Computational Analysis and Experimental Investigation of Heat and Moisture Transfer in Multilayer Textile Package

Rimantas BARAUSKAS[1], Lina VALASEVIČIŪTĖ[2*], Audronė JUREVIČIŪTĖ[2]

[1]*Kaunas University of Technology, Studentų 50, LT-51368 Kaunas, Lithuania*
[2]*Lithuanian Textile Institute, Demokratų 53, LT-48485 Kaunas, Lithuania*

Received 04 June 2008; accepted 24 October 2008

The transfer properties of the moisture and heat through multilayer textile packages have an influence on the wearing comfort of the clothing assemblies produced from such materials. The necessary properties of the textile package are obtained by means of proper selection of the structure of the package and physical properties of each individual textile layer. The research of wearing comfort is focused on analysis of air permeability, thermal resistance and the resistance and absorption of water vapour. In this work a typical assortment of textile materials, which is used in summer and winter military clothing, was selected. During the experimental investigation the thermal and water vapour resistance of the textile packages consisting of different combinations of layers made of different materials have been compared. The finite element computational model has been developed for the analysis of heat transfer through the textile package caused by heat conduction and advection due to ventilation air flow. The model enabled to obtain values and time laws of temperatures in each layer of the package. The validity of the model is ensured by employing the experimentally measured thermal resistance values for each individual layer of the structure. The numerical results have been compared against experimentally measured data of the textile package.
Keywords: wearing comfort, military clothing, moisture and heat transfer, textile package, finite element analysis.

INTRODUCTION

Creating and manufacturing of contemporary protective clothing is based on the main purposes: to ensure optimal protection of the human body and to ensure the satisfactory wearing characteristics.

In the modern protective clothing manufacturing a number of fabrics with different structure and composition (woven, nonwoven, knitted, multilayer, etc.) are used. Such fabrics can be processed with different surface treatment or finishing technologies and have very different characteristics of wearing comfort. Besides, it is important to notice that for the evaluation of such materials different investigation methods are applied. The new materials indicated for the development of the protective clothing usually enter the manufacturing process still not investigated properly or the results of such investigations are obtained using different methods. For this reason it is rather difficult to predict and to describe theoretically the heat and moisture processes in multilayer protective clothing [1 – 3].

Primary theoretical research of heat and moisture exchange in clothes began only in recent years. Source [4] defines that generally the amount of heat and moisture generated by the human body is considered, which is transferred through the clothes to the environment, and what are the moisture and thermal conditions in the air layer closest to the human skin (called microclimate layer). Also the work points out that the heat and moisture exchange takes place not only due to diffusion (i. e. propagation through textiles due to their heat and moisture conductivity), however, also due to advective exchange by means of ventilation flow in-between fabric. Commonly the ventilation flow is caused by the motion of the fabric layers when the person wearing them is moving, however, sometimes the ventilation flow can be intentionally generated by special ventilators or other devices. Such kind of complex processes by means of computational models was analysed by N. Pan and P. Gibson [4] and in earlier research by authors of this work [5].

In this work the investigations of the modern warrior clothing comfort characteristics were performed. The aim of this research was to develop the theoretical prognostication methods for the comfort characteristics of the textile package. Such investigations are essential as the wearing comfort assurance is one of the main goals in the development of perspective military clothing, also indicated in NATO normative documents [6 – 8].

It can be summarised that in this work a number of theoretical investigations of the comfort characteristics in the military clothing was performed and the computative model of the finite elements was developed. Such a model describes the processes of the ventilation, heat and moisture interchange in the multilayer clothing and at the body's microclimate zone.

FINITE ELEMENT MODEL OF HEAT AND MOISTURE EXCHANGE IN CLOTHES

Calculation of ventilation air flow

The scheme of air flow at the surface of human skin and in the textile package is presented in Fig. 1.

The thickness of the air gap between the skin and the fabric varies due to the motion of the surface of the skin and forces the motion of the air in the gap. The equipped active ventilation system may blow a certain amount of air in-between the fabric and the skin. The air flow moves

*Corresponding author. Tel.: +370-37-308665, fax.: +370-37-308668.
E-mail address: *valaseviciute@lti.lt* (L. Valasevičiūtė)

towards the zones where the microclimate gap has a contact with the outer air the pressure of which is P_∞. Certain amounts of the moving air cannot be removed through the open boundaries of the microclimate gap, however, they are transferred through the pores of the textiles and finally reach the open air through the outer surface of the textile package. The process can be described by means of partial differential equations, which serve as the basis for the finite element model. The finite element models enable to present adequately the thermal and moisture exchange properties of various compositions of textile packages and to investigate them theoretically.

