An advanced model of heat and mass transfer in the protective clothing – verification

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Abstract. The paper presents an advanced mathematical and numerical models of heat and mass transfer in the multi-layers protective clothing and in elements of the experimental stand subjected to either high surroundings temperature or high radiative heat flux emitted by hot objects. The model included conductive-radiative heat transfer in the hygroscopic porous fabrics and air gaps as well as conductive heat transfer in components of the stand. Additionally, water vapour diffusion in the pores and air spaces as well as phase transition of the bound water in the fabric fibres (sorption and desorption) were accounted for. The thermal radiation was treated in the rigorous way e.g.: semi-transparent absorbing, emitting and scattering fabrics were assumed a non-grey and all optical phenomena at internal or external walls were modelled. The air was assumed transparent. Complex energy and mass balance as well as optical conditions at internal or external interfaces were formulated in order to find exact values of temperatures, vapour densities and radiation intensities at these interfaces. The obtained highly non-linear coupled system of discrete equation was solve by the in-house iterative algorithm which was based on the Finite Volume Method. The model was then successfully partially verified against the results obtained from commercial software for simplified cases.

1. Introduction
Personal protective garments guard people from the health risk associated with exposition to either high ambient temperature or high heat fluxes coming from hot external objects as well as with direct contact with hot bodies. Such hazardous environment may be encountered in many industries, motor sports, battleground or in firefighting. The protective clothing should perform dual role: maintain comfortable conditions during regular activities and protect from getting severe burns injuries during emergence situations.

The protective clothing are usually made of several layers of fabrics which may be separated by thin air gaps. Usually three or four layers are used i.e.: the outer shell, moisture barrier, thermal insulation and lining. The most external layer – the outer shell – protects from short thermal and mechanical risks. The moisture barrier secures from penetration of water or other liquids. The thermal insulation provides protection from long-term heat expositions. The lining ensures comfort of exploitation of garments. Each textile layer has different thermophysical and optical properties.

Heat and mass transfer processes in the protective clothing expose to either high temperature or radiative heat flux coming from hot objects are very complex. The textile layer are porous materials

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made of hygroscopic fibres. Therefore, coupled energy transfer phenomena \textit{i.e.}: heat conduction by fibres and air in the pores, forced convection induced by body motion or blast of the external air and thermal radiation coming from external heat source and penetrating a non-grey semi-transparent clothing are strongly depended on the structure of the fabrics. Additionally, these processes are accompanied by diffusion and convection of water vapour in the garment as well as sorption and desorption phenomena in fabric fibres. The water content affects energy transfer processes as well as optical and thermophysical properties of the clothing. The surrounding and human body are two main sources of the moisture in garments. Moreover, high temperature which may be observed in the protective clothing lead to thermochemical reaction and changes in the fabric structure as well as in optical and thermophysical properties. All these coupled and non-linear transport phenomena make the thermal modelling of protective garments very difficult.

Several mathematical and numerical models of heat and mass transfer in the protective clothing were presented in the literature but due to complexity of simulated phenomena the simplifying assumptions were usually introduced. Therefore, the role of creditibility analysis of the models by means of either verification or validation is very important. The first substantial models were developed and validated by Torvi and Dale \cite{1} and Torvi and Threlfall \cite{2} for single- and multi-layers protective clothing, respectively. The models accounted for heat conduction and absorption of thermal radiation \textit{(the Beer’s law based model)} in the fabrics, variable thermal properties, thermochemical reactions in the textile layers, heat transfer in the air space between fabric and test sensor and heat transfer in the sensor. The results obtained by the numerical model were compared to those measured for two single-layer clothing. The numerically predicted fabrics temperatures and Stroll second-degree burn criterions were close to those measured. Similar model of conductive-radiative heat transfer in the clothing assembly made of several fabrics separated by thin air gaps was presented by Mell and Lawson \cite{3}. Thermal radiation was modelled in a simplified way in two-step algorithm: inside the fabric by assuming only absorption \textit{(the Beer’s law and averaged optical properties obtained by integrating their wavelength dependent values)} and in the air gaps by assuming textile layers as infinitely thin planes which absorb, transmit and reflect thermal radiation. At first the model was verified by comparing obtained results with solution of simplified analytical problem and then validated by experimental measurements for three-layers protective turnout coat. Next thermal model of single-layer protective garment worn by an instrumented manikin exposed to laboratory-controlled flash fire was developed by Song \cite{4}. They considered conductive-radiative heat transfer in a similar way as in the previous papers \cite{1-3}. The model accounted for characteristics of the experimentally simulated flash fire, the heat-induced changes in the fabric thermophysical properties and the size of the air gap between garment and the manikin. The model was validated using an instrumented manikin fire test system. A model, which included coupled conductive and radiative heat transfer as well as moisture transport in the multi-layers firefighter protective gear during flash fire exposure and cooling process was presented by Song \textit{et al.} \cite{5}. In this paper textile layers were treated as hygroscopic porous media which consisted of solid fibres, bounded water and mixture of air and water vapour filling pores. Thermal radiation inside fabrics was modelled in a simplified way similarly as in \cite{1}. The model was validated by using experimental results for different fabric systems (from one- and two- to multi-layers protective gear) and different system configurations (without and with an air gap between garment and the sensor). Good agreement between model predictions and experimental tests was observed. In turn Ghazy and Bergstrom \cite{6} developed a model of heat transfer in a single-layer fire resistant fabric which dealt in a more sophisticated way with the air gap between the fabric and skin. The Beer’s law accounted for absorption of the incident thermal radiation in the textile layer while the radiative transfer equation was solved in the air gaps. The model was validated by simulating the thermal protective performance tests for single textile layer. The numerical results closely predicted experimental observations. Then the model was extended to predict thermal behaviour of the protective clothing composed of three textile layers separated by two air gaps \cite{7}. In the next paper Zhu and Li \cite{8} developed and validated an interesting numerical model of heat and mass transfer during combined drying and pyrolysis process of fabrics. The model incorporated heat induced changes in fabric thermophysical properties \textit{(pyrolysis)}. The model predictions were validated by experimental data from modified radiant

