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Analysis of Influence of Different Heat Transfer Modes on Temperature Distribution in the Protective Clothing and Skin

Piotr Łapka**, Piotr Furmański, Tomasz S. Wiśniewski

*Institute of Heat Engineering, Warsaw University of Technology, Nowowiejska 21/25, 00-665 Warsaw, Poland

Abstract

Analyses of influence of different heat transfer modes on temperature distributions in the firefighter’s multi-layer protective clothing, skin and muscle were carried out. The system under consideration was irradiated from an external source of thermal radiation and consisted of several fabrics separated by thin air gaps and the tissue made of several sublayers. Simulations were performed by applying the in-house 1D numerical model which accounted for coupled heat conduction and thermal radiation in the protective clothing with the associated phase transition of the bound water in fabric fibers and diffusion of water vapor in fabrics and air spaces as well as for heat conduction, thermal radiation and blood flow in the tissue. Complex thermal and mass transfer conditions at the internal and external boundaries were proposed. Special attention was paid to modelling of non-grey thermal radiation penetrating the clothing and being absorbed by the tissue. The results obtained were used to estimate influence of different heat transfer modes present in the system, on temperature distribution in the clothing and tissue and on variation of times needed to reach the I, II and III degree burns.

Keywords: heat and vapor transfer; heat injuries; numerical modelling; protective clothing; skin; thermal radiation;

1. Introduction

Protective garments guard people in many industries, and motor sports or firefighters from heat fluxes coming from high temperatures sources. During regular activity they should keep body temperature as low as possible to ensure

* Corresponding author. Tel.: +48-22-234-5251; fax: +48-22-825-0565.
E-mail address: plapka@itc.pw.edu.pl
Heat and mass transfer processes in the clothing subjected to high heat flux are very complex. Under absence of convection in porous textiles and in air gaps the main heat transfer modes are heat conduction and thermal radiation in a non-grey semi-transparent porous fabric layers and in transparent air spaces. These processes are accompanied by vapor diffusion in the garment and air gaps as well as phase transition of the bound water in fibers in fabrics. The water content takes part both in energy and mass transfer and affects thermal properties of the protective clothing. There are two sources of the moisture in garments: the surrounding and human body. The heat and mass transfer in the protective clothing are coupled with heat transfer in the human tissue and mass transfer at the skin surface. Biological systems are externally complicated and therefore difficult to model. In the human skin and superficial muscle heat is generated by metabolism, which intensity depends on the level of human activity. Simultaneously, heat is transferred by conduction in porous tissue, thermal radiation in a non-grey semi-transparent body and convection of blood in the veins and arteries. All these coupled and non-linear heat and mass transfer processes should be included during modelling of thermal behavior of protective garments and predicting of thermal injuries.

