1. Introduction

Foundry workers can be identified as one of many professions, where employees are exposed to hot factors. Workers involved in the melting metal process are subjected directly to high and variable temperatures, flames as well as molten metal splashes. Depending on the workplace, the founder is also exposed to toxic gases, vibrations, noise, and dust. Currently, in most plants, many secondary hazards have been minimized or eliminated, but the high temperature and splashes of molten metal cannot be eliminated during this specific work [1]. Especially, operating next to the foundry furnace, discharge of molten metals and slags can be hazardous to foundry workers’ health, and because of this there has been a surge in demand for protective clothing [2].

The most popular solutions of the cloths protecting against flames and heat radiation are based on E-glass fibers. Characteristic features of glass fibers are their non-flammability and high heat resistance. Their strength increases slightly for temperature above 200°C, around 300°C further, more intense strength growth is observed, while a sharp decrease takes place, if 600°C is exceeded. If the glass fibers stay at 400°C for 24 h their strength is reduced by 50%. The developed technologies of glass fiber production allow for a good resistance of products made of these fibers to short-term exposure to a very high temperature and expand the boundary of resistance to long-term heat effects [3–5].

Basalt fibers are classified as ultra-high heat-resistant textile materials. Comparisons of their (basalt) properties with traditionally used E-glass fibers show the higher values of tensile strength and higher Young’s modulus. Additionally, basalt fibers express better chemical resistance, withstand a higher range of working temperature, and show better ecological properties. The working temperature of basalt fibers can reach 700°C with the resistance to short-term exposure up to 750°C. They have excellent thermal properties compared to E-type glass fibers. Basalt fiber textiles, due to the high thermal resistance, can be used under the range of temperature from −260°C to 500°C. Moreover, basalt fibers do not melt and do not plasticize under the high temperature. Basalt fibers are also characterized by similar or even higher effectiveness of protection against hot factors than glass fibers [6–8]. Additionally, their low price is a very important advantage. Thus, basalt fibers are considered an attractive alternative to the glass fibers currently used for the protective clothing production.
Different configurations of protective packages, composed of different types of fabrics are used for thermal protection [9, 10]. A protective clothing package shields the human body against hot factors, and at the same time, it creates a barrier that limits the heat transfer from the human body to the environment. Thus, it is a compromise between the thermal comfort of workers and their ability to perform specific activities. One of the main body functions is to maintain a constant body temperature. Due to specific properties of protective package destined for foundry workers, the outer layers of clothing may cause thermal discomfort, because heat and moisture cannot be transferred from the skin to the environment. However, the most protective products meet ergonomic requirements, so that protective suits do not cause physiological or psychological stress. Nevertheless, new materials that minimize the effects of harmful heat factors are in the development stage. An increase in comfort of using protective products is possible due to deep knowledge and understanding of heat transfer phenomena that occur between the human body, clothing, and the environment. The heat produced by the user’s body can be transferred by conduction, convection, radiation, and perspiration. Abdel-Rehim et al. [9] indicated heat conduction as the main process of heat transfer inside the textiles. However, other processes cannot be disregarded; especially, if the interaction with the environment, where radiation and convection are of high importance, is considered. Therefore, reliable numerical modeling of these processes in textiles can be helpful to design high-quality protective products [11, 12].

Flows of heat and moisture through textiles have been extensively studied. The mathematical models predicting the heat transfer phenomena and thermal properties of textiles have been also used. Das et al. [13] presented a theoretical model for the prediction of heat transmission through a multilayer clothing assembly with air gaps in between fabric layers. The model was based on the general equations of heat transfer through porous media taking into account heat conduction and radiation. It was validated against the experimental data for different multilayer clothing assemblies with variable air gap thickness and a fairly good correlation was observed. Voelker et al. [14] proposed a typical balance model of heat and mass transfer from the human body through the clothing layer to the environment including moisture absorption by tested fabrics. Simplifications in the structure of textiles are frequently done. Zhu and Li [15] developed a model of heat and moisture transport through a cotton fabric. They proposed the homogenization of analyzed textile layers or even whole textile packages. This kind of simplification of textile products was also applied by Korycki and Wiezowska [16] in their investigations of heat transfer resistance of four knitted fabrics. They assumed fabrics as isotropic materials of constant thickness, and established their overall heat transfer coefficients (HTCs) for the entire knitwear instead of determining them for individual layers. Banerjee et al. [17] modeled the heat transfer process in a thin porous fibrous material, such as a paper sheet subjected to an incident heat flux introduced by a laser beam. The model took into account conduction, convection, and radiation processes solved with a control volume method for a single material layer. The authors indicate that the model can be extended to any thin porous fibrous media such as textiles.