\cite{1-8}. Good agreement between model predictions and experimental tests was observed.
protective performance tests of single cotton fabric. The results obtained (fabric mass loss rates, temperature profiles in the textile layer and skin simulant and the required time to 2nd degree skin burn) were in reasonably good agreement with experimental results. A model, which investigated heat transfer in a flame-resistant fabric which covered the cylinder simulating human limb and which was exposed to convective and radiative heat fluxed was developed by Zhu et al. [9]. The model included heat induced changes in the fabric and dry air thermophysical properties and was based on the one presented by Torvi and Dale [1], but in contrast to other papers cylindrical coordinate system was used. The model predictions were validated by comparing results obtained (temperatures at front and back side of fabric and at skin simulant) with experimental measurements for single textile layer. An integrated numerical simulator for thermal performance assessment of the protective clothing was reported by Jiang et al. [10]. The model consisted of 3D general purpose computational fluid dynamics code for calculations of heat and fluid flow during the fire and 1D model for simulation of conductive-radiative heat transfer through the clothing and human skin simulant. Double-way integration of 1D and 3D simulators was elaborated. Then the model was validated by a full-scale benchmark experiments. The predicted temperature distributions in the clothing, heat fluxes falling on the skin simulant surface and burn degrees agreed with experimental measurements reasonably well. In turn Fu et al. [11] presented heat and moisture transfer model in the multi-layers protective clothing with the air gaps exposed to low levels of thermal radiation. They included absorption of thermal radiation by moisture, which was present in the fabrics and air gaps. The model was successfully verified and validated.

Recently, Łapka et al. [12, 13] presented a novel model of heat and mass transfer in the protective clothing exposed to the external source of thermal radiation. In comparison to the previous models the one developed in [12, 13] in a rigorous way dealt with thermal radiation which penetrated the garment. The semi-transparent fabrics were assumed a non-grey and may absorb, emit and scatter thermal radiation. Additionally, different values of refractive indices as well as optical phenomena at interfaces separating different layers of the clothing were accounted for. Moreover, complex energy and mass balance as well as optical conditions at internal or external interfaces were formulated in order to find exact values of temperatures, vapour densities and radiation intensities at these interfaces. Although the model produced reasonable results, it accuracy was not proven. Therefore verification procedure of the model is presented in this paper. The credibility analyses consisted of two steps. In the first one the influences of spatial, time, angular and wavelength discretizations levels on the produced results were investigated. Then in the second step the model predictions were compared with the predictions obtained applying commercial software for simplified cases.

![Diagram of the protective clothing and experimental stand](image)

**Figure 1.** Model of the protective clothing and experimental stand ($T_c$, $T_h$, $T_i$, $T_p$, $T_s$ and $T_w$ are temperatures of the cooling water, external heat source, interfaces between the fabric layers and air gaps, the surface of the plate, the right external surface and the left external surface, respectively).
2. Mathematical formulation

A system under consideration was composed of three fabric layers: the outer shell, moist barrier and thermal insulation separated by two narrow air gaps, the wide air gap and the plate stabilizing temperature as presented in Figure 1. The external heat source was located on the left hand side, while right boundary was convectively cooled by flowing water. The model assumed one dimensional heat and moisture transfer due to the small thickness of the considered system in comparison to its lateral dimensions along the protective clothing and assumed no variation of external thermal conditions in this direction.