Heat and mass transfer processes in the protective clothing were modelled by many researchers. The first meaningful model was developed and validated by Torvi and Dale [1] for flame-resistant fabrics under high heat flux conditions in an arrangement similar the thermal protective performance test. The model included heat conduction and Beer’s law based volumetric absorption of thermal radiation in the fabric, variable thermal properties and thermochemical reactions in the material, heat transfer in the air space between fabric and test sensor and heat transfer in the sensor during exposure period. The next model for the clothing assembly composed of several fabrics separated by air gaps which accounted for conductive-radiative heat transfer in the system was elaborated by Mell and Lawson [2]. Thermal radiation was modelled in a simplified way in two-step algorithm: inside the fabric by assuming only absorption (Beer’s law) and in air gaps by assuming textile layers as infinitely thin planes absorbing, transmitting and reflecting thermal radiation. The averaged optical properties were obtained by integrating their wavelength dependent values. The model was verified and validated. In turn a complete model, which included coupled conductive and radiative heat transfer as well as moisture transport in the multilayer firefighter protective gear during flash fire exposure, was presented in a series of papers by Chitrphiromsri and Kuznetsov [3], Chitrphiromsri et al. [4] and Song et al. [5]. The regular firefighting protective garments were considered in [3,5], while in [4] an intelligent firefighting thermal-protective gear with water injection system was studied. In these papers textile materials were treated as hygroscopic porous media which consisted of solid fibers, bounded water and gaseous mixture of air and water vapor [3,5] as well as liquid water [4]. Thermal radiation inside fabrics was modelled in a simplified way by introducing a source term into the energy equation similar to the one applied by Torvi and Dale [1]. The Pennes bioheat model [6] and Henriques and Moritz integral [7] were applied to predict burn injuries. The model was validated by using experimental results [5]. The next interesting model was developed by Ghazy and Bergstrom [8,9] and dealt in a more sophisticated way with the air gap between the fabric and skin [8] and additionally with air spaces between fabric layers [9]. First they considered a single-layer fire-resistant fabric [8] and then the multi-layer protective gear [9]. For solution of governing equations the Finite Volume Method (FVM) was applied with Pennes skin model [6]. The Beer’s law accounted for absorption of the incident thermal radiation in the first fabric layer while the Radiative Transfer Equation (RTE) was solved in air gaps. Ghazy and Bergstrom [8,9] investigated time variation of temperature in the clothing, air gaps, and in the skin, time to receive skin burns as well as influence of different parameters on conductive-radiative heat transfer in air gaps. The model presented in [9] with some modifications was also applied for investigation of influence of periodic clothing movement on garments performance [10]. In turn Zhu and Li [11] developed numerical model which dealt with heat and mass transfer during combined drying and pyrolysis process of fabrics in protective gear. The model incorporated heat induced changes in fabric thermophysical properties (pyrolysis) and drying process described by a one-step chemical reaction. The model predictions were in reasonably good agreement with experimental results. In contrast to previous papers thermal wave model of bioheat transfer was applied for simulation of heat transfer in the skin. A model, which investigated heat transfer in a flame-resistant fabric covering the cylinder, when suddenly exposed to convective and radiative heat flux was developed and validated by Zhu et al. [12]. The applied geometry simulated human limb covered by a fabric. The model included heat induced changes in the fabric and dry air thermophysical properties and was based on the one presented in [1], but in contrast to other papers cylindrical coordinate system was used. The effect of air gap thicknesses on mean incident heat flux to the skin
simulant surface was discussed. In the next paper Fu et al. [13] presented and validated heat and moisture transfer model in the multi-layer protective clothing exposed to a low level of thermal radiation. The model included absorption of thermal radiation by moisture, which was present in fabrics and air gaps. Recently, Łapka et al. [14,15] presented a novel model which rigorously dealt with thermal radiation in the fire-clothing-air gap-tissue system. In contrast to other papers spectral optical properties, different values of refractive indices and optical phenomena at interfaces separating different layers were accounted for. Then series of simulations for different heating times and variable incident radiative heat fluxes were performed and the occurrence of possible heat injuries was evaluated.

In the present paper studies on influence of different heat and mass transfer modes on temperature distribution in the clothing and tissue as well as on thermal destruction of the skin were carried out under different incident heat fluxes. Pure heat conduction or combined heat conduction and thermal radiation with either absence or presence of moisture transport were considered. A series of simulations were carried out applying an advanced model, which was based on the previous one presented by Łapka et al. [14,15]. Such analyses will help in a design of better passive thermal personal protections. Till now similar studies were not conducted.

2. Mathematical model

The 1D protective clothing model consisted of three fabric layers and the human tissue separated by air spaces as shown in Fig. 1. The tissue consisted of the skin made of four sublayers (the epidermis, papillary dermis, reticular dermis and subcutaneous) and superficial muscle of different thermophysical and optical properties. The source of thermal radiation was located on the left hand side, while human body was on the right hand side of the system.

