_{w,f} - D_{v-a,ef} \left. \frac{\partial \rho_v}{\partial x} \right|_{w,f} c_{p,v} T_{w,f} + q_{amb} \\
& + \int_0^\infty \left\{ q_{r,\lambda,f,in} - \varepsilon_{\lambda,w} E_{b,\lambda}(T_w) - r_{\lambda,w} q_{r,\lambda,f,in} - t_{\lambda,w} q_{r,\lambda,amb,in} \right\} d\lambda \\
& + \int_0^\infty \left\{ q_{r,\lambda,amb,in} - \varepsilon_{\lambda,w} E_{b,\lambda}(T_w) - r_{\lambda,w} q_{r,\lambda,amb,in} - t_{\lambda,w} q_{r,\lambda,f,in} \right\} d\lambda = 0
\end{aligned} \quad (24)$$

The ambient and incident radiative heat fluxes in equation (24) are given by the flowing expressions:

$$q_{amb} = h_{amb} (T_{amb} - T_w) + h_h (T_h - T_w) + h_m (\rho_{v,amb} - \rho_{v,w}) c_{p,v} T_{amb} \quad (25)$$

$$q_{r,\lambda,amb,in} = \varepsilon_{\lambda,h} E_{b,\lambda}(T_h) + \varepsilon_{\lambda,amb} E_{b,\lambda}(T_{amb}) \quad (26)$$

where: h_{amb} , h_h and T_{amb} , T_h are heat transfer coefficients and temperatures of the ambient air and hot gases, respectively. The symbol h_m is the ambient air mass transfer coefficient while ε_{amb} and ε_h are the ambient air and hot gases monochromatic emissivities, respectively.

The temperature T_i at the internal interfaces between layers was found from following balance of energy:

$$\begin{aligned}
& -k_L \left. \frac{\partial T}{\partial x} \right|_{i,L} - D_{v-a,ef,L} \left. \frac{\partial \rho_v}{\partial x} \right|_{i,L} c_{p,v} T_i - k_R \left. \frac{\partial T}{\partial x} \right|_{i,R} - D_{v-a,ef,R} \left. \frac{\partial \rho_v}{\partial x} \right|_{i,R} c_{p,v} T_i \\
& + \int_0^\infty \left[q_{r,\lambda,L,in} - \varepsilon_{\lambda,i} E_{b,\lambda}(T_i) - r_{\lambda,i} q_{r,\lambda,L,in} - t_{\lambda,i} q_{r,\lambda,R,in} \right] d\lambda \\
& + \int_0^\infty \left[q_{r,\lambda,R,in} - \varepsilon_{\lambda,i} E_{b,\lambda}(T_i) - r_{\lambda,i} q_{r,\lambda,R,in} - t_{\lambda,i} q_{r,\lambda,L,in} \right] d\lambda = 0
\end{aligned} \quad (27)$$

where the subscripts L and R denote the left and right side of the interface, respectively.

Distribution of temperature in the equilibrium steady state when clothing-skin system is only in contact with the ambient air at temperature T_{amb} were assumed as initial condition for equations (6).

5. Mass transfer in the fabric layers and the air gaps

The mass balance of the water bounded in the fabric, accounting for water sorption and desorption, can be cast in the following form:

$$\frac{\partial \rho_w \varepsilon_{bw}}{\partial t} = \dot{m}_{vbw} \quad (28)$$

Variation of the mass of water vapor filling the pores in the fabric layers and air gaps can be found from the equation:

$$\frac{\partial \rho_v \varepsilon_g}{\partial t} = \frac{\partial}{\partial x} D_{v-a,ef} \frac{\partial \rho_v}{\partial x} - \dot{m}_{vbw} \quad (29)$$

The following boundary conditions were assumed for the equation (29):

- Skin surface was impermeable.
- At the left external wall (clothing surface) density $\rho_{v,w}$ was calculated from the expression:

$$h_m (\rho_{v,amb} - \rho_{v,w}) = -D_{v-a,ef} \left. \frac{\partial \rho_v}{\partial x} \right|_w \quad (30)$$

- At the internal interfaces density $\rho_{v,i}$ was found from following balance of mass:

$$-D_{v-a,ef,L} \left. \frac{\partial \rho_v}{\partial x} \right|_{i,L} = -D_{v-a,ef,R} \left. \frac{\partial \rho_v}{\partial x} \right|_{i,R} \quad (31)$$

After solving equation (29) the dry air and vapor volume fractions were obtained from the formulae:

$$\varepsilon_a = \frac{p_a}{p} \varepsilon_g \text{ and } \varepsilon_v = \frac{p_v}{p} \varepsilon_g \quad (32)$$

where the respective pressures were calculated from the perfect gas relation and Dalton's Law, i.e.: $p_v = \rho_v BT/M_v$ and $p_a = p - p_v$.