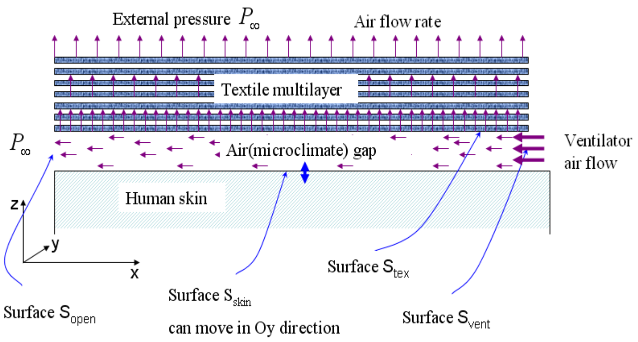

Fig. 1. Scheme of ventilation air flow of the textile package

The incompressible Navier-Stokes equations are presented as [4]:

$$\rho_0 \frac{d\vec{\mathbf{v}}}{dt} + \rho_0 \vec{\mathbf{v}}\nabla\vec{\mathbf{v}} = -\nabla p + \mu\nabla^2\vec{\mathbf{v}}; \tag{1}$$

$$div\vec{\mathbf{v}} = 0, \tag{2}$$

where: $\vec{\mathbf{v}} = (u, v, w)$ are the velocities of the air flow, which are different at every point of the domain, ρ_0 is the air mass density; μ is the dynamic viscosity coefficient of the air; p is the pressure.

The assumption that the air flow velocities are small enables to neglect the convective acceleration terms and to present equation (1) as:

$$\rho \frac{d\vec{\mathbf{v}}}{dt} = -\nabla p + \mu\nabla^2\vec{\mathbf{v}}; \tag{3}$$

$$div\vec{\mathbf{v}} = 0. \tag{4}$$

Equations (3) and (4) presented in terms of vector components read as:

$$\begin{cases} \rho \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right); \\ \rho \frac{\partial v}{\partial t} = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right); \\ \rho \frac{\partial w}{\partial t} = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right). \end{cases} \tag{5}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \tag{6}$$

The presented differential equations are subjected top boundary conditions, which are prescribed for different parts of the surface in Fig. 1 and are presented in Table 1.

The average velocity of air penetration w_0 through the textiles employed in boundary conditions Table 1 can be expressed as:

$$w_0 = \alpha(p_0 - p_1), \tag{7}$$

where: α is the coefficient obtained experimentally, p_0 is the pressure value at the fabric surface S_0 of the microclimate gap (Fig. 2), which is obtained by solving the air flow problem expressed by (5) and (6), p_1 is the pressure value at the other side of the fabric layer. For the outer layer of the textile package value $p_1 = p_\infty$, i.e., is equal to the outer air pressure. The pressure value in the gap in-between package layers is obtained as:

$$\begin{cases} u_1 = -\frac{Z^2}{12\mu}\frac{\partial p_1}{\partial x}; \\ v_1 = -\frac{Z^2}{12\mu}\frac{\partial p_1}{\partial y}; \\ \frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y} + \frac{w_2 - w_1}{Z} = 0. \end{cases} \tag{8}$$

where Z is the thickness of the air gap.

Equation (8) indicates also that additional amount of air is supplied to the gap due to the infiltration through adjacent layers of material.

In equation (8) it is also assumed that the air flow between the fabric layers can be regarded as steady Poiseuille flow.

Table 1. Boundary conditions for the ventilation problem

Surface	Boundary condition	Comments
S_{skin}	$\vec{\mathbf{v}}\vec{\mathbf{n}} = v^*(t), \in S_{skin}$	The surface of the skin may vibrate with prescribed velocity v^* in the normal direction, where $\vec{\mathbf{n}}$ – outer normal of the surface.
S_{vent}	$\vec{\mathbf{v}}\vec{\mathbf{n}} = v^*(t), \in S_{skin}$	The air flow generated by the ventilator. If no active ventilation is used $v^*_{vent} = 0$.
S_{open}	$p = p_\infty, \in S_{open}$	Open boundary of the microclimate zone, where the pressure is equal to the outer pressure.
S_0	$\vec{\mathbf{v}}\vec{\mathbf{n}} = w_0, \in S_0$	The boundary of the "microclimate" zone with the textile package through which certain amount of air is transferred. Velocity w_0 is defined by relating the pressure difference on both sides of the fabric layer against the average velocity of air penetration. The physical meaning of it and be considered as Darcy velocity, which is generally employed for the solution of filtration problems.