Progress in numerical methods and computer performance has given the possibility of full three-dimensional (3D) numerical modeling of different objects and processes. However, fabric threads consist of thousands of individual fibers joined together in the spinning process, arranged in threads during the weaving process. Fibers in yarns are stochastically distributed. In practical applications fabrics are deformed continuously, fibers and threads are moved and slipped under the influence of stretching or bending the clothing [18]. Therefore, the enormous complexity of fabrics makes the problem of their full modeling far beyond contemporary capabilities. However, simplified 3D models have been developed.

The active field of the 3D numerical modeling of textiles concerns their strength analysis. Various approaches to the reproduction of fabric structure can be found in the literature [19–21]. In most cases, numerical modeling is used to determine the mechanical properties of fabrics, e.g., the bending resistance or ballistic injuries [18, 22, 23]. Hivet and Boissea [24] examined real thread geometries in different cases of yarn structure and weaving. The proposed 3D geometrical models of 2D fabrics ensured a realistic contact surface between threads without interpenetration, which is suitable for the most shapes and weavings. They proved the model operation for an elementary fabric cell under shear and biaxial tensions. Badel et al. [25] developed the simulation method for the deformation of woven composite fabric at the mesoscopic scale. Basing on the Hivet and Boissea [24] geometry study, they build the 3D finite element model of the unit cell of reinforced warp and weft threads and proposed the hypo-elastic constitutive model for the thread behavior. Simulations of cell deformation in biaxial tension and in-plane shear were in a good agreement with tomography analyses. In all these studies the stochastic distribution of threads in fabrics was disregarded and the authors operated with the averaged models. Moreover, threads are simplified and treated as uniform bodies, disregarding the composition of thousands of individual fibers.

A similar approach can be also applied in the case of numerical investigations of heat transfer. However, the presence of the air voids in the textiles has to be taken into account as it influences the heat transfer process. Elnashar [26] described two types of porosities distinguished in the fabrics: the porosity between yarns (inter-yarn porosity), and the porosity between fibers inside yarns (intra-yarn porosity). He showed that the volume porosity of double-layered tightly woven fabrics cannot be adequately modeled with the use of a classical 2D model of homogenous porosity. Szosland [10] divided the void spaces (also called pores) into the three-dimentional fabric with pores situated in the fibers, between fibers in the thread, and between warp and weft threads in the fabric. The last group is
In research presented in this paper, the computer simulation was used as a tool to determine thermal properties of the protective clothing based on the basalt fabric. The considered basalt fabric can be treated as tightly woven with relatively stiff warp and weft threads [26]. Thus, the 3D numerical model, based on the idea proposed by Komeili and Milani [18], was developed. The warp and weft of weaves were reproduced and the macropores (inter-yarn porosity) were considered in the textile geometry. Similarly, as in the numerical strength analysis [24, 25], the yarns were simplified and treated as uniform bodies. However, the intra-yarn porosity was taken into account specifying the heat transfer properties of yarns.

The simulations of heat transfer in the protective clothing package presented in this paper are a novelty. The geometry of basalt fabric, as well as all calculations described in this paper, has never been presented by other researchers. The main aim of research was to develop a numerical model of heat transfer in the basalt fabric. The model allowed us to determine the thermal properties of basalt textiles modeled as porous media based on experimental data obtained with the use of the Alambeta device. For this purpose, measurements of the thermal conductivity coefficient on that device were made. Obtained data were used in the Ansys CFX model. The next step was to carry out heat flow simulations through the tested materials. The fabric selected for testing is a layer of protective clothing with an interlayer of wool with the non-flammability finishing, designated for employees exposed to high temperatures and the layer of underwear.

2. Materials and methods

Different textile materials were applied as components of the protective clothing package. A basalt fabric covered by aluminum foil was used as the external layer being an alternative solution to the glass fabric used nowadays. A piece of wool fabric with the non-flammability finishing was used as the intermediate layer. Cotton underwear was the last layer in this package.