Distributions of the volume fraction of bound water and vapor density in the equilibrium steady state when clothing-skin system is only in contact with the ambient air were assumed as initial conditions for equations (28) and (29).

6. Radiative heat transfer in the fire-clothing-air gap-skin system

Distribution of spectral radiative intensity along path s in a system fire-clothing-air gap-skin is described by the following radiative transfer equation:

$$\frac{dI_\lambda}{ds} = -(K_{a,\lambda} + K_{s,\lambda}) I_\lambda + K_{a,\lambda} I_{b,\lambda} + \frac{K_{s,\lambda}}{4\pi} \int_{4\pi} I_\lambda \Phi_\lambda(\mathbf{s}' \rightarrow \mathbf{s}) d\Omega \quad (33)$$

where: I_λ is the spectral radiation intensity, $I_{b,\lambda}$ is the spectral intensity emitted by the blackbody, $K_{a,\lambda}$ and $K_{s,\lambda}$ denote the linear absorption and scattering coefficients, respectively, and Φ_λ is monochromatic scattering phase function. All mechanisms (absorption, scattering and emission) of radiation transport were accounted for in the fabric layers. In the skin, due to its low temperature, the self-emission was neglected. The air contained in the gaps was assumed transparent therefore equation (33) was reduced to $dI_\lambda/ds = 0.0$. The spectral blackbody intensity was calculated applying Planck's Law, i.e.:

$$I_{b,\lambda} = \frac{1}{\pi} E_{b,\lambda}(T) = \frac{1}{\pi} \frac{2hc}{\lambda^5} (e^{hc/\lambda kT} - 1)^{-1} \quad (34)$$

where: h is Planck constant, c is speed of light in the medium, k is Boltzmann constant.

The boundaries between the surroundings and first fabric layer, between fabric layers and air gaps and between air gap and skin surface were assumed semi-transparent i.e.: emitting, reflecting and transmitting diffusively thermal radiation. Interfaces between the skin sublayers were assumed totally transparent while boundary between the subcutaneous and the body interior was ideally black. Conditions for the radiation intensities at the internal and external boundaries were therefore following:

- External wall (clothing surface) between the surroundings and the first fabric layer:

$$I_{\lambda,w} = \varepsilon_{\lambda,w} I_{b,\lambda}(T_w) + r_{\lambda,w} \frac{q_{r,\lambda,f,in}}{\pi} + t_{\lambda,w} \frac{q_{r,\lambda,amb,in}}{\pi} \text{ for } \mathbf{s} \cdot \mathbf{n}_w > 0 \quad (35)$$

where: $\mathbf{n}_w$ is inward normal vector at the external wall.

- Internal interface between the fabric layer and air gap (see figure 2):

$$I_{\lambda,i,L} = \varepsilon_{\lambda,i} I_{b,\lambda}(T_i) + r_{\lambda,i} \frac{q_{r,\lambda,L,in}}{\pi} + t_{\lambda,i} \frac{q_{r,\lambda,R,in}}{\pi} \quad \text{for } \mathbf{s} \cdot \mathbf{n}_{i,L} > 0 \quad (36)$$

$$I_{\lambda,i,R} = \varepsilon_{\lambda,i} I_{b,\lambda}(T_i) + r_{\lambda,i} \frac{q_{r,\lambda,R,in}}{\pi} + t_{\lambda,i} \frac{q_{r,\lambda,L,in}}{\pi} \quad \text{for } \mathbf{s} \cdot \mathbf{n}_{i,R} > 0 \quad (37)$$

where: $\mathbf{n}_{i,L}$ and $\mathbf{n}_{i,R}$ are normal vectors at interface – see figure 2.