2.1. Heat and mass transfer in the clothing

Neglecting convection in the porous textiles and air spaces and presence of free liquid water in fabrics and additionally assuming that cloths contain humid air and are semi-transparent, the energy equation in the protective garment can be written in the following form:

\[
(\rho c)_f \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_f \frac{\partial T}{\partial x} + D_{v-a,ef} \frac{\partial \rho_a}{\partial x} c_{p,v} T \right) + \dot{m}_{v,bw} \left( \Delta h_{vap} + \Delta h_{abs} \right) \frac{\partial q_r}{\partial x}
\]

(1)

where: the first term on the right hand side accounted for heat conduction, the second one for heat transfer associated with diffusion of water vapor, the third one for heat absorbed (released) during transition of water vapor into liquid water bounded in fibers, while the fourth one for thermal radiation. The continuity equation for bounded water which
describes sorption and desorption phenomenon in fibers as well as continuity equation for diffusion of water vapor in air gaps and pores in fabrics, and its phase transition to or from bounded state were given by:

\[
\frac{\partial \rho_w \varepsilon_{bw}}{\partial t} = \dot{m}_{bw} \quad \text{and} \quad \frac{\partial \rho_g \varepsilon_g}{\partial t} = -\frac{\partial}{\partial x} D_{w,a,eff} \frac{\partial \rho_g}{\partial x} - \dot{m}_{bw}
\]

(2)

The quantities in eq. (1) and (2) denote: \(c_p\) – specific heat at constant pressure, \(D_{eff}\) – effective mass diffusivity, \(k_{eff}\) – effective thermal conductivity, \(\dot{m}_{bw}\) – mass rate of transition of moisture from bounded to gaseous state (zero for the air gap), \(q_r\) – radiative heat flux, \(T\) – temperature, \(\Delta h_{abs}\) – heat of desorption, \(\Delta h_{vap}\) – heat of vaporization, \(\varepsilon\) – volume fraction, \(\rho\) – density and \((\rho c)_{eff}\) – effective heat capacity. The sum of volume fractions satisfied the following constraint:

\[\varepsilon_{bw} + \varepsilon_g = 1 \quad \text{or} \quad \varepsilon_g = \varepsilon_a + \varepsilon_v = 1 \quad \text{in the fabric or in the air gap, respectively.}\]

In the equations above the subscripts: \(a, bw, f, g, w,\) and \(v\) correspond to: dry air, bound water, dry fabric, moist air, liquid water and water vapor, respectively. More details on calculation of effective properties and other quantities in eq. (1) and (2) can be found in [3-5,14,15].

2.2. Heat transfer in the tissue

The Pennes bioheat transfer model [6], which assumed isotropic blood perfusion, uniform arterial blood temperature in the tissue and the venous blood temperature equal to the local tissue temperature was in majority applied for modeling of thermal behavior of the skin [3-5,8-11,14,15]. Usually the tissue was modeled as an opaque for thermal radiation. However, it is well known that the skin blood vessels have rather directional structure than isotropic [16]. Moreover, the high incident radiative heat fluxes may increase arterial blood temperature if the tissue is considered as semi-transparent. Therefore in this paper the new bioheat transfer model in the tissue was proposed after Dombrovsky et al. [17]. The model took into account heat transfer in the tissue and in the arterial blood as well as radiative heat transfer and in \(i\)-th tissue layer can be expressed by the formulae:

\[
(1-\varepsilon_1) (\rho c)_b \frac{\partial T}{\partial t} + \frac{\partial}{\partial x} \left[ (1-\varepsilon_3) k_b \frac{\partial T}{\partial x} \right] + h_{b,i} (T_b - T) + (1-\varepsilon_1) q_{m,i} - \left( 1-\varepsilon_1 \right) \frac{K_{a,b}}{K_{a,i}} \frac{\partial q_{r,i}}{\partial x}
\]

(3)

\[
\varepsilon_1 (\rho c)_b \left[ \frac{\partial T}{\partial t} + u_{x,i} \frac{\partial T}{\partial x} \right] = \frac{\partial}{\partial x} \left[ \varepsilon_1 k_b \frac{\partial T}{\partial x} \right] - h_{b,i} (T_b - T) - \varepsilon_1 \frac{K_{a,b}}{K_{a,i}} \frac{\partial q_{r,i}}{\partial x}
\]

(4)

where: \(b\) is blood, \(\varepsilon\) – volumetric fraction of the blood in the tissue, \(h_b\) – volumetric convective heat transfer coefficient between the arterial blood and tissue, \(q_m\) – metabolic heat rate, \(u_x\) – arterial blood velocity. The ratio of panchromatic absorption coefficients of the blood and tissue was assumed to be \(K_{a,b}/K_{a,i} = 1.0\).