Investigations described in this paper were divided into two main parts: experimental and numerical. They were performed for three different samples of cloths based on the basalt fabric. The basic one was a single-layer basalt fabric. The second was the basalt fabric covered with aluminum foil with the use of an adhesive mean. The final one, besides the aluminized basalt fabric, included layers of wool cloth and cotton underwear. Data obtained during measurements of the single-layer basalt fabric and the aluminized basalt fabric allowed us to determine the thermal properties of the textile composite. These data supplemented with available material properties were used to develop and tune the numerical models of heat transfer in these fabrics. The test performed for the cloth package served as the validation data for the proposed model.

2.1. Experimental setup

Measurements of heat transfer through different materials were performed with the use of the Alambeta apparatus. It is a plate method, which is a computer-controlled device shown schematically in Figure 1. The method reproduces the real conditions of warm-cool feeling evaluation. A tested sample is placed between two plates. The upper plate is heated to the average skin temperature (32°C) and the lower plate is maintained at the ambient temperature (21°C). The device measures several thermal properties at one measurement process [27]. During tests, different clothing packages were placed between the plates and compressed with the stress of 200 Pa. Their thermal conductivity coefficients were determined and later used for the calibration and verification of numerical models. The average values of parameters for selected fabrics from measurements are presented in Table 1. Comparing the thickness of the protective clothing package with the sum of its components, one can notice a 10% difference. It results from the difference in compression of individual samples and that when the whole package was exposed to the same stress. Taking into account the structure of particular fabrics, it was clear that the wool cloth and cotton underwear are deformed much more than the basalt fabric. Thus, in the numerical model of the full package, the thickness of aluminized basalt fabric was kept without an alternation and the thickness of the remaining layers was increased by 10%. Their lower compression influences the heat transfer; thus, in the numerical analysis of the package, the thermal conductivity coefficients of wool cloth and cotton underwear were reduced by 10%.

2.2. Numerical models

The next step of the investigation was to develop a numerical model of the clothing package. For this purpose, a simplified

![Figure 1. Scheme of the Alambeta instrument.](http://www.autexrj.com/)

**Figure 1.** Scheme of the Alambeta instrument, 1. Heater; 2. Thermometer; 3. Power supply; 4. Heat flow sensor with movable warm plate at 32°C; 5. Measured sample; 6. Measuring head with cool plate at an ambient temperature of 21°C; 7. Head movement device; h – the initial distance between upper and lower plates of the device.
The computer aided design (CAD) model of basalt fabric macroscopic structure used in the simulation was created with the use of the PTC Creo 3.0 software. Based on the fabric thickness and the averaged dimensions from Table 2, the separate threads of weft and warp were defined. The thread trajectories were approximated by spline curves allowing to represent smooth changes of thread curvature. The trajectory and the cross-section of weft threads are illustrated in Figure 3. A basalt threads exhibited a significant stiffness; thus, contact areas of weft and warp threads were limited. Moreover, small gaps between threads can be observed. The cross-section of warp thread in the symmetry plane of weft and the contact between them is illustrated in Figure 4.

Table 1. Average values of parameters for selected fabrics taken from measurements.

<table>
<thead>
<tr>
<th>Fabrics</th>
<th>Thermal conductivity ( (\text{W} \text{ m}^{-1} \text{ K}^{-1}) )</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt fabric</td>
<td>0.0568</td>
<td>0.31</td>
</tr>
<tr>
<td>Aluminized basalt fabric</td>
<td>0.0624</td>
<td>0.35</td>
</tr>
<tr>
<td>Wool cloth</td>
<td>0.0548</td>
<td>5.31</td>
</tr>
<tr>
<td>Underwear (cotton)</td>
<td>0.0576</td>
<td>0.79</td>
</tr>
<tr>
<td>Aluminized basalt fabric + Wool cloth + Underwear</td>
<td>0.0501</td>
<td>7.06</td>
</tr>
</tbody>
</table>

Table 2. Average data based on the microscope measurements and used in the model generation.