2.1. Heat and mass transfer in the fabrics and air gaps as well as heat transfer in the plate

Neglecting convection in the hygroscopic porous fabrics and in the air gaps as well as presence of free liquid water in the fabric (only liquid water bounded by fibres) and additionally assuming that cloths contain humid air (dry air is stationary, water vapour may diffuse) and are semi-transparent, the energy equation in the protective garment can be written in the following form:

\[
\left( \rho c_p \right)_f \frac{dT}{dt} = \frac{\partial}{\partial x} \left[ k_{ef} \frac{\partial T}{\partial x} + D_{v-a,ef} \frac{\partial}{\partial x} \left( \rho c_p T \right) \right] + m_{v-bw} \left( \Delta h_{vap} + \Delta h_{abs} \right) - \frac{\partial q_r}{\partial x}
\]

(1)

where: the first term on the right hand side accounted for heat conduction in the fabrics or air gaps, the second one for heat transfer associated with diffusion of water vapour in the fabrics and air gaps, the third one for heat absorbed (released) during transition of water vapour into liquid water bounded in fibres in fabrics, while the fourth one for thermal radiation in the fabrics (the air was transparent).

The continuity equation for bounded water in fibres (describes sorption and desorption phenomenon) was as follows:

\[
\frac{\partial \rho c_p \varepsilon_{bw}}{\partial t} = m_{v-bw}
\]

(2)

while diffusion of water vapour through pores and air gaps and its phase transition to or from bounded state was modelled by following equation:

\[
\frac{\partial \rho c_p \varepsilon_v}{\partial t} = \frac{\partial}{\partial x} D_{v-a,ef} \frac{\partial}{\partial x} \left( \rho c_p \right) - m_{v-bw}
\]

(3)

The energy equation for conductive heat transfer in the aluminium plate was in the following form:

\[
\left( \rho c_p \right)_p \frac{dT}{dt} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right)
\]

(4)

The quantities in equations (1)-(4) denote: \( c_p \) – specific heat at constant pressure, \( D_{eff} \) – effective mass diffusivity, \( k_{eff} \) – effective thermal conductivity, \( m_{v-bw} \) – mass rate of transition of moisture from gaseous state to liquid state, \( q_r \) – radiative heat flux, \( T \) – temperature, \( \Delta h_{vap} \) – heat of evaporation, \( \Delta h_{abs} \) – heat of adsorption, \( \varepsilon_{bw} \) – volume fraction of liquid water, \( \varepsilon_v \) – volume fraction of water vapour, \( \epsilon_s \) – volume fraction of dry air, \( \rho \) – density and \( (\rho c_p)_{eff} \) – effective heat capacity. The sum of volume fractions satisfied the following constraint: \( \varepsilon_{bw} + \varepsilon_v + \varepsilon_s = 1 \) or \( \varepsilon_s = \varepsilon_v + \varepsilon_s = 1 \) in the fabrics or in the air gaps, respectively. In the equations above the subscripts: \( a, bw, f, g, p, w, \) and \( v \) correspond to: dry air, bound water, dry fabric, moist air, plate, liquid water and water vapour, respectively. More details on calculation of effective properties and other quantities in equations (1)-(4) can be found in [5, 12-14].

2.2. Radiative heat transfer

The clothing was assumed semi-transparent and a non-grey. Therefore, distribution of spectral radiative intensity was given by the following radiative transfer equation [15-18]:

\[
\text{...}
\]

\[
\text{...}
\]
\[ \frac{dI_s}{ds} = -\left( K_{a,\lambda} + K_{r,\lambda} \right) I_s + K_{s,\lambda} I_{b,\lambda} + \frac{K_{s,\lambda}}{4\pi} \int I_s \Phi_{\lambda} (s' \rightarrow s) d\Omega \]  

(5)

where: \( I \) is radiation intensity, \( I_b \) – the blackbody intensity \[15\], \( K_a \) and \( K_r \) – linear absorption and scattering coefficients, respectively, \( s \) – direction vector, \( \lambda \) – wavelength, \( \Phi \) – scattering phase function (isotropic in the fabric) and \( \Omega \) – solid angle.