2.3. Boundary, interface and initial conditions

Conditions at the external and internal walls for eq. (1)-(4) took the following form:

- The left external wall:

\[
-k_{f} \frac{\partial T}{\partial x} - D_{v,a,eff} \frac{\partial \rho_w}{\partial x} = c_p \left[ T_{in} + q_{\varepsilon} \right] + \int_{\lambda=a}^{\lambda=0} \left[ q_{r,\lambda,f}^{m} - r_{\lambda,f} \sum_{\varepsilon} q_{r,\lambda,\varepsilon}^{m} - (1-r_{\lambda,a}) q_{r,\lambda,a}^{m} \right] d\lambda = 0
\]

(5)

\[
h_{m,e} (\rho_v - \rho_{v,w}) = -D_{v,a,eff} \frac{\partial \rho_g}{\partial x}
\]

(6)
The interface between fabrics and air gaps:

\[
-k_L \frac{\partial T}{\partial L} - D_{v_a}\frac{\partial \rho}{\partial L} - c_{p_s}T_i - k_R \frac{\partial T}{\partial R} - D_{v_a}\frac{\partial \rho}{\partial R} = \frac{q_{r,\lambda,a}^m - q_{r,\lambda,a}^m - (1-r_{a,a})q_{r,\lambda,a}^m}{\lambda_{\lambda,a}} + \frac{q_{r,\lambda,R}^m - q_{r,\lambda,R}^m - (1-r_{a,a})q_{r,\lambda,R}^m}{\lambda_{\lambda,R}}\quad d\lambda = 0
\] (7)

\[
-D_{v_a}\frac{\partial \rho}{\partial L} = - D_{v_a}\frac{\partial \rho}{\partial R}
\] (8)

The skin surface:

\[
-k_a \frac{\partial T}{\partial a} - D_{v_a}\frac{\partial \rho}{\partial a} = \left( c_{p_s}T_a + \Delta h_{\text{vap}} \right) - k_{ep} \frac{\partial T}{\partial ep} + \frac{q_{r,\lambda,a}^m - q_{r,\lambda,a}^m - (1-r_{a,a})q_{r,\lambda,a}^m}{\lambda_{\lambda,a}} + \frac{q_{r,\lambda,ep}^m - q_{r,\lambda,ep}^m - (1-r_{a,a})q_{r,\lambda,ep}^m}{\lambda_{\lambda,ep}}\quad d\lambda = 0
\] (9)

\[
\rho_{v,a} = \rho_{v,\text{sat}} + w\left[ \rho_{v,\text{sat}}(T_i) - \rho_{v,a} \right]
\] (10)

Interfaces between tissue layers: continuity of temperature and heat flux,

The right external wall: \( T_{cr} = 37 \degree C \).

External convective and radiative heat fluxes in eq. (5) were given by following relationships:

\[ q_e = h(T_e - T_w) + h(T_h - T_w) + h_m(\rho_{e,\text{w}} - \rho_{e,\text{w}})c_{v,\text{w}}T_e \text{ and } q_{r,\lambda,a,e} = \epsilon_{\lambda,a}E_h(T_h) + \epsilon_{\lambda,a}E_b(T_e). \]

In the above equations subscripts: \( a \), \( cr \), \( e \), \( ep \), \( f \), \( h \), \( i \), \( in \), \( s \), \( sat \), \( w \), \( \lambda \), \( L \) and \( R \) denote the air, body core, surroundings, epidermis, fabric, hot gases or source of thermal radiation, interface, incident, skin surface, saturated, wall, wavelength, left and right side of the interface, respectively, \( Eb \) is the blackbody emissive power [18], \( h \) and \( hm \) – convective heat and mass transfer coefficients, respectively, \( r \) – surface hemispherical reflectivity [18-20], \( w \) – skin wettedness and \( \epsilon \) – emissivity.