<table>
<thead>
<tr>
<th>Basalt fabric</th>
<th>Weft thread (mm)</th>
<th>Warp thread (mm)</th>
<th>Gaps between threads (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>0.820</td>
<td>1.350</td>
<td>0.325</td>
</tr>
<tr>
<td>Width</td>
<td>0.960</td>
<td>0.830</td>
<td>0.118</td>
</tr>
</tbody>
</table>

The computer aided design (CAD) model of basalt fabric macroscopic structure used in the simulation was created with the use of the PTC Creo 3.0 software. Based on the fabric thickness and the averaged dimensions from Table 2, the separate threads of weft and warp were defined. The thread trajectories were approximated by spline curves allowing to represent smooth changes of thread curvature. The trajectory and the cross-section of weft threads are illustrated in Figure 3. A basalt threads exhibited a significant stiffness; thus, contact areas of weft and warp threads were limited. Moreover, small gaps between threads can be observed. The cross-section of warp thread in the symmetry plane of weft and the contact between them is illustrated in Figure 4.

2.2.1. Basalt fabric numerical model

Available data are not sufficient to fully reproduce the extremely complex structure of the fabric. Therefore, the macroscopic numerical model was based on own data and information found in the literature. The actual structure of warp and weft threads of basalt fabric used in these investigations was photographed using a microscope as shown in Figure 2. Taking into account limited changes of individual thread cells, it was decided to disregard variation of dimensions of individual warp and weft threads and to operate with the averaged model. Thus, the dimensions collected from measurements for multiple threads cells were averaged and listed in Table 2. Additionally, the thickness of fabric equal to 0.31 mm was measured.

Data published by Hivet and Boissea [24] were used to reproduce trajectories and shapes of warp and weft. The constant shapes of threads were assumed, disregarding the impossible to determine warp and weft thread deformations in the regions of their contact.

http://www.autexrj.com/
The mesh was refined in the regions of transition between domains and the regions of thread edges to maintain a high quality of control volumes. The mesh is illustrated for the more complex task configuration described in the next subsection (see Figure 8); however, the same mesh settings were used in both models for basalt threads and air domains.

The computational mesh was transferred to the Ansys CFX solver, where the steady-state numerical simulations of heat transfer were performed. In this case, the computational space consisted of two domains. Space occupied by the air was modeled as a fluid domain with well-known air properties. Taking into account the fact that basalt monofilaments surrounded by the air are distributed in a thread in a stochastic manner, it was decided to define the thread as a porous domain. Its porosity, defined as the ratio of the volume of air to the total volume of basalt fabric, was determined by measuring its mass. The apparent density of fabric thread was equal to 1,500 kg/m$^3$.

Basing on the rock basalt density (2,650 kg/m$^3$) [30] as well as the volume of textile specimen reproduced by the numerical model, the porosity was determined to be equal to 0.434. The heat transfer modeling in a porous material required two additional parameters to be Heat Transfer coefficient (HTC) and Interfacial Area Density (IAR). IAR is defined as the surface area of the solid in contact with the fluid per unit volume [31, 32]. Taking into account the porosity of thread and typical fiber dimensions this parameter was estimated to be equal to 13.000/m$^2$. A series of additional simulations were conducted to determine the value of HTC to meet the experimental results obtained for the fabric sample by the Alambeta device. HTC equal to 495 W/(m$^2$ K) was determined, assuming the thermal conductivity of basalt equal to 1.9 W/(m K), (values 1.69 - 2.11 W/(m K) are reported in [17]).

The boundary conditions were defined according to settings during the Alambeta device tests. Thus, the upper surfaces of the porous basalt fabric and air domains were defined with a temperature equal to 32°C. At the corresponding bottom surfaces, the ambient temperature of 21°C was set. The symmetry boundary condition was applied at all side surfaces of the fabric cell (Figure 6).

The full CAD model of basalt fabric is presented in Figure 5. There are no data available to define the differences in the heat transfer within the warp and weft threads and in the zone of their contact. Thus, it was decided to combine the warp and weft threads into one body of homogenous porous material. It was assumed that the heat transfer across the fabric dominates the process and the net heat flux between thread cells can be disregarded. Therefore, only one cell of the averaged fabric indicated in red in Figure 5 was selected for further processing. This approach allowed us to take advantage of symmetry boundary conditions and minimize the size of the computational domain. It is commonly used practice in various numerical simulations [28, 29] to minimize computational resources and time of simulations.

The cell of fabric prepared in PTC Creo 3.0 was imported to Design Modeler, i.e., the CAD software in the Ansys package. The space between threads was filled to represent in simulations the presence of macroscopic pores filled with the air, as shown in Figure 6. This enabled us to get perfect contact surfaces between basalt threads and air domains, which influences meshing and the solution quality. During the experiment in the Alambeta device, the specimen was compressed. Thus, the corners of the fabric section were flattened to meet the measured distance between the two plates of the device.