- Internal interface between the skin and air gap:

$$I_{\lambda,i,a} = \varepsilon_{\lambda,s} I_{b,\lambda}(T_s) + r_{\lambda,s} \frac{q_{r,\lambda,a,in}}{\pi} + t_{\lambda,s} \frac{q_{r,\lambda,ep,in}}{\pi} \quad \text{for } \mathbf{s} \cdot \mathbf{n}_{i,a} > 0 \quad (38)$$

$$I_{\lambda,i,ep} = \varepsilon_{\lambda,s} I_{b,\lambda}(T_s) + r_{\lambda,s} \frac{q_{r,\lambda,ep,in}}{\pi} + t_{\lambda,s} \frac{q_{r,\lambda,a,in}}{\pi} \quad \text{for } \mathbf{s} \cdot \mathbf{n}_{i,s} > 0 \quad (39)$$

- Interface between the subcutaneous sublayer and body interior:

$$I_{\lambda,cr} = I_{b,\lambda}(T_{cr}) \quad \text{for } \mathbf{s} \cdot \mathbf{n}_{cr} > 0 \quad (40)$$

where: $\mathbf{n}_{cr}$ is inward normal vector at the interface.

The additional relationships needed to close the whole system of equations were following:

- Monochromatic incident heat flux which appears in relationships for thermal and optical boundary conditions:

$$q_{r,\lambda,in} = \int_{\mathbf{s} \cdot \mathbf{n} < 0} I_{\lambda} \mathbf{s} \cdot \mathbf{n} d\Omega \quad \text{for } \mathbf{s} \cdot \mathbf{n} < 0 \quad (41)$$

- Divergence of radiative heat flux vector which appears in energy equations (1)-(3) and (6) in the skin sublayers and clothing, respectively:

$$\frac{\partial q_r}{\partial x} = \int_0^{\infty} K_{a,\lambda} \left(4\pi I_{b,\lambda}(T) - \int_{4\pi} I d\Omega \right) d\lambda \quad (42)$$

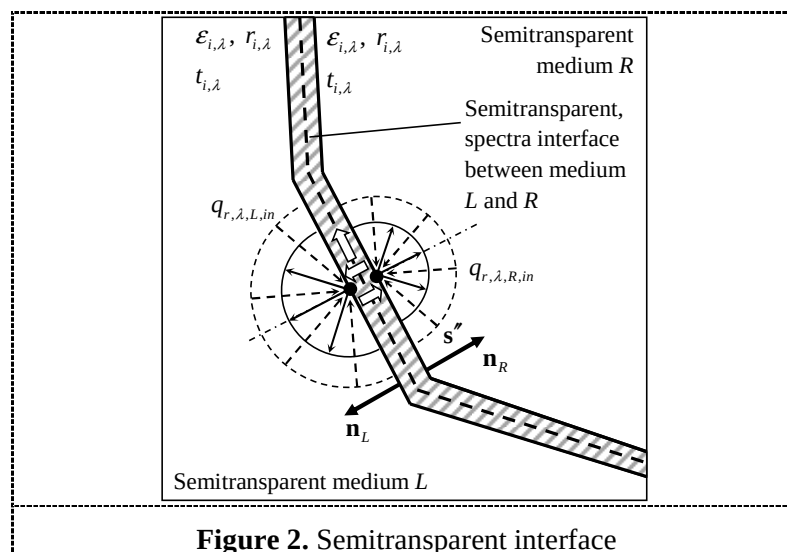
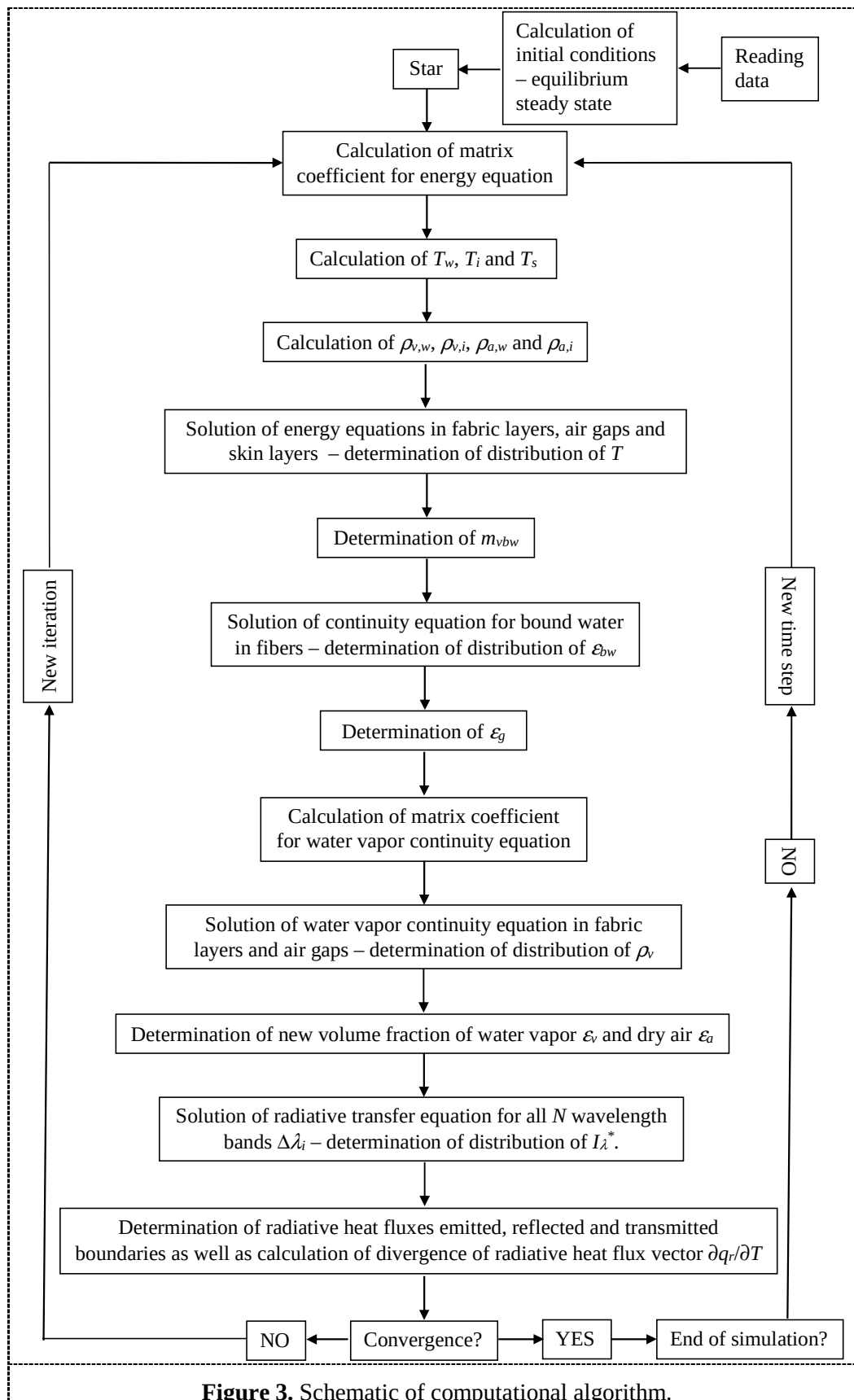