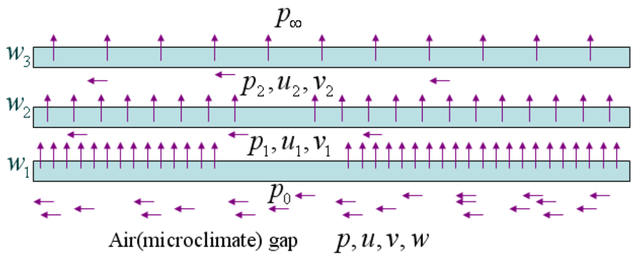

Fig. 2. Scheme of the air flow through the layers of textile package

The air flow in the next air gap is governed by equations:

$$w_1 = \alpha(p_1 - p_2),$$

$$\begin{cases} u_2 = -\dfrac{Z^2}{12\mu}\dfrac{\partial p_2}{\partial x}; \\ v_2 = -\dfrac{Z^2}{12\mu}\dfrac{\partial p_2}{\partial y}; \\ \dfrac{\partial u_2}{\partial x} + \dfrac{\partial v_2}{\partial y} + \dfrac{w_3 - w_2}{Z} = 0. \end{cases} \tag{9}$$

It should be noticed that equations (3 – 9) are interrelated and have to be solved together. The outer layer of the fabric can be described by single equation (7) as the outer air pressure is known.

Calculation of thermal exchange

The heat exchange in the microclimate gap is governed by the diffusion-advection equation:

$$\frac{\partial}{\partial x}\left(\lambda_a\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_a\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_a\frac{\partial T}{\partial z}\right)- c_a\rho_a u\frac{dT}{dx}-c_a\rho_a v\frac{dT}{dy}-c_a\rho_a w\frac{dT}{dz}+b(x,y,z)=\rho_a c_a\frac{\partial T}{\partial t}, \tag{10}$$

where: T is the air temperature [K]; b is the volumetric heat source (if present); λ_0 is the heat conduction coefficient of the air, [W/(Km)]; c_a is the mass heat capacity of the air, [J/(K kg)]; ρ_a is the mass density of the air, [kg/m^3], terms u, v, w define the velocity components of air particles as they move between the skin and the fabric layer; they are obtained as a solution of the ventilation problem (4), (5).

Equation (10) describes the heat transfer by diffusion (first three terms in the left-hand side of equation (10) and advection (fourth to sixth terms), as air moves in the microclimate gap. The boundary conditions on different surfaces (Fig. 3) are summarized in Table 2.

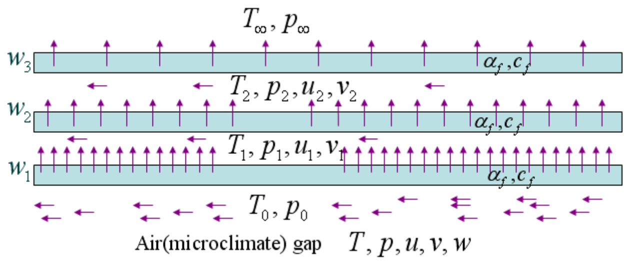

Fig. 3. Scheme of the temperatures calculated by solving the diffusion-advection equation

The heat exchange through the first fabric layer of the textile package is described by the equation:

$$c_f\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{Bmatrix}\dot T_0\\ \dot T_1\end{Bmatrix}+\left(\alpha_f\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}+w_1\rho_a c_a\begin{bmatrix}0 & 0\\ -1 & 1\end{bmatrix}\right)\begin{Bmatrix}T_0\\ T_1\end{Bmatrix}=\begin{Bmatrix}0\\ 0\end{Bmatrix}, \tag{11}$$

where: α_f is the thermal conductivity coefficient of the textile layer in the normal direction defined for the unity surface area of the fabric; ρ_a, c_a are the mass density and mass thermal capacity of the air; c_f is the thermal capacity coefficient of the textiles defined for unity surface area of the fabric; T_0, T_1 are the temperature values at the boundary with the microclimate zone and in the first gap in-between the fabric layers; w_1 is the average filtration velocity of the air through the first fabric layer obtained by solving the ventilation problem.