The geometrical model was composed of two domains of basalt threads and the air was divided into tetrahedral control volumes with the use of the Ansys Meshing application. Taking into account that only a small section (cell) of fabric was modeled, it was possible to use a very fine mesh composed of 1.9 million nodes still obtaining the solution within a short time (less than an hour). The mesh was refined in the regions of transition between domains and the regions of thread edges to maintain a high quality of control volumes. The mesh is illustrated for the more complex task configuration described in the next subsection (see Figure 8); however, the same mesh settings were used in both models for basalt threads and air domains.
The fluid in the air and porous basalt fabric domains were kept in the fully enclosed space without inlets and outlets. Their very small dimensions caused the fluid movement due to natural convection was hardly noticeable and the mass and momentum equations converged rapidly. The heat transfer was determined by solving for both the fluid and porous domains the Thermal Energy form of the energy equation in the Ansys CFX solver [31]:

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho U h) = \nabla \cdot (\lambda \nabla T) + \tau : \nabla U + S_E \tag{1}$$

where: $h$ – enthalpy, $\rho$ – density, $\lambda$ – thermal conductivity coefficient, $U$ – velocity vector, $\tau : \nabla U$ – term of work resulting from fluid viscosity, $S_E$ – energy source.

However, due to the lack of fluid motion and energy sources in the domains, the analyzed process is governed by the thermal conduction term (the first term on the right side of Eq. (1)). In all considered cases described in the article, the heat transfer was treated as a stationary process. Thus, the convergence of the solution was reached, when the first term of the energy equation approached zero. In practice, computations were carried out in the iterative process and terminated once the Root Mean Square residuals of the energy equation reached the 1E-9 convergence level. It guaranteed a very precise solution and the full balance of the heat transferred through the fabric.

2.2.2. Aluminized basalt fabric model

In the second step of numerical model development, the basalt fabric presented in the previous section was supplemented by additional layers of aluminum foil and the adhesive mean. Data supplied by the manufacturer of aluminized basalt fabric allowed for the evaluation of the thickness and topology of both layers. According to obtained information, the 0.012-mm-thick aluminum foil was covered with the adhesive mean layer. The foil was bonded with the basalt fabric under 120°C and pressure, when the adhesive mean was melted and filled gaps and/or pores of basalt fabric. The fabric inspection indicated that the adhesive mean did not reach the opposite side of basalt fabric. As no further details were available, it was assumed that the adhesive mean did not penetrate the basalt threads significantly and in consequence, did not change their thermal properties. Taking into account the initial thickness of adhesive mean, it was assumed that it reached a half of fabric thickness in the air gaps between the basalt fabric threads. The aluminum foil was assumed to keep the constant thickness, but it was deformed in the process of bonding and took on a wavy form. All the elements of fabric were modeled and presented in Figure 7 for one cell considered in the numerical study. In figure 7 the air is blue, the basalt fabric is orange, the aluminum foil is gray, and the adhesive mean is green.

Mesh settings for the basalt and air domains were identical to those prepared for the model described in the previous section. The same mesh sizes were applied to the adhesive mean and aluminum foil domains. The mesh for the foil was generated with six layers along with its thickness, which ensured a proper solution of heat transfer in this zone. The mesh was composed of 2.6 million nodes. In Figure 8 one can see its details in the cross-section through the middle plane of the fabric cell.

In this case, the model was divided into five domains: two fluid domains of the air at the top and bottom, the basalt threads modeled as a porous material, and the aluminum and adhesive mean domains modeled as solids. The settings of the air and basalt fabric domains were the same as in the study described in the previous section. The properties of aluminum with the thermal conductivity of 237 W/(m K) were selected from the material database of Ansys CFX. The initial data for the adhesive mean were assumed based on available information...
for such substances and determined in the iterative procedure, basing on the experimental results for the aluminized basalt fabric tests done by the Alambeta device. Finally, the density of adhesive mean equal to 1,300 kg/m$^3$ and the thermal conductivity coefficient equal to 1.26 W/(m K) were selected for further studies.

The boundary conditions were set in the same manner as in the task described in the previous section. The temperature at the top surfaces was set to 32°C, and at the bottom surface, it was defined as 21°C. Symmetry conditions were applied to all sides of the considered cell for all components of the assembly. The analyzed process was governed by the thermal conduction term of energy equation for the basalt and air domains as well as for solid domains of aluminum foil and adhesive mean. Thus, the same numerical procedure and convergence criteria were applied as in the simulations described in the previous section. The solution reached a tight convergence with the Root Mean Square residual of the energy equation well below 1E-8.