The unknown interface temperatures: \( T_{a}, T_{i} \) and \( T_{s} \) as well as water vapor densities: \( \rho_{v,\text{w}}, \rho_{i}, \rho_{s} \) were calculated from eq. (5), (7) and (9) as well as eq. (6), (8) and (10), respectively. Initial conditions for eq. (1)-(4) corresponded to the steady state distributions of temperature, volume fraction of bound water and water vapor density in the whole system which was in contact only with the surroundings at \( T_{s} \) and relative humidity \( \phi \).

2.4. Radiative heat transfer

The clothing and tissue were assumed semi-transparent and non-grey. Therefore, distribution of spectral radiative intensity was given by the following RTE:

\[
\frac{dI_\lambda}{ds} = - \left( K_{a,\lambda} + K_{\lambda,\lambda} \right) I_\lambda + K_{a,\lambda} I_{a,\lambda} + K_{\lambda,\lambda} I_{\lambda,\lambda} + \frac{K_{\lambda,\lambda}}{4\pi} \int I_\lambda \Phi_\lambda(s' \rightarrow s) d\Omega
\] (11)

where: \( I \) is radiation intensity, \( I_h \) – the blackbody intensity [18], \( K_a \) and \( K_r \) – linear absorption and scattering coefficients, respectively, \( s \) – direction vector, \( \Phi \) – scattering phase function (isotropic in the fabric and Heneyy-Greenstein in the tissue [21]) and \( \Omega \) – solid angle.

The conditions for radiation intensity for \( s \cdot n > 0 \) (where \( n \) is the inward normal vector at the interface) were following:

The left external wall:

\[
I_{\lambda,\lambda} = \frac{q_{r,\lambda,i,\lambda}}{4\pi} + \frac{(1-r_{a,a})q_{r,\lambda,i,\lambda}}{4\pi}
\] (12)
• Interfaces between fabric layers, air gaps and the tissue layers:

\[ I_{\lambda,L} = r_{\lambda,L} \frac{q_{\lambda,L}^{in}}{\pi} + \left(1-r_{\lambda,L}\right) \frac{q_{\lambda,R}^{in}}{\pi} \quad \text{and} \quad I_{\lambda,R} = r_{\lambda,R} \frac{q_{\lambda,L}^{in}}{\pi} + \left(1-r_{\lambda,R}\right) \frac{q_{\lambda,L}^{in}}{\pi} \]  

(13)

• The interface between the muscle and body interior (black wall): \( I_{\lambda,c} = I_{\lambda,b}(T_c) \).

The eq. (12) and (13) assumed diffusive reflection and transmission of incident radiation intensity due to different values of refractive indices on both sides of interfaces. For more details see [14,15,18-20].

2.5. Estimation of tissue thermal damage

The following Henriques and Moritz integral [7] was applied for estimation the degree of burn injuries:

\[ \Omega = \int_{t}^{T_i} P e^{-\Delta E/B T} dt \quad \text{for} \quad T_i \geq 44^\circ C \]  

(14)

where: \( t \) is the time, \( P \) – frequency factor, \( B \) – universal gas constant, \( \Delta E \) – the skin activation energy and \( T_i \) – the interface temperature either between the epidermis and dermis \((e/d)\) for the I and II degree burns or between the dermis and subcutaneous \((d/sc)\) for the III degree burns. The I degree burns occur for \( T_{e/d} \geq 44^\circ C \) and for \( \Omega_{e/d} = 0.53 \), the II ones for \( T_{e/d} \geq 44^\circ C \) and for \( \Omega_{e/d} = 1.0 \), while the III ones for \( T_{d/sc} \geq 44^\circ C \) for \( \Omega_{d/sc} = 1.0 \).