The temperatures in the first gap of the textile package are described as:

$$\frac{\partial}{\partial x}\left(\lambda_0\frac{\partial T_1}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_0\frac{\partial T_1}{\partial y}\right)- c_0\rho_0 u_1\frac{dT_1}{dx}-c_0\rho_0 v_1\frac{dT_1}{dy}=\rho_0 c_0\frac{\partial T_1}{\partial t},\in V_0, \tag{12}$$

Equation (12) assumes that the heat transfer to the environment at the boundaries of the zone is negligible. Equations (11) and (12) are repeated for every fabric layer in the textile package. For example, the application of equations for the second gap reads as:

$$c_f\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{Bmatrix}\dot T_1\\ \dot T_2\end{Bmatrix}+\left(\alpha_f\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}+w_2\rho_a c_a\begin{bmatrix}0 & 0\\ -1 & 1\end{bmatrix}\right)\begin{Bmatrix}T_1\\ T_2\end{Bmatrix}=\begin{Bmatrix}0\\ 0\end{Bmatrix} \tag{13}$$

Table 2. Boundary conditions for the heat exchange problem

Boundary	Boundary condition	Comment
S_{skin}	$n_x\lambda\frac{\partial T}{\partial x}+n_y\lambda\frac{\partial T}{\partial y}+n_z\lambda\frac{\partial T}{\partial z}-q^* = 0, \in S_{skin}$	q^* is the amount of heat generated by the human body through the unity area of the skin.
S_{vent}	$T = T_\infty, \in S_{vent}$	Ventilator air flow temperature T_∞ is known and equal to the outer temperature. If no forced ventilation applied, the boundary condition is expressed as $n_x\lambda\frac{\partial T}{\partial x}+n_y\lambda\frac{\partial T}{\partial y}+n_z\lambda\frac{\partial T}{\partial z}=0.$
$S_0 \cup S_{open}$	$n_x\lambda\frac{\partial T}{\partial x}+n_y\lambda\frac{\partial T}{\partial y}+n_z\lambda\frac{\partial T}{\partial z}+ cp(n_x u+n_y u+n_z u)=0, \in S_0 \cup S_{open}$	At the ventilated boundary of the zone and at the contact zone with the textiles the heat is being lost by advection as the air flow exits from the investigated zone.

$$\frac{\partial}{\partial x}\left(\lambda_0 \frac{\partial T_2}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_0 \frac{\partial T_2}{\partial y}\right)- \\ -c_0\rho_0 u_2 \frac{dT_2}{dx} - c_0\rho_0 v_2 \frac{dT_2}{dy} = \rho_0 c_0 \frac{\partial T_2}{\partial t}, \in V_0 \quad (14)$$

The ventilation equations (3 – 8) and heat exchange equations (10 – 14), in the present formulation are solved independently.

Calculation of moisture exchange

The moisture exchange in the textile package can be described by diffusion-advection equations similar to the heat exchange equations (10 – 14). The only difference is that the vapour concentration is to be analyzed instead of the temperature.

Necessary experimental data and relations

A series of experiments have been carried out for obtaining coefficient values used in the formulated equations:

a) Values of coefficients α, c_f, α_f are expressed by equations (7) and (11). The coefficient α defines the air penetration conductivity of the fabric layer, c_f is the mass thermal capacity coefficient of the fabric, α_f is the thermal conductivity coefficient in the direction perpendicular to the fabric.

b) Experimentally obtained temperatures of the textiles T_0 and T_1 in time. The relationships are necessary for the model validation on the base of the following equation:

$$c_f\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{Bmatrix}T_0\\ T_1\end{Bmatrix}+\left(\alpha_f\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}+w_1\rho_a c_a\begin{bmatrix}0 & 0\\ -1 & 1\end{bmatrix}\right)\begin{Bmatrix}T_0\\ T_1\end{Bmatrix}=\begin{Bmatrix}Q_0\\ 0\end{Bmatrix}, \quad (15)$$

If temperature T_0 is known, temperature T_1 on the other side of the material theoretically can be obtained from the equation:

$$c_f T_1 + (\alpha_f + w_1\rho_a c_a)T_1 = (\alpha_f + w_1\rho_a c_a)T_0 . \quad (16)$$

On the other hand, values of T_1 can be measured experimentally at certain intervals of time at some steady value of T_0, as well as, when T_0 increases.

c) Similar experiments of the measurement of temperatures T_0 and T_1 are conducted for the textile packages at known values of air flow velocity w_1.