2.3. Boundary, interface and initial conditions

The external and internal interfaces were considered either transparent \( e.g. \): diffusively reflecting and transmitting the incident thermal radiation or semi-transparent absorbing, emitting and diffusively reflecting and transmitting the incident thermal radiation. The conditions at the external and internal walls for energy equations (1) and (4) as well as for continuity equation (3) for water vapour took the following form:

- The left external wall:

\[ -k_{ef} \frac{\partial T}{\partial x} \bigg|_L - D_{v,a,ef} \frac{\partial \rho_s}{\partial x} \bigg|_L c_{p,ef} T_{ef} + q_{v/net}^{ef} + q_{r/net}^{ef} = 0 \]  

(6)

\[ h_{m,e} (T_{v,ef} - T_{v,ea}) = -D_{v,a,ef} \frac{\partial \rho_s}{\partial x} \bigg|_{ef} \]  

(7)

Considering two optical types of the interfaces the conditions for radiation intensity at the left external wall (for \( s \cdot n_f > 0 \), where: \( n_f \) is the inward normal vector at the interface) and sum of net radiative heat fluxes were following:

- For transparent interface:

\[ I_{\lambda,w} = \tilde{r}_{\lambda,f} \frac{q_{\lambda,f}^{in}}{\pi} + (1 - \tilde{r}_{\lambda,a}) \frac{q_{\lambda,e}^{in}}{\pi} \]  

(8)

\[ q_{v,ef}^{net} + q_{r,ef}^{net} = \int_0^\infty \left[ q_{\lambda,f}^{in} - \tilde{r}_{\lambda,f} q_{\lambda,f}^{in} - (1 - \tilde{r}_{\lambda,a}) q_{\lambda,e}^{in} + q_{\lambda,e}^{in} - \tilde{r}_{\lambda,a} q_{\lambda,e}^{in} - (1 - \tilde{r}_{\lambda,f}) q_{\lambda,f}^{in} \right] d\lambda \]  

(9)

- For semi-transparent interface:

\[ I_{\lambda,w} = \epsilon_{\lambda,f} I_{b,\lambda} (T_{w}) + r_{\lambda,f} \frac{q_{\lambda,f}^{in}}{\pi} + t_{\lambda,a} \frac{n_{\lambda,f}^2 q_{\lambda,e}^{in}}{n_{\lambda,a}^2} \]  

(10)

\[ q_{v,ef}^{net} + q_{r,ef}^{net} = \int_0^\infty \left[ q_{\lambda,f}^{in} - \epsilon_{\lambda,f} E_{b,\lambda} (T_{w}) - r_{\lambda,f} q_{\lambda,e}^{in} + t_{\lambda,a} \frac{n_{\lambda,e}^2 q_{\lambda,e}^{in}}{n_{\lambda,a}^2} + q_{\lambda,e}^{in} - \epsilon_{\lambda,a} E_{b,\lambda} (T_{w}) - r_{\lambda,a} q_{\lambda,e}^{in} - t_{\lambda,f} \frac{n_{\lambda,e}^2 q_{\lambda,f}^{in}}{n_{\lambda,f}^2} \right] d\lambda \]  

(11)

- The interface between fabric layers and air gaps or between two fabric layers if there is no air gap (where: \( L \) and \( R \) denote the left and right side of the interface, respectively):

\[ -k_L \frac{\partial T}{\partial x} \bigg|_L - D_{v,a,ef,L} \frac{\partial \rho_s}{\partial x} \bigg|_L c_{p,ef} T_{ef} - k_R \frac{\partial T}{\partial x} \bigg|_R - D_{v,a,ef,R} \frac{\partial \rho_s}{\partial x} \bigg|_R c_{p,ef} T_{ef} + q_{v,ef}^{net} + q_{r,ef}^{net} = 0 \]  

(12)

\[ -D_{v,a,ef,L} \frac{\partial \rho_s}{\partial x} \bigg|_L = -D_{v,a,ef,R} \frac{\partial \rho_s}{\partial x} \bigg|_R \]  

(13)
For transparent or semi-transparent interface radiation intensities (for \( \mathbf{s} \cdot \mathbf{n}_L > 0 \) and \( \mathbf{s} \cdot \mathbf{n}_R > 0 \), where: \( \mathbf{n}_L \) and \( \mathbf{n}_R \) are the inward normal vectors at the interface) and sum of net radiative heat fluxes were following:

- **For transparent interface:**
  \[
  I_{\lambda,L} = r_{\lambda,L,R} \frac{q_{\lambda,L}^{in}}{\pi} + (1 - r_{\lambda,L,R}) \frac{q_{\lambda,R}^{in}}{\pi} \quad \text{and} \quad I_{\lambda,R} = r_{\lambda,R,L} \frac{q_{\lambda,R}^{in}}{\pi} + (1 - r_{\lambda,R,L}) \frac{q_{\lambda,L}^{in}}{\pi}
  \]
  \[q_{r,e}^{net} + q_{r,f}^{net} = \hat{\int}_0 \left[ q_{\lambda,L}^{in} - r_{\lambda,L} q_{\lambda,L}^{in} - (1 - r_{\lambda,L}) q_{\lambda,R}^{in} + r_{\lambda,R} q_{\lambda,R}^{in} - r_{\lambda,R} q_{\lambda,L}^{in} - (1 - r_{\lambda,R}) q_{\lambda,L}^{in} \right] \, d\lambda \]  