Table 1. Thicknesses [mm] of the fabrics and air gaps

<table>
<thead>
<tr>
<th>Layer</th>
<th>I layer</th>
<th>I gap</th>
<th>II layer</th>
<th>II gap</th>
<th>III layer</th>
<th>III gap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.56</td>
<td>0.1</td>
<td>0.73</td>
<td>0.1</td>
<td>1.66</td>
<td>6.35</td>
</tr>
</tbody>
</table>

Table 3. Optical properties of the fabrics \((iso \text{ – isotropic})\)

<table>
<thead>
<tr>
<th></th>
<th>( K_s, [1/m] )</th>
<th>( K_a, [1/m] )</th>
<th>( K_r, [1/m] )</th>
<th>( n_i )</th>
<th>( \Phi_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I layer</td>
<td>8223.6</td>
<td>4111.8</td>
<td>4111.8</td>
<td>1.19</td>
<td>iso</td>
</tr>
<tr>
<td>II layer</td>
<td>6308.4</td>
<td>3154.2</td>
<td>3154.2</td>
<td>1.11</td>
<td>iso</td>
</tr>
<tr>
<td>III layer</td>
<td>2774.2</td>
<td>1387.1</td>
<td>1387.1</td>
<td>1.07</td>
<td>iso</td>
</tr>
</tbody>
</table>

Table 4. Values of constants in the Henriques-Moritz integral

<table>
<thead>
<tr>
<th>Component</th>
<th>( P ) [1/s]</th>
<th>( \Delta E ) [J/kmole]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_i )</td>
<td>( &lt; 50^\circ C )</td>
<td>( T_i \geq 50^\circ C )</td>
</tr>
<tr>
<td>( T_i )</td>
<td>( &lt; 50^\circ C )</td>
<td>( T_i \geq 50^\circ C )</td>
</tr>
<tr>
<td>I &amp; II</td>
<td>2.18 \times 10^{-12}</td>
<td>1.82 \times 10^{-12}</td>
</tr>
<tr>
<td>III</td>
<td>4.32 \times 10^{-12}</td>
<td>9.39 \times 10^{-10}</td>
</tr>
</tbody>
</table>

3. Results

All equations were coupled and highly non-linear, therefore to solve them the FVM-based in-house iterative algorithm was developed and implemented in C [14,15]. In turn simulations were conducted assuming the following data listed below. The dimensions of the clothing are given in Table 1. Thermophysical and optical properties of fabrics are given in Table 2 and 3, respectively [3,5,14,15]. Fabrics were assumed grey with scattering albedo equal to \( \omega = 0.5 \). The Table 4 contains values of constants in the Henriques and Moritz integral [5]. The thermophysical and optical properties of the skin and muscle are given in Table 5 and 6, respectively [16,17,21]. Due to lack of the optical data for tissues in the wide wavelength range some of them were assumed and distinguish with the red color in Table 6. Optical properties for tissue were available between 0.4 and 1.6 \( \mu \)m [21]. Below 0.2 and above 5.0 \( \mu \)m the tissue was...
assumed opaque (similarly as water), while in the range: 0.2-0.4 \mu m and 1.6-5.0 \mu m constant values corresponding to values for 0.4 and 1.6 \mu m, respectively were taken. The refractive index of the tissue was equal to n_i = 1.45 \cite{21}. Other material properties, boundary and operating parameters were assumed following [4,14,15]: \rho_k = 998.2 \text{ kg/m}^3, c_p = 4185 \text{ J/kg/K}, k_k = 0.5984 \text{ W/m/K, } T_e = 26^\circ \text{C, } p = 101325 \text{ Pa, } \phi = 0.68, \varepsilon = 1.0, \varepsilon_h = 0.15, h_e = 10 \text{ W/m}^2\text{K, } h_m = 0 \text{ W/m}^2\text{K and } h_m = 0.021 \text{ m/s.}