Generation and implementation of the computational model

The above presented equations (3 – 8) and (10 – 14) are solved by using the finite element method. The 3D finite elements are employed for presenting the microclimate zone, and 2D meshes present each layer of the fabric (Fig. 4). In 3D mesh numerical models of equations (4) and (8) are implemented, and in each 2D mesh the elements are obtained on the base of equations (7, 8) and (11, 12). The 3D and 2D domains and each pair of the adjacent 2D domains are joined by using equations (3) and (7).

MATERIALS AND METHODS

Objects of investigation for the evaluation of moisture and heat interchange were selected from military fabrics which are used for soldier's summer (two fabric layers: T-shirt and uniform) and winter (in this case five fabric layers) clothing. The assortment and the main fabrics characteristics are presented in Table 3: military clothing is manufactured from knitted, woven and multilayer breathing materials (number of clothing layer is indicated in ascending order from the body). Recently for the upper layer of a soldier clothing three-layer materials are used. Such materials are characterized by water resistance from outside and good vapor penetration from inside, i. e. breathing materials. Water vapor penetration characteristics of such materials mostly depend on the parameters of membranes which are used in multilayer fabrics [9, 10].

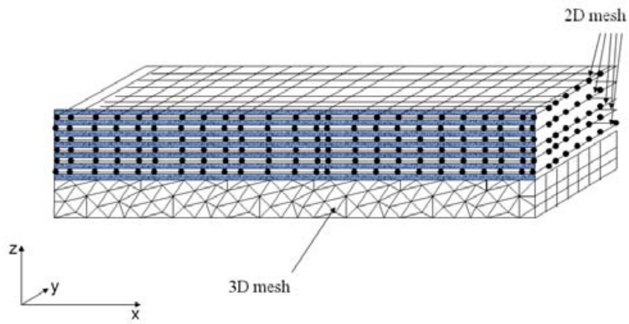

Fig. 4. Finite element mesh

The experimental investigation of the heat insulation properties was performed according the LST EN 31092:2002 (ISO 11092:1993) method [11] defining the values of water vapour and thermal resistance of 1, 2 and 5 layers packages (Table 4). Such multilayer packages are of the same and different fibre composition and structure.

RESULTS AND DISCUSSION

According to the results indicated in Table 4, it can be concluded that at the increasing number of layers, the air permeability of the package decreases while thermal resistance increases. Such a growth in thermal resistance is caused by heat transportation in air gaps between layers [12, 13]. The results of the investigation indicated that the best thermal resistance properties are achieved for double faced knitted pile material (material No 3, Table 4).

The thermal resistance and air permeability investigation results of textile packages with different fibre content and structure are presented in Table 5. The reliability of the results corresponds the requirements indicated in the standard (deviation does not exceed 7 %).

According to the results of the Table 5, it can be concluded that the air permeability of the multilayer textile package depends on the minimal values of the consisting materials. The air permeability characteristics of the three-layer membrane materials also influence the air permeability of the whole multilayer textile package (materials No 5a and 5b, Table 4). The air permeability of the two layer textile packages is close to the lower value of the separate material, i. e. to the air permeability of the rip-stop weaving fabric (material No 2a, Table 4).

Another extremely important wearing comfort characteristic of the multilayer clothing is the moisture transportation. As it was mentioned [3, 9 – 16], the wearing comfort mostly depends on the textile material water vapour resistance and absorption characteristics. Water vapour transportation and condensation is not the same in

Table 3. The assortment and characteristics of the textile materials used for military clothing