Figure 2. Semitransparent interface

**Figure 3.** Schematic of computational algorithm.

7. Numerical solution

Energy equations (1)-(3) and (6) in the skin, fabrics layers and air gaps were discretized applying Finite Volume Method on an irregular mesh. Each equation was integrated over infinitesimal distance dx and time interval dt . In the similar way discrete form of continuity equations (28) and (29) for the bound water and water vapour were obtained. Unknown temperature at external and internal interfaces were calculated from conditions (4), (24) and (27) by using Newton-Raphson method. Radiative transfer equation (33) was also discretized by applying Finite Volume Method – the equation was integrated over infinitesimal distance dx , solid angle $d\Omega$ and bandwidth $d\lambda$. Band model was introduced to account for spectral optical properties. All solved equations are coupled, therefore the set of equations obtained was highly nonlinear. The solution was found using the specially developed iterative algorithm which was implemented in the in-house C code. The general schematic of algorithm is presented in figure 3.

8. Results of simulation

Numerical simulations were performed for three layers of the protective clothing. Each layer was separated by a narrow air gap. The widest air gap was between the most inner fabric layer and skin. Configuration of the system is presented in table 1 and the thermophysical properties of fabric layers in table 2. Thermophysical properties of skin and blood are shown in table 3. All data were taken from the available literature [2] and [7]. The optical properties of fabric were assumed as the averaged values presented in [1]-[7] and [12], and are given in table 4. The spectral absorption coefficient (seven bands) for the first layer was assumed using results of measurements presented in [12] – see table 5 and figure 4. Additionally the isotropic scattering with the scattering albedo equal to $\omega = K_a/(K_a + K_s) = 0.5$ were assumed in all fabric layers. The optical properties of the human skin were taken as the averaged ones basing on data cited in [10], [13] and [14]. Constants appearing in equation (5) for determination of the burn degree – Henriques and Moritz integral are given in table 7 and were taken from [3]. Other material properties, boundary and operating parameters were taken from [2] and [7] and had the following values: $\rho_w = 998.2 \text{ kgm}^{-3}$, $c_w = 4185 \text{ Jkg}^{-1}\text{K}^{-1}$, $k_w = 0.5984 \text{ Wm}^{-1}\text{K}^{-1}$, $k_v = 0.018 \text{ Wm}^{-1}\text{K}^{-1}$, $T_{amb} = 26^\circ\text{C}$, $p = 101325 \text{ Pa}$ – constant in the whole system, $\phi_{amb} = 0.68$, $T_h = 1723^\circ\text{C}$, $\varepsilon_h = 0.02$, $\varepsilon_{amb} = 1.0$, $h_{amb} = 10 \text{ Wm}^{-2}\text{K}^{-1}$, $h_h = 120 \text{ Wm}^{-2}\text{K}^{-1}$ and $h_m = 0.021 \text{ ms}^{-1}$.

Table 1. Geometrical configuration of the system [2], [7].

First layer (m)	First gap (m)	Second layer (m)	Second gap (m)	Third layer (m)	Third gap (m)	Skin
0.00056	0.0001	0.00073	0.0001	0.00166	0.00635	

Table 2. Thermophysical properties of fabrics [2], [7].

	First layer Kombat 7.5 oz/yd ²	Second layer ComfortZone™	Third layer Aralite™
$\rho_f (\text{kgm}^{-3})$	1384	1295	1380
$c_f (\text{Jkg}^{-1}\text{K}^{-1})$	1420	1325	1200
$k_f (\text{Wm}^{-1}\text{K}^{-1})$	0.179	0.144	0.130
ε_f	0.334	0.186	0.115
$R_{f,\phi=0.65}$	0.084	0.038	0.045
τ	1.50	1.25	1.00
$D_f (\text{m}^2\text{s}^{-1})$	$6.0 \cdot 10^{-14}$	$6.0 \cdot 10^{-14}$	$6.0 \cdot 10^{-14}$
$d_f (\text{m})$	$1.6 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$

Table 3. Thermophysical properties of the skin and blood [2], [7].

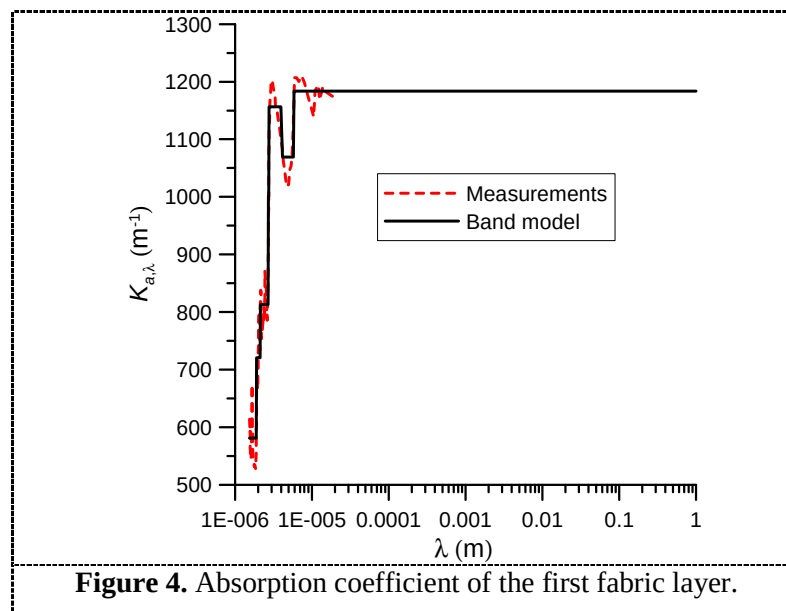
	Epidermis	Dermis	Subcutaneous	Blood
ρ (kgm ⁻³)	1200	1200	1000	1060
c (Jkg ⁻¹ K ⁻¹)	3598	3222	2760	3770
k (Wm ⁻¹ K ⁻¹)	0.255	0.523	0.167	-
L (m)	8·10 ⁻⁵	2·10 ⁻³	1·10 ⁻²	-
q_m (Wm ⁻³)	0	0	0	-
ω_b (s ⁻¹)	-	-	-	1.25·10 ⁻³
T_a (°C)	-	-	-	37.0

Table 4. Optical properties of fabrics.