- **For semi-transparent interface:**
  \[
  I_{\lambda,L} = \varepsilon_{\lambda,L} I_{\lambda,0,L} (T_c) + r_{\lambda,L} \frac{q_{\lambda,L}^{in}}{\pi} + t_{\lambda,L} \frac{n_{\lambda,L}^2}{n_{\lambda,R}^2} q_{\lambda,R}^{in} \quad \text{and} \quad I_{\lambda,R} = \varepsilon_{\lambda,R} I_{\lambda,0,R} (T_c) + r_{\lambda,R} \frac{q_{\lambda,R}^{in}}{\pi} + t_{\lambda,R} \frac{n_{\lambda,R}^2}{n_{\lambda,L}^2} q_{\lambda,L}^{in}
  \]
  \[q_{r,e}^{net} + q_{r,f}^{net} = \hat{\int}_0 \left[ q_{\lambda,L}^{in} - \varepsilon_{\lambda,L} E_{b,L} (T_c) - r_{\lambda,L} q_{\lambda,L}^{in} - t_{\lambda,L} \frac{n_{\lambda,L}^2}{n_{\lambda,R}^2} q_{\lambda,R}^{in} + q_{\lambda,R}^{in} - \varepsilon_{\lambda,R} E_{b,R} (T_c) - r_{\lambda,R} q_{\lambda,R}^{in} - t_{\lambda,R} \frac{n_{\lambda,R}^2}{n_{\lambda,L}^2} q_{\lambda,L}^{in} \right] \, d\lambda + \]

- **The plate surface:**
  \[
  -k_e \frac{\partial T}{\partial x} - k_r \frac{\partial T}{\partial x} + q_{r,e}^{net} = 0
  \]
  \[-D_v \frac{\partial \rho}{\partial x} = 0
  \]

For opaque interface radiation intensity (for \( \mathbf{s} \cdot \mathbf{n}_p > 0 \), where: \( \mathbf{n}_p \) is the inward normal vector at the interface) and net radiative heat flux were following:

- **For opaque interface:**
  \[
  I_{\lambda,p} = \varepsilon_{\lambda,p} I_{\lambda,0,p} (T_p) + (1 - \varepsilon_{\lambda,p}) \frac{q_{\lambda,p}^{in}}{\pi}
  \]
  \[q_{r,e}^{net} = \hat{\int}_0 \left[ q_{\lambda,p}^{in} - \varepsilon_{\lambda,p} E_{b,p} (T_p) - (1 - \varepsilon_{\lambda,p}) q_{\lambda,p}^{in} \right] \, d\lambda
  \]

- **The right external wall:**
  \[
  -k_p \frac{\partial T}{\partial x} = h_t (T_r - T_c)
  \]

The external convective and radiative heat fluxes in equation (6), (8)-(11) were given by following relationships:

\[
q_e = h_t (T_r - T_c) + h_n (T_n - T_w) + h_m\rho_{v,e} \rho_{v,w} c_p v_c T_e \quad \text{and} \quad q_{\lambda,e} = \varepsilon_{\lambda}\varepsilon_{b,e} (T_e) + \varepsilon_{\lambda} E_{b,\lambda} (T_e)
\]

In the above equations subscripts and superscripts: \( a, c, e, f, h, i, \text{in}, p, s, v, L \) and \( R \) denote the air, cooling water, surroundings, fabric, hot gases or source of thermal radiation, interface, incident, plate surface, left and right side of the interface, respectively, while \( E_b \) is the blackbody emissive power.
[15], \( h \) and \( h_m \) – convective heat and mass transfer coefficients, respectively, \( n \) – refractive index, \( q \) – heat flux, \( r \) and \( \tilde{r} \) – surface reflectivity and hemispherical surface reflectivity [15, 18, 19], respectively, \( t \) – surface transmissivity and \( \epsilon \) – surface emissivity.

The unknown interface temperatures: \( T_w \), \( T_i \), \( T_p \) and \( T_s \) as well as water vapour densities: \( \rho_{v,w} \), \( \rho_{v,i} \) and \( \rho_{v,p} \) were calculated from equations (6), (12), (18) and (21) as well as equations (7), (13) and (19), respectively. The equations (8) and (14) assumed diffusive reflection and transmission of incident radiation intensity due to different values of refractive indices on both sides of interfaces, while equations (10) and (16) emission and diffusive reflection and transmission of incident radiation intensity. For more details see [17-19]. Initial conditions for equations (1)-(4) corresponded to the steady state distributions of temperature, volume fraction of bound water and water vapour density in the whole system which was in contact only with surroundings at \( T_e \) and relative humidity \( \phi_e \).