Table 5. Thermophysical properties of the skin and blood (\ell_i – the thickness of the \textit{i}-th tissue layer, \omega_h – the blood perfusion rate of the \textit{i}-th tissue layer)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Epidermis</th>
<th>Papillary dermis</th>
<th>Reticular dermis</th>
<th>Subcutaneous</th>
<th>Muscle</th>
<th>Blood</th>
</tr>
</thead>
<tbody>
<tr>
<td>\rho_i [kg/m^3]</td>
<td>1200.0</td>
<td>1200.0</td>
<td>1200.0</td>
<td>1000.0</td>
<td>1085.0</td>
<td>1060.0</td>
</tr>
<tr>
<td>c_i [J/kg/K]</td>
<td>3589.0</td>
<td>3300.0</td>
<td>3300.0</td>
<td>2674.0</td>
<td>3800.0</td>
<td>3770.0</td>
</tr>
<tr>
<td>k_i [W/m/K]</td>
<td>0.235 0.445</td>
<td>0.445</td>
<td>0.185</td>
<td>0.51 0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L_i [m]</td>
<td>0.1\cdot10^{-3} 0.7\cdot10^{-3}</td>
<td>0.8\cdot10^{-3}</td>
<td>2.0\cdot10^{-3}</td>
<td>8.0\cdot10^{-3}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>\alpha_{w,i} [W/m^3]</td>
<td>0.0 368.1</td>
<td>368.1</td>
<td>368.3</td>
<td>684.2 -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>\omega_h [1/s]</td>
<td>0.0 0.0002</td>
<td>0.0013</td>
<td>0.00011</td>
<td>0.0027 -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>\ell_i [%]</td>
<td>0.0 0.15</td>
<td>0.96</td>
<td>0.07</td>
<td>2.0 -</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>\alpha_{\ell,i} [m/s]</td>
<td>0.0 0.04\cdot10^{-6}</td>
<td>0.52\cdot10^{-6}</td>
<td>0.1\cdot10^{-6}</td>
<td>10.8\cdot10^{-6}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>h_{\ell,i} [W/m^3/K]</td>
<td>0.0 0.79\cdot10^{-1}</td>
<td>5.15\cdot10^{-1}</td>
<td>0.27\cdot10^{-1}</td>
<td>11.13\cdot10^{-1}</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6. Optical properties of the skin and muscle: the black one – from Bashkatov et al. \cite{21}, the red one – assumed (K_a and K, in l/cm, g – the scattering anisotropy parameter)

<table>
<thead>
<tr>
<th>\lambda [nm]</th>
<th>Epidermis</th>
<th>Dermis</th>
<th>Subcutaneous</th>
<th>Muscle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K_{a,\ell}</td>
<td>g_{\ell}</td>
<td>K_{s,\ell}</td>
<td>g_{\ell}</td>
</tr>
<tr>
<td>0 200</td>
<td>Opaque</td>
<td>Opaque</td>
<td>Opaque</td>
<td>Opaque</td>
</tr>
<tr>
<td>200 350</td>
<td>12.96 368.75</td>
<td>0.712</td>
<td>9.13 269.47</td>
<td>0.715</td>
</tr>
<tr>
<td>350 450</td>
<td>12.96 368.75</td>
<td>0.712</td>
<td>9.13 269.47</td>
<td>0.715</td>
</tr>
<tr>
<td>450 550</td>
<td>7.07 276.86</td>
<td>0.745</td>
<td>3.36 162.11</td>
<td>0.715</td>
</tr>
<tr>
<td>550 650</td>
<td>3.08 227.43</td>
<td>0.774</td>
<td>1.72 112.98</td>
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During analyses the clothing was exposed to the external radiative heat flux of q_{total} = \varepsilon_h \sigma T_e^4 = 20, 40 and 80 kW/m^2. These values corresponded to the following temperatures of the external radiation source: T_e = 1237.8, 1472.0 and 1750.5 K, respectively. The exposition time varied between \ell_s = 5 and 140 s. After the heating the system was cooled down in the ambient air. Additionally, influence of moisture transport on clothing performance was analyzed by assuming different perspirations: w = 0.0 (no sweat), 0.1, 0.2, 0.4, 0.8 and 1.0 (wet skin).
Fig. 2. Distributions of temperature: A), B) and C) – in the protective clothing, D), E) and F) in the tissue and arterial blood for different heat transfer modes (C – heat conduction, MT – moisture transport, R – thermal radiation), for variable incident heat fluxes and for $t_e = 40$ s at the end of heating period.