Sequence of fabric layers	Material No.	Fibre content	Surface density, g/m^2	Thickness, mm	Description of the material
1 – closest to the body	1a	Cotton – 100 %	120	0.8	Knitted material (rib (1×1))
	1b	Cotton – 92 % Polyester – 6.3 % Elastane – 1.7 %	215	1.2	Knitted material (rib (1×1))
2	2a	Cotton – 32 % Polyester – 68 %	187	0.7	Woven material (rip-stop)
	2b	Cotton – 62 % Polyester – 38 %	251	0.8	Woven material (rip-stop)
3	3	Polyester – 100 %	287	4.8	Double faced knitted material (pile)
4	4	Cotton – 34 % Polyester – 66 %	173	0.9	Woven material (plain)
5 – furthermost from the body	5a	Outer layer – polyester 100% Middle layer – polyurethane 100 % Inner layer – polyamide 100%	219	0.8	Three-layer material with micro pore membrane
	5b	Outer layer – polyester 100% Middle layer – polyurethane 100% Inner layer – polyamide 100%	258	0.9	Three-layer material with micro pore membrane

Table 4. Thermal resistance and air permeability characteristics of the same structure and composition textile packages

Material No.	Thickness of textile package, mm			Thermal resistance, m^2 K/W, LST EN 31902:2002)			Air permeability, mm/s, (LST EN ISO 9237:1997)		
	1 layer	2 layers	5 layers	1 layer	2 layers	5 layers	1 layer	2 layers	5 layers
1a	0.8	1.6	4.0	0.025	0.070	0.149	1629	931	418
1b	1.2	2.4	6.1	0.035	0.078	0.141	652	338	128
2a	0.7	1.4	3.5	0.007	0.013	0.067	122	60	23
2b	0.8	1.5	3.9	0.008	0.015	0.075	60	41	16
3	4.8	9.6	24.0	0.147	0.264	0.627	666	358	132
4	0.9	1.8	4.6	0.023	0.034	0.109	234	124	53
5a	0.8	1.6	3.9	0.005	0.008	0.050	0	0	0
5b	0.9	1.9	4.7	0.006	0.009	0.060	0	0	0

Table 5. The results of thermal resistance and air permeability of different structure and composition textile packages

Number of layers in textile package	Set of materials in the textile package	Thickness of the textile package, mm	Thermal resistance, m^2 K/W, (LST EN 31902:2002)	Air permeability, mm/s, (LST EN ISO 9237:1997)
2	1a+2a	1.5	0.057	117
2	2a+1a	1.5	0.044	113
5	1a+2a+3+4+5a	8.0	0.231	0
5	1b+2a+3+4+5a	8.4	0.241	0

Table 6. The results of water vapour resistance and absorption of the same structure and composition textile packages

Material No.	Surface density, g/m^2, (LST EN 12127:1999)	Water vapour resistance, m^2 Pa /W, (LST EN 31902:2002)			Water vapour absorption, %, at relative humidity	
		1 layer	2 layers	5 layers	100 %	40 %
1a	120	0.37	7.42	13.65	8.3	5.2
1b	215	4.07	7.21	11.37	7.3	5.5
2a	187	0.43	6.19	20.82	3.4	2.4
2b	251	3.14	5.47	14.71	5.3	3.2
3	287	13.11	21.89	47.53	0.9	0.3
4	173	2.02	3.13	12.66	3.5	2.1
5a	219	11.31	15.02	40.78	1.8	0.4
5b	258	9.57	13.42	42.72	2.3	1.1

Table 7. The results of water vapour permeability of different structure and composition textile packages

Number of layers in the package	Set of materials in the textile package	Thickness of the textile package, mm	Water vapour resistance, m^2 Pa /W, (LST EN 31902:2002)
2	1a+2a	1.5	9.12
2	2a+1a	1.5	9.52
5	1a+2a+3+4+5a	8.0	35.91
5	1b+2a+3+4+5a	8.4	31.78

all the layers of the multilayer textile package [13, 15] and depends on the thickness of air gaps in the multilayer textile package, air humidity and water absorption of the textile materials [15 – 17]. Also, the amount of moisture in different layers of multilayer textile package depending on the hydrophilic properties of used materials [13, 17].

Besides the research of the thermal resistance, the investigations on the water vapour resistance and absorption characteristics in the multilayer textile packages with the same fibre structure and composition were also accomplished. The average values of the obtained results are presented in Table 6.

The results of water vapour permeability research for different structure and composition textile materials are presented in Table 7.

The results of the heat insulation characteristics obtained using the experimental investigations were applied for the theoretical research of heat and moisture processes in the multilayer textile package.

CONCLUSIONS

In present research mathematical expressions of processes of the ventilation, heat and moisture interchange were presented. Also process modelling was performed and computative model of the finite elements was developed.