![Flowchart of solution algorithm](image_url)

**Figure 2.** Flowchart of solution algorithm.
3. Numerical solutions
The energy, mass balance and radiative transfer equations (1)-(5) were discretized applying the Finite Volume Method [20]. The equations (1)-(4) were integrated over infinitesimal distance \( dx \) and time interval \( dt \), while the radiative transfer equation over infinitesimal distance \( dx \), solid angle \( d\Omega \) and bandwidth \( d\lambda \). The unknown temperatures at the external and internal interfaces were calculated from non-linear conditions given by equations (6), (12) and (18) by using iterative algorithm based on the Newton-Raphson Method [21], while the water vapour densities at these walls were found from discretized mass balance conditions described by equations (7), (13) and (19). The Band Model [15] accounted for spectral optical properties. All equations were coupled and highly non-linear, therefore for the solution of the system of equations special in-house iterative algorithm was developed and implemented in programming language C. The general flowchart of the computational algorithm is presented in Figure 2.

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

| Layer | Gap | Layer | Gap | Layer | Gap |
|-------|-----|-------|-----|-------|-----|
| I     | 0.56| II    | 0.73| III   | 1.66 |
|       | 0.1 |       | 0.1 |       | 6.35 |

### Table 2. Thermophysical properties of fabrics (\( R_{f,\phi=0.65} \) – the fibre regain at \( \phi = 0.65 \), \( D_f \) – the effective diffusivity of the bound water in the fibre, \( d_f \) – the average fibre diameter, \( \tau \) – the tortuosity factor, other quantities explained in the text).

| Layer | \( \rho_f \) [kg/m\(^3\)] | \( c_f \) [J/kg/K] | \( k_f \) [W/m/K] | \( \varepsilon_f \) | \( R_{f,\phi=0.65} \) | \( D_f \) [m\(^2\)/s] | \( d_f \) [m] |
|-------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|
| I     | 1384.0          | 1295.0          | 0.179           | 0.334          | 0.084           | 1.5             | 1.6 \( \times \) 10\(^{-5}\) |
| II    | 1295.0          | 0.144.0         | 0.186           | 0.115          | 0.038           | 1.25            | 1.6 \( \times \) 10\(^{-5}\) |
| III   | 1380.0          | 0.130           | 1.0             | 1.0            | 0.045           | 6.0 \( \times \) 10\(^{-14}\) | 1.6 \( \times \) 10\(^{-5}\) |

### Table 3. Optical properties of the fabrics (\( iso. \) – isotropic).

| Layer | \( K_e \) [1/m] | \( K_a \) [1/m] | \( K_s \) [1/m] | \( n \) | \( \Phi \) |
|-------|-----------------|-----------------|-----------------|------|-------|
| I     | 8223.6          | 4111.8          | 4111.8          | 1.19 | iso.  |
| II    | 6308.4          | 3154.2          | 3154.2          | 1.11 | iso.  |
| III   | 2774.2          | 1387.1          | 1387.1          | 1.07 | iso.  |

4. Data for simulations
Most of numerical simulations were conducted assuming the following data listed below [5, 12-14]. The dimensions of the clothing are given in Table 1. Thermophysical and optical properties of fabrics are presented in Table 2 and 3, respectively. Fabrics were assumed grey with scattering albedo equal to \( \omega = 0.5 \). Other necessary material properties, boundary and operating parameters were following [5, 12-14]: \( \rho_w = 998.2 \) kg/m\(^3\), \( c_w = 4185 \) J/kg/K, \( k_w = 0.5984 \) W/m/K (\( w \) – water), \( k_v = 0.018 \) W/m/K, \( T_c = 32^\circ \)C, \( T_e = 26^\circ \)C, \( p = 101325 \) Pa, \( \phi = 0.6 \), \( \varepsilon_s = 1.0 \), \( h_e = 100 \) W/m\(^2\)/K, \( h_v = 15 \) W/m\(^2\)/K, \( h_b = 0 \) W/m\(^2\)/K and \( h_m = 0.021 \) m/s. The plate thickness was \( L_p = 0.012 \) m and was made of aluminium of following properties: \( \rho_p = 2800 \) kg/m\(^3\), \( c_p = 913 \) J/kg/K, \( k_p = 165 \) W/m/K and \( \varepsilon_p = 0.1 \). The plate was convectively cooled by water at \( T_c = 32^\circ \)C and with \( h_e = 100 \) W/m\(^2\)/K. During analyses the protective clothing was exposed to the external radiative heat flux of \( q_{total} = \varepsilon_s \sigma T_h^4 = 20, 40 \) and \( 80 \) kW/m\(^2\). These
values corresponded to the following temperatures of the external radiative heat source: $T_h = 1237.79$, 1471.99 and 1750.50 K, respectively. The exposition time varied between $t_e = 4$ and 30 s. After the initial heating the system was cooled down in the ambient air. During the simulations default discretization levels were as follows:

- Spatial: each layer was divided into $N_l = 25$ elements (all together $N_s = 175$ nodes were generated in the computational domain).
- Angular: the polar and azimuthal angles were divided into $N_\theta \times N_\phi = 2 \times 4$.
- Time: time step was equal to $dt = 0.05s$.