Fig. 3. Temperature distributions in the tissue and arterial blood for different perspiration rates for $t_e = 40$ s.

Influence of different heat transfer modes and incident heat fluxes on the temperature distribution in the protective clothing, tissue and arterial blood at the end of heating period for exposition time $t_e = 40$ s are shown in Fig. 2, where: C, R and MT denotes: heat conduction, thermal radiation and moisture transport, respectively. During simulations of the moisture transfer no presence of the sweat at the skin surface was assumed ($w = 0.0$). The highest temperatures in the garment were attained for pure heat conduction in the clothing. Due to low heat transfer rate through the garment the incident heat flux considerably increased clothing surface temperature. For this case the tissue and arterial blood temperatures were on the low level with no risk of getting burns e.g.: the skin surface temperature did not exceeded 39, 41 and 45°C for 20, 40 and 80 kW/m², respectively. In the case of conjugated heat conduction and thermal radiation energy was more effectively transferred through protective garment to the skin surface and in the tissue. Therefore the temperatures at the external clothing surface and in the fabrics were lower while in the tissue higher than for pure heat
Due to thermal radiation the tissue temperature rose up to 44, 56 and 82°C for 20, 40 and 80 kW/m², respectively. Presence of moisture decreased temperature both in the clothing and tissue. The water vapor on one hand increased heat capacity of the multilayer protective garment and on the other hand decreased its isolating properties. Next influence of the sweating intensity on temperature distribution in the tissue and arterial blood is presented in Fig. 3. The perspiration on the skin surface reduced its temperature compared to the case without sweating, but the sweating intensity did not have significant influence on a drop of the skin temperature. This was due to neglecting convective mass transfer from the skin surface – assumed diffusive vapor transport in the air gap was very low. The perspiration rate also did not affected considerably temperature distribution in the clothing.

The time variations of temperature at epidermis/dermis as well as dermis/subcutaneous interfaces important for burns estimation are presented in Fig. 4. Thermal radiation had the meaningful effect on tissue temperature while moisture transport slightly reduced the interface temperature for all cases. In turn variations of the Henriques and Moritz integral at the interface between the epidermis and dermis (ep/d) as well as the dermis and subcutaneous (d/sc) with the exposition time for different heat and mass transfer modes (C+R and C+R+MT with w = 0.0 and 0.1) are presented in Fig. 5. The times to get different types of burns significantly depended on heat and mass transfer modes. For 20/40/80 kW/m² the II degree burnings appeared after 45/20/10, 50/25/10 and 70/35/15 s for C+R, R+C+MT with w = 0 and R+C+MT with w = 0.1, respectively. Similarly, the III degree burns for 20/40/80 kW/m² occurred after 75/35/20, 80/40/25 and 120/55/30 s, for C+R, R+C+MT with w = 0 and R+C+MT with w = 0.1, respectively. For cases with pure heat conduction (C) as well as heat conduction and moisture transport (C+MT) calculated times to get burns were very long, therefore results for these cases were not presented here.
4. Conclusions

Analysis of influence of different heat and mass transfer modes on temperature distribution in the multilayer protective clothing and in the tissue were carried in this paper. Pure heat conduction as well as combined heat condition and thermal radiation without and with moisture transfer and with different intensities of perspiration were considered. Based on the results obtained the Henriques and Moritz integrals were calculated. The simulations were carried out applying the advanced numerical model, which included heat conduction and thermal radiation in a non-grey fabrics and tissue accompanied by water diffusion in the fabric pores and air gaps with sorption/desorption of liquid water in fibers. The results showed that thermal radiation and moisture transfer exerted a strong influence on the protective clothing and tissue temperatures. Radiative heat transfer led to a rise of the skin temperature, which may result in thermal burns. On the contrary presence of moisture and sweating decreased tissue temperature of about several degrees and extended time to get the II and III degree burns of about 25/15/5 s and 45/20/10 s, respectively, for the following incident heat fluxes: 20/40/80 kW/m².

Acknowledgements

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References