	K_a (m ⁻¹)	K_s (m ⁻¹)	Φ	ϵ	r	t
First layer	Variable	Variable	isotropic	0.661	0.219	0.120
Second layer	3617.2	3617.2	isotropic	0.545	0.268	0.187
Third layer	2025.13	2025.13	isotropic	0.643	0.236	0.121

Table 5. Optical properties of the first fabric layer.

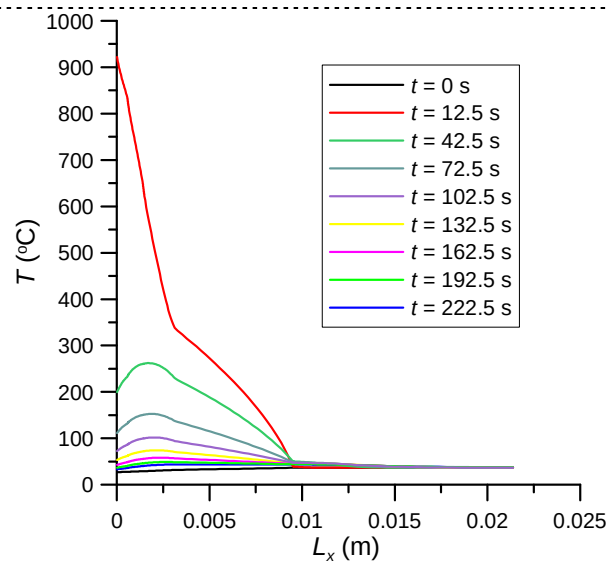
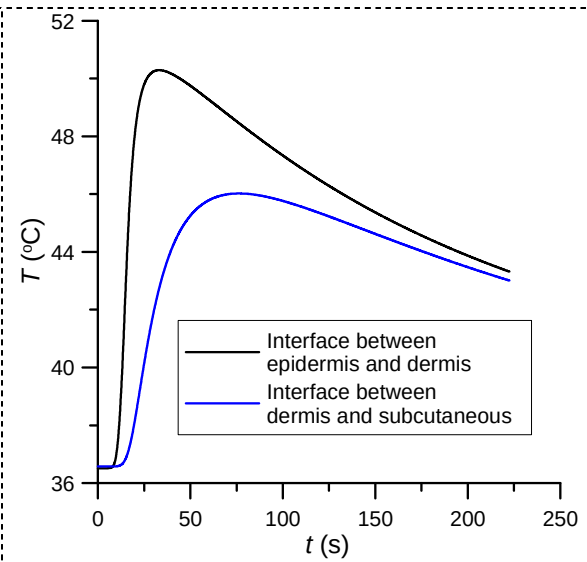
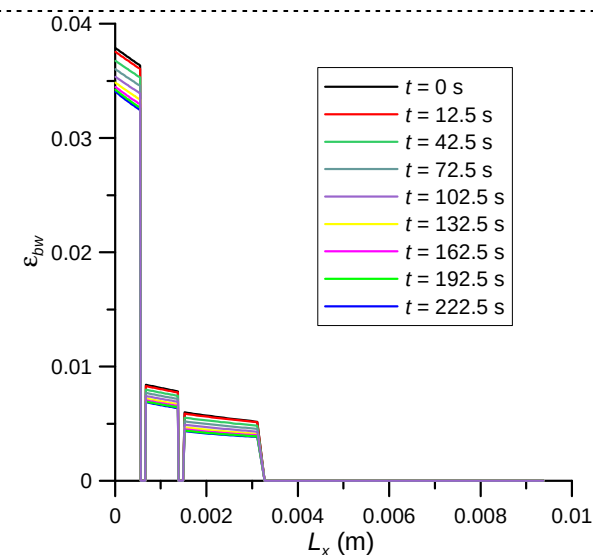
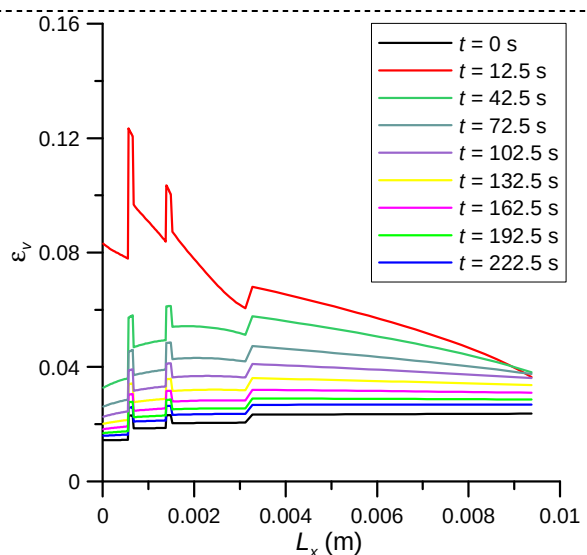
Band no.	1	2	3	4	5	6	7
λ_1 (m)	0	1.89·10 ⁻⁶	2.12·10 ⁻⁶	2.70·10 ⁻⁶	2.75·10 ⁻⁶	3.97·10 ⁻⁵	5.77·10 ⁻⁵
λ_2 (m)	1.89·10 ⁻⁶	2.12·10 ⁻⁶	2.70·10 ⁻⁶	2.75·10 ⁻⁶	3.97·10 ⁻⁵	5.77·10 ⁻⁵	1.0
$K_{a,\lambda}$ (m ⁻¹)	580.68	720.57	812.85	1000.90	1156.33	1069.31	1183.57
$K_{s,\lambda}$ (m ⁻¹)	580.68	720.57	812.85	1000.90	1156.33	1069.31	1183.57