5. Results of simulations

5.1. Influence of discretization levels

In the first step of verification of developed model influences of spatial, time, angular and wavelength discretizations levels on the obtained solutions were investigated. Simulations were performed for multi-layers protective clothing presented in Figure 1 and for three values of incident radiative heat flux $q_{\text{total}} = 20$, 40 and 80 kW/m$^2$ as well as for three times of exposition $t_e = 10$, 20 and 30 s. Other material properties and parameters assumed during the simulations were described in section 4.

![Graph A](image1.png)

![Graph B](image2.png)

![Graph C](image3.png)

**Figure 3.** Distributions of temperature in the clothing and in a former part of the aluminium plate for $t_e = 20$ s and for: A) $q_{\text{total}} = 20$ kW/m$^2$, B) $q_{\text{total}} = 40$ kW/m$^2$ and C) $q_{\text{total}} = 80$ kW/m$^2$ just after the heating period as well as after 10 and 20 s of the cooling stage in the surroundings.
5.1.1. Spatial grid size studies
The first calculations were performed for variable numbers of nodes in the spatial domain. Each layer of the system was divided into \( N_l = 12, 25 \) and 50 elements. All together three meshes of \( N_s = 84, 175 \) and 350 nodes were generated. Obtained distributions of temperature in the clothing and in a former part of the aluminium plate for exposition time \( t_e = 20 \text{ s} \) and for variable incident radiative heat flux i.e.: \( q_{\text{total}} = 20, 40 \) and 80 \( \text{kW/m}^2 \) just after the heating period as well as after 10 and 20 s of the cooling stage in the surroundings are presented in Figure 3. For clarity only results for clothing, the wide air gap and top part of the plate (2 mm) are presented. The results for different meshes matches each other. Small discrepancies between results for different grids are observed in the largest air gap. The source of them is probably temperature dependent thermal conductivity of the air. In the numerical model the thermal conductivity was calculated for nodal values of temperature instead of averaged over the mesh element.

5.1.2. Time step size studies
Next studies were performed for variable time step size. Three values were considered: \( dt = 0.025, 0.05 \) and 0.1 s. It was found that decreasing or increasing of time step size had negligible effect on obtained results e.g.: relative differences between temperature distributions calculated for two different time step sizes were below 1% for all analysed cases.

5.1.3. Angular discretization level and number of bands studies
In turn influence of angular discretizations levels were studied. Four divisions of polar and azimuthal angles were considered: \( N_\theta \times N_\phi = 2 \times 4, 4 \times 4, 4 \times 8 \) and 8\times8. It was observed that increasing polar angle discretisation from \( N_\theta = 2 \) to 4 and from 4 to 8 had minor effect on relative differences between temperature distributions in the clothing obtained for two different polar angle divisions, but changing azimuthal angle division from \( N_\phi = 4 \) to 8 results in maximal relative differences between temperature distributions calculated for two different azimuthal angle discretization up to 7%. This effect is related to rise in the accuracy of calculations of thermal radiation with increasing of angular discretization level. For larger number of discrete direction the ray effect is reduced.

At the end influence of number of bands was investigated. Simulations were performed for number of bands equal to: \( N_b = 1, 4 \) and 8. Each band had the same constant optical properties which were defined in Table 3. It was found that number of bands did not affect the obtained results.

| \( \lambda_1 [\mu m] \) | \( \lambda_2 [\mu m] \) | \( K_{a,1} [1/m] \) | \( K_{s,1} [1/m] \) | \( \Phi_{\lambda} \) |
|-----------------|-----------------|-----------------|-----------------|--------|
| 0               | 1.0             | 1386.3          | 0.0             | iso.   |
| 1.0             | 2.5             | 2772.6          | 0.0             | iso.   |
| 2.5             | 5.0             | 5991.5          | 0.0             | iso.   |
| 5.0             | \( \infty \)    | opaque          | 0.0             | iso.   |