It has been defined that for the approval of the developed model experiments, which determine air permeability, thermal and water vapour resistance characteristics of various composition multilayer textile packages must be accomplished.

The results of the accomplished experiments will be used for the approval of the developed computative model in order to adjust it for the description of the comfort characteristics in military clothing at the body's microclimate zone.

The presented mathematical relations and experimental data are the initial base for future investigations. Further tests and validation comparisons of computed results against the experimental ones are going to be accomplished at the next phase of research.

Acknowledgments

This work was supported by the Lithuanian State Science and Studies Foundation under international research work programme, reg. No. V-08048.

REFERENCES

1. **Mattila, H. R.** Intelligent Textiles and Clothing. Cambridge: Woodhead Publishing Limited, 2006: 506 p.
2. **Epstein, Y., Moran, D. S.** Thermal Comfort and the Heat Stress Indices *Industrial Health* 44 2006: pp. 388 – 398.
3. **Bhattacharjee, D., Kothar, V. A.** Neutral Network System for Prediction of Thermal Resistance of Textile Fabrics *Textile Research Journal* 77 (1) 2007: pp. 4 – 12.
4. **Pan, N., Gibson, P.** Thermal and Moisture Transport in Fibrous Materials. CRC Press, 2006: 615 p.
5. **Abraitienė, A., Valasevičiūtė, L., Barauskas, R., Vilkauskas, A.** Finite Element Analysis of Ballistic Properties of a Multilayer Textile Package in LSDYNA *Materials Science* (*Medžiagotyra*) 8 (4) 2002: pp. 500 – 506.
6. STANAG 4364. Waterproof Chlothing (Edition 2). North Atlantic Treaty Organization (NATO).
7. STANAG 2311. Principles Governing the Design of the Individual Load Carrying Equipment of the Combat Soldier (Edition 4). North Atlantic Treaty Organization (NATO).
8. STANAG 2333. Performance and Protective Properties of Combat Chlothing (Edition 4). North Atlantic Treaty Organization (NATO).
9. **Milenkovic, L., Radijovic, D., Ristic, N., Škundric, P.** Possibility of Usage of Polymer Membranes for Protective Clothing Production *Working and Living Enviromental Protection* 1 (3) 1998: pp. 67 – 78.
10. **Gulbinienė, A., Jankauskaitė, V., Sacevičienė, V., Mickus, K. V.** Investigation of Water Vapour Resobtion/ /Desorbtion of Textile Laminates *Materials Science* (*Medžiagotyra*) 13 (3) 2007: pp. 255 – 261.
11. LST EN 31092:2002 en. Textiles. Determination of Physiological Properties. Measurement of Thermal and Water-vapour Resistance Under Steady-state Conditions (Sweating Guarded-hotplate Test).
12. **Nedzinskienė, J., Milašius, R., Deikus, J., Eičinas, J., Kerpauskas, P.** Evaluating Thermal Insulation Properties of Garment Packet Air Interlayer *Fibres & Textiles in Eastern Europe* 14 (1) 2006: pp. 52 – 55.
13. **Rossi, R. M., Gross, R., May, H.** Water Vapour Transfer and Condensation Effects on Multilayer Textile Combinations *Textile Research Journal* 1 2004: pp. 1 – 6.
14. **Matusiak, M.** Investigation of the Thermal Isulation Properties of Multilayer Textiles *Fibres & Textiles in Eastern Europe* 14 (5) 2006: pp. 98 – 102
15. **Barker, R. L., Guerth-Schacher, C., Grimes, R. V., Hamouda, H.** Effects of Moisture on the Thermal Protective Performance of Firefighter Protective Clothing in Low-level Radiant heat Exposures *Textile Research Journal* 76 (1) 2006: pp. 27 – 30.
16. **Kobiela-Mendrek, K., Marcinkowska, E.** Kinetics of Humidification and Drying Clothing Microclimate in Simulating Researches *Fibres & Textiles in Eastern Europe* 15 (5 – 6) 2007: pp. 91 – 93.
17. **Keiser, C., Becker, C., Rossi, R. M.** Moisture Transport and Absorption in Multilayer Protective Clothing Fabrics *Textile Research Journal* 78 (1) 2008: pp. 604 – 613.

Presented at the 17th International Conference
"Materials Engineering'2008"
(*Kaunas, Lithuania, November 06 – 07, 2008*)