**Figure 4.** Absorption coefficient of the first fabric layer.**Table 6.** Optical properties of the skin.

	K_a (m ⁻¹)	K_s (m ⁻¹)	Φ	ϵ	r	t
Epidermis	200.0	2800.0	isotropic	0.20	0.50	0.30
Dermis	700.0	2000.0	isotropic	-	-	-
Subcutaneous	100.0	1000.0	isotropic	-	-	-

Table 7. Constants appearing in determination of the burn degree [3].

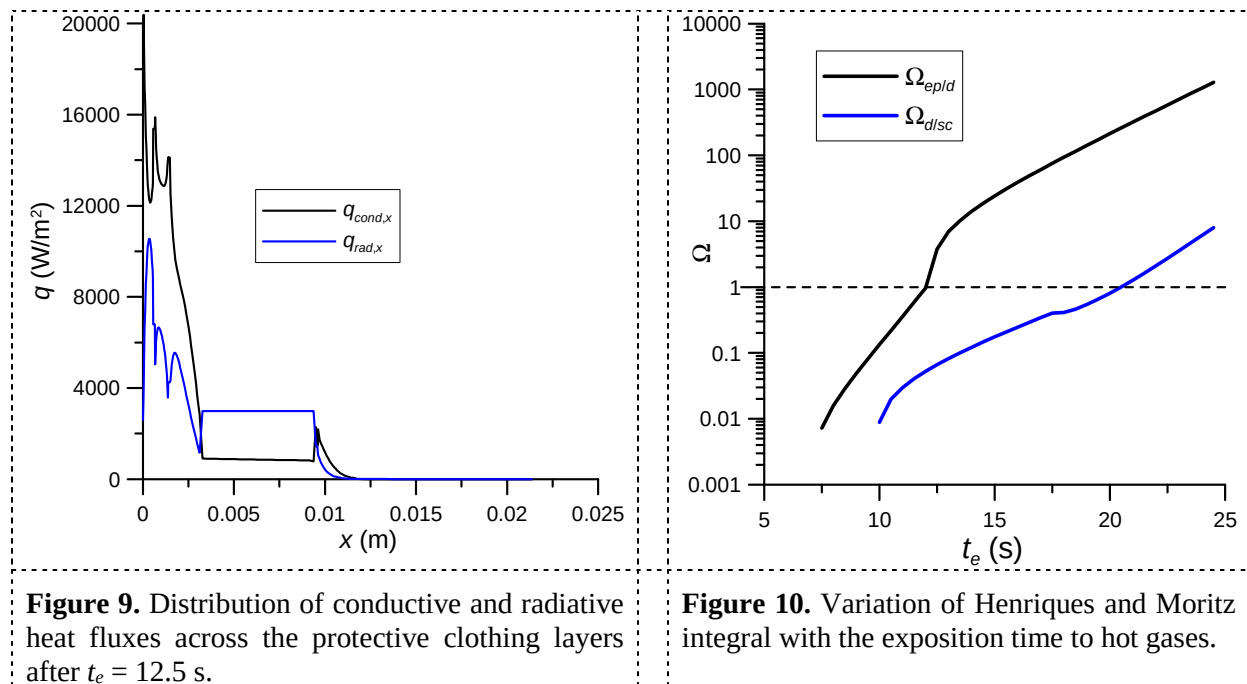
	$P \text{ (s}^{-1}\text{)}$		$\Delta E \text{ (Jkmole}^{-1}\text{)}$	
	$T_i < 50^\circ\text{C}$	$T_i \geq 50^\circ\text{C}$	$T_i < 50^\circ\text{C}$	$T_i \geq 50^\circ\text{C}$
First and second degree	$2.18 \cdot 10^{124}$	$1.82 \cdot 10^{51}$	$7.784 \cdot 10^8$	$3.222 \cdot 10^8$
Third degree	$4.32 \cdot 10^{64}$	$9.39 \cdot 10^{104}$	$4.143 \cdot 10^8$	$6.654 \cdot 10^8$