### 2.2.3. Clothing package geometry

The main goal of the study was to determine the selected aspects of thermal protection of foundry workers; thus, in this step, the inner cloth layers were included in the final analysis. The wool cloth and the cotton underwear were added to the model of aluminized basalt fabric to form the complete package of protective clothing (Figure 9). Both layers were porous materials; however, in contrast to the basalt fabric, the structure of threads was of much smaller scale, and their distribution in the underwear and especially in the wool fabric was much more stochastic. Therefore, both layers were represented by blocks of homogenous and isotropic materials and they were simulated as solid bodies with the thermal conductivity determined as in previous studies with the use of the Alambeta device. However, there are some differences in the properties of compressed and free state fabrics. In this study data from the Alambeta device were available only. Therefore, it was assumed that layers of the wool fabric and the underwear were much more prone to compression than aluminized basalt fabric. Thus, the thicknesses of the wool and underwear layers were increased by approximately 10% for the data presented in Table 1 and were assumed to be equal to 5.83 mm and 0.88 mm, respectively. Consequently, the thermal conductivity coefficients were decreased by approximately 10%. The parameters used in all simulations are listed in Table 3.

The boundary conditions and other simulations settings were the same as in the modeling of the aluminized basalt fabric. The mesh of the aluminized basalt textile shown in the previous section was used in this simulation. The wool clothing and cotton underwear domains were meshed with a similar element refinement. The whole mesh was composed of nearly 5.3 million nodes and over 14.2 million elements. Once again a high convergence of the solution was reached with the RMS residual of energy equation around 1E-8, which allows one to consider results to be of very high quality.

### 3. Results and discussion

To develop a reliable numerical model of the textile package, the dedicated simulations were performed to determine the apparent HTC of porous basalt fabric. Another set of simulations were carried out to determine the thermal conductivity of adhesive mean used in the aluminized basalt fabric. Both these coefficients were changed in numerical simulations until the required level (relative difference <0.5%) of correlation with data obtained from measurements of

![Figure 9. Model of the whole clothing package and its magnification showing the aluminized basalt textile.](image)

<table>
<thead>
<tr>
<th>Assembly layer</th>
<th>Thermal conductivity (W/mK) or (W m$^{-1}$ K$^{-1}$)</th>
<th>Specific heat (J/kg/K) or (J kg$^{-1}$ K$^{-1}$)</th>
<th>Density (kg/m$^3$)</th>
<th>Domain definition in simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.0261</td>
<td>1,004.4</td>
<td>1.185</td>
<td>Gas</td>
</tr>
<tr>
<td>Aluminum</td>
<td>237</td>
<td>903</td>
<td>2,702</td>
<td>Solid body</td>
</tr>
<tr>
<td>Adhesive</td>
<td>1.26</td>
<td>1,300</td>
<td>1,300</td>
<td>Solid body</td>
</tr>
<tr>
<td>Basalt fabric</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>Defined as above</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>1.9</td>
<td>860</td>
<td>2,650</td>
<td>Porous material (porosity 0.434; HTC = 495 W/(m K); IAR = 1.3 · 10$^4$ /m)</td>
</tr>
<tr>
<td>Wool</td>
<td>0.0497</td>
<td>1,760</td>
<td>116</td>
<td>Solid body</td>
</tr>
<tr>
<td>Underwear</td>
<td>0.0517</td>
<td>1,070</td>
<td>209</td>
<td>Solid body</td>
</tr>
</tbody>
</table>

HTC, heat transfer coefficient; IAR, interfacial area density.

http://www.autexj.com/
particular textile samples with the use of the Alambeta device was reached. The apparent HTC of porous basalt fabric equal to 495 W/(m² K) and the thermal conductivity of adhesive mean equal to 1.26 W/(m K) were selected. These parameters were used in the further numerical modeling of heat transfer through the tested package composed of aluminized basalt textile, wool cloth, and cotton underwear. The experimental value of thermal conductivity for the whole package was measured to be 0.05081 W/(m K) and determined from the numerical simulations was equal to 0.05096 W/(m K). The difference of 0.3% with the very high level of convergence reaching 1E-8 was considered as satisfactory to validate the model.