5.2. Conductive-radiative heat transfer in the single- and multi-layers clothing system
Consecutively, the part of the numerical simulator responsible for calculations of conjugated conductive and radiative heat transfer was verified by comparing predicted temperature distributions with the results obtained by applying commercial code ANSYS Fluent. At first the system which consisted of a single fabric layer (layer I, outer shell – see Table 1 and 2), the wide air gap and the plate was considered. The fabric was assumed a non-grey with the spectral absorption and scattering coefficients given in Table 4 [3], while the refractive index was the same in each band and was presented in Table 3. Additionally, the outer fabric surface was assumed opaque (\( \varepsilon_w = 0.9 \)), while the inner one transparent to the thermal radiation. The system was convectively heated by hot gases at \( T_h = 1400.0 \text{ K} \) and with \( h_h = 120.0 \text{ W/m}^2\text{K} \). The exposition time was \( t_e = 4 \text{ s} \). Then clothing was convectively and radiatively cooled down in the surroundings at \( T_e = 26^\circ \text{C} \) and with \( h_e = 15 \text{ W/m}^2\text{K} \).
Other parameters were defined in section 4. The obtained distributions of temperature in the system just after the heating period as well as after 5 and 10 s of the cooling stage are presented in Figure 4. Perfect matching of predictions obtained applying present model with results from ANSYS Fluent was observed. Relative difference between results were below 1%.

**Figure 4.** Comparison of distributions of temperature in the single-layer clothing just after the heating period \((t = t_e)\) as well as after 5 \((t = t_e+5)\) and 10 s \((t = t_e+10)\) of the cooling stage in the surroundings (PM – present model, Ref. – ANSYS Fluent).

The next comparison was performed for a system which consisted of a multi-layers protective clothing (three fabric layers separated by thin air gaps), the wide air space and the aluminium plate – see Figure 1. Similarly as in the previous analyses, the system was exposed by \(t_e = 4\) s to the hot gases at \(T_h = 1400.0\) K and with \(h_e = 120.0\) W/m²/K and then cooled down in the surroundings at \(T_e = 26°C\) and with \(h_e = 15\) W/m²/K. The clothing configuration and thermophysical data assumed during simulations were given in Table 2 and 3. Additionally, fabrics were assumed a non-grey. The spectral absorption and scattering coefficients were the same in each textile layer and were presented in Table 5, while refractive index was wavelength independent and fixed for each fabric – see Table 3. Moreover, the outer fabric surface was assumed opaque \((\varepsilon_w = 0.9)\), while the interfaces between fabrics and air gaps inside the clothing were transparent to the thermal radiation. Other parameters were defined in section 4. Again very good agreement between results from present numerical simulator and from commercial code can be noticed in Figure 5. This time relative difference between results from the in-house and commercial software were below 2%.

**Figure 5.** Comparison of distributions of temperature in the multi-layers clothing just after the heating period \((t = t_e)\) as well as after 5 \((t = t_e+5)\) and 10 s \((t = t_e+10)\) of the cooling stage in the surroundings (PM – present model, Ref. – ANSYS Fluent).

### 6. Conclusions

The paper presents partial credibility analysis of a novel advanced numerical simulator of a heat and mass transfer in the multi-layers protective clothing and in the elements of the experimental stand subjected to either high temperature environment or high incident radiative heat flux emitted by hot objects. The developed numerical model accounted for conjugated conductive and radiative heat transfer in the hygroscopic and a non-grey porous fabrics and in transparent air filling the gaps as well as conductive heat transfer in opaque components of the stand. Moreover water vapour diffusion in the pores and air spaces as well as phase transition of the bound water in the fabric fibres (sorption and desorption) were included. Complex energy and mass balance as well as optical conditions between clothing layers were formulated in order to find exact values of temperatures, vapour densities and radiation intensities at these interfaces. The obtained highly non-linear coupled system of discrete
equations was solved by in-house iterative numerical algorithm which was based on the Finite Volume Method. Additionally, the unknown temperatures at the external and internal interfaces were calculated using the Newton-Raphson Method, while the Band Model accounted for spectral optical properties.

In turn, the correctness and accuracy of the results predicted by the developed model were assessed. At first, influences of spatial, time, angular and wavelength discretization levels on the obtained solutions were investigated. No problems were detected. For different discretization levels obtained results were closed to each other. In succession, the part of the solver responsible for calculations of a transient conductive and radiative heat transfer in a non-grey fabrics and other elements of the system was verified. Two clothing configurations \textit{i.e.}: single- and multi-layers were investigated. Then the results obtained were compared with ANSYS Fluent predictions and a very good agreement was observed. Although partial credibility of the model was shown, it needs further verification. The correctness and accuracy of moisture transfer model in the fabrics and air gaps as well as coupled heat and mass transfer model in the multi-layers clothing should be also proven.

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