**Figure 5.** Variation of temperature across the protective clothing, air gaps and skin in time for $t_e = 12.5$ s.**Figure 6.** Variation of temperature at interfaces between epidermis and dermis as well as dermis and subcutaneous in time $t_e = 12.5$ s.**Figure 7.** Distribution of moisture content of the bound water across the protective clothing layers in time for $t_e = 12.5$ s.**Figure 8.** Distribution of water vapour content across the protective clothing layers and air gaps in time for $t_e = 12.5$ s.

Numerical simulations were performed in the following way. Initially temperature and moisture distributions corresponded to the steady state for interaction of the clothing-skin system with the ambient air at temperature T_{amb} . Subsequently the considered protective clothing was convectively and radiatively heated up by hot gases at temperature T_h . The exposition time t_e varied from 1 to 25 s. Next the protective garment was by 210 s cooled down in the surroundings at temperature T_{amb} .

Figure 5 shows temporary distribution of temperature in the clothing, air gap and the skin for $t_e = 12.5$ s. Figure 6 displays variation of temperature at interface between the epidermis and dermis as well as the dermis and subcutaneous for $t_e = 12.5$ s. During the exposition temperature in the garment significantly increased but the skin temperature did not exceeded 46°C . Figures 7 and 8 present distributions of the volume fraction of bound water and water vapor in the fabric layers and air gaps for different moments of time for $t_e = 12.5$ s. The bound water content in the fibers did not change much in time but the volume fraction of water vapor significantly varied during heating and cooling processes. The high concentration of water vapor can be observed in the air gaps. Distribution of conductive and radiative heat fluxes in the clothing, air gap and the skin after $t_e = 12.5$ s is shown in fig. 9. In the clothing and epidermis heat conduction dominated thermal radiation – conductive heat flux was about two times higher than radiative one. But in the air gap between the most inner fabric layer and the skin radiative heat flux was about three times higher than conductive one. Heat flux associated with moist diffusion in the clothing was in the range of 10 to 100 W/m^2 .

Values of Henriques and Moritz integral, calculated from equation 5, are presented in figure 10. The first degree burns appears for exposition time t_e between 11.0 and 11.5 s, the second degree burns for the exposition times higher than $t_e = 12.0$ s while the third degree burns for the exposition times higher than $t_e = 20.0$ s.



9. Conclusions

The advanced thermal model of the fire-protective clothing-air gap-skin system was presented in the paper. The model accounted for different modes of heat and mass transfer i.e. heat conduction and thermal radiation in the fabric layers, air gaps and skin, moisture diffusion in the fabrics pores and air gaps as well sorption and desorption of water in textile fibers. Complex thermal and mass transfer conditions on the internal or external boundaries between the fabric layers and air gaps as well as between the air gap and skin were introduced. Special attention was paid to modelling of thermal

radiation which was coming from the fire, penetrated through the protective clothing and was absorbed by the skin. For the first time non-grey properties as well as optical phenomena at the internal or external boundaries between the fabric layers and air gaps as well as air gap and skin were accounted for. All governing equations were discretized with Finite Volume Method and an iterative solution algorithm of high non-linear system of equations was elaborated. Simulations were performed for different exposition (heating) times and fixed cooling down period. Distributions of temperatures as well the bound water and water vapor contents were calculated. It was found that on contrary to the bound water the water vapor content significantly varied in time. Share of heat conduction and thermal radiation in total heat transfer were analyzed. Subsequently the Henriques and Moritz integral was calculated allowing the risk of skin burns to be evaluated.

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