The temperature and temperature gradient changes in the studied textiles are shown in Figure 10. The same temperature range (21–32°C) resulting from the conditions in the Alambeta device was used in the case of basalt fabric (Figure 10a) and aluminized basalt fabric (Figure 10b). In the case of a textile package including wool layer and underwear (Figure 10c), the range of temperature changes was limited to 30.5–32°C to

![Figure 10. Temperature and temperature gradient distributions in the sections of: the basalt fabric (A), aluminized basalt fabric (B), and the textile package (C).](http://www.autexrj.com/)
more clearly visualize temperature changes in the aluminized basalt fabric part of the model. In this case aside from a thin region in contact with the basalt fabric, the temperature of wool cloth and underwear at the particular depths was uniform and the temperature gradient was constant along the whole layer thicknesses. Scales of temperature gradient in each case were different and they were adjusted in each case for clarity. The black lines indicate boundaries between the layers of different materials.

Differences in the temperature distribution resulted from the different thermal conductivity of particular materials. The highest temperature gradients were in the regions of transition between different materials, especially, at the basalt domain sides. Additionally, high gradients were observed in the regions, where the porous domain of basalt fabric was in contact with the warm and cool plates of the Alambeta device (Figure 10a, b). Almost the uniform temperature distribution in the upper side of aluminized basalt fabric resulted from the very high thermal conductivity of aluminum foil. It transferred heat to the adhesive mean and the air trapped between the foil and the warm plate of the device. The thermal conductivity of adhesive mean was also relatively high; therefore, despite differences in its thickness along the fabric sample one can hardly notice any variation of its temperature. In Figure 10c one can see that the temperature distribution along the wool cloth becomes uniform in the distance of approximately 0.3 mm.

The heat flux distributions at the bottom of the basalt fabric are shown in Figure 11. Even though the porosity of basalt threads is high, their thermal conductivity is much higher than for the air. Therefore, the substantial part of heat transfer took place through the regions of threads in contact with the hot and cold plates of the Alambeta device (corners of the fabric section in red in Figure 11a, b). The low heat flux region in the middle of the fabric section corresponds to the edges of threads and the gap between them. In the case of the textile package (Figure 11c), the heat flux in the interface between wool clothing and the air gap was much more uniform and much lower than in the region of wool clothing in contact with basalt threads.

One can notice that in the case of heat protection clothing the aluminum layer is counterproductive, but its main role is to reflect radiation, which was not the object of the present study.

4. Conclusions

Continuous progress in numerical methods as well as easier access to high-performance computers, has allowed studying details of various processes. In the case of textiles, various aspects are investigated numerically. One of the active fields of research is the problem of heat transfer analysis. The investigations presented in this paper aimed to develop the numerical model of heat transfer in the textile package, which is based on the aluminized basalt fabric.

In comparison to other textiles, the basalt fabric has large-scale weft and warp threads; thus, there was a possibility to reproduce its geometry with sufficient precision for the needs of the numerical study. However, it is impossible to reproduce the stochastic structure of fibers/monofilaments in its threads. Therefore, in the numerical simulations, the threads were modeled as homogenous porous material. To tune the model, the thermal conductivity of particular fabrics, as well as the whole textile package, was necessary. The measurement data of the bare and aluminized basalt fabrics from the Alambeta device were used to find the HTC of basalt fabric and the thermal conductivity of adhesive mean. The coefficients were determined in the series of numerical simulations, which were carried out for numerical models of single layer and aluminized basalt fabrics.

The numerical model of aluminized basalt fabrics was supplemented with the wool clothing and cotton underwear, which together form the protective clothing of foundry workers. This clothing combination is giving a new solution for the protective clothing destined for foundry workers. The heat transfer through the tested protective package was determined numerically and a good agreement with measurements done by the Alambeta device was found. Therefore, the model can be helpful for investigations of similar textile packages based on basalt or glass fabrics. However, the experimental data would be necessary to adjust the model for the specific textile package. It is also necessary to remember that the numerical model depends on the contact between layers and compression level of the package, which influences the porosity of particular fabric and air gaps between the package layers. This requires further development of the model supported by a precise determination of textile geometry and heat transfer measurements.

The numerical model created in this work is a new approach in the field of computer modeling of heat flow through textiles. It allows us to reproduce the heat transfer process in good agreement with measurements.
References