ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 21, No. 1. 2015

Influence of Structure of Multilayer System on Functional Characteristics of Clothing for Firefighters

Diana GRINEVIČIŪTĖ *, **Lina VALASEVIČIŪTĖ**, **Romualda BAGDONIENĖ**, **Paulė BEKAMPIENĖ**, **Virginija TAMULIENĖ**

Textile Institute of Center for Physical Sciences and Technology, Demokratu str. 53, LT-48485 Kaunas, Lithuania

crossref http://dx.doi.org/10.5755/j01.ms.21.1.3812

Received 18 March 2013; accepted 01 August 2013

In this work investigation of influence of textile materials surface relief on protective and comfort properties of multilayer system used for firefighter's clothing was performed. For the research different types of multilayer systems consisting of outer shell, thermal and moisture barrier layers and lining were formed. After testing of fabrics mechanical and physical characteristics it was revealed that the structure of a separate fabric layer has a direct influence on protective and comfort properties of a multilayer system of firefighter's garment. In order to decrease a total weight of the protective garment, multilayer systems formed of lower area density fabrics having relief surface were compared to the systems having flat surface structure. The results showed that systems composed of relief structure fabrics ensured the required level of protection creating additional air gaps, also low weight of the systems improved wearing comfort properties.

Keywords: firefighters clothing, moisture and heat transfer, multilayer textile system, surface relief, protective properties, wearing comfort.

INTRODUCTION

Creating of protective clothing for firefighters is based on the main purposes: to ensure optimal protection of the human body and to ensure the satisfactory functional characteristics. The multilayer system for firefighters clothing usually consists of several layers: an outer shell, moisture barrier of water resistant and water-vapour permeable membrane, a thermal insulation layer and lining. The optimal combination of functional and comfort properties may be achieved not only selecting the proper fibre content, but also the structure of separate elements and of the whole system.

Investigations of various researchers have revealed that protective properties of the multilayer clothing system depend mostly on the weight of materials, i. e. when the weight increases, the protective performance enhances [1 – 4]. It was also stated that thermal resistance of clothing as a multilayer textile system depends on thickness and porosity of a particular layer [6, 7]. Considering comfort properties of the protective garment, the weight is unfavourable factor – an additional weight increases the amount of metabolic heat, generated by human body and at the same time restricts the heat loss [5].

Fabric surface structure is also one of the most important factors influencing protective performance. Textile materials, which are recently used for the firefighters clothing, have a surface structure which is flat or relief. It is known that system performance may be enhanced creating an air layer [8, 9]. The amount of air volume in the system can be increased by incorporating a three-dimensional (3D) fabric structure in a multilayer textile system, hereby creating an additional air gap between two layers. Air gaps can be also created by segmentation process, when the air layer is split into periodic segments, hereby preventing the flame spreading to the further segments [10].

R. M. Rossi *et al.* have studied performance after heat exposure of different aramid fabrics systems, typical for those used in firefighters clothing paying attention to their structure [2]. As it was stated above, thick clothing systems are trusted for higher total thermal resistance. But in the case if the relatively high weight of multilayer fabric system is chosen, the results have shown a negative impact of moisture on the predicted burn protection [11]. Authors of the same study also revealed that it is obvious that moisture level in the system depends on whether permeable or impermeable multilayer system is. Following investigation of moisture concentration in the system, C. Keiser has noted different moisture levels in the systems of hydrophilic and hydrophobic textile fabrics [12].

Analyzing moisture barrier fabrics suitability for multilayer system designed for protective clothing investigation was performed by researchers [13] presenting the results of tests of different microporous membranes. In study [14] it was presented that the outer shell and moisture barrier have significant effects on the thermal resistance of multilayer system. Also authors have shown in their work a reciprocal correlation between water vapour transmission rate and the thickness of multilayer system. As air permeability is one of the most important properties of textile materials that ensure their comfort, authors of the study [15] determined experimental and theoretical dependencies between following parameter and textile fabric structure parameters, including fabric thickness. It was also determined that in a multilayer system changing thickness of needle punched nonwoven fabric by different treatment, thermal resistance was higher than commercial firefighters' clothing [16].

The aim of this work was to compose multilayer system for firefighters clothing with higher protective and wearing comfort properties and to investigate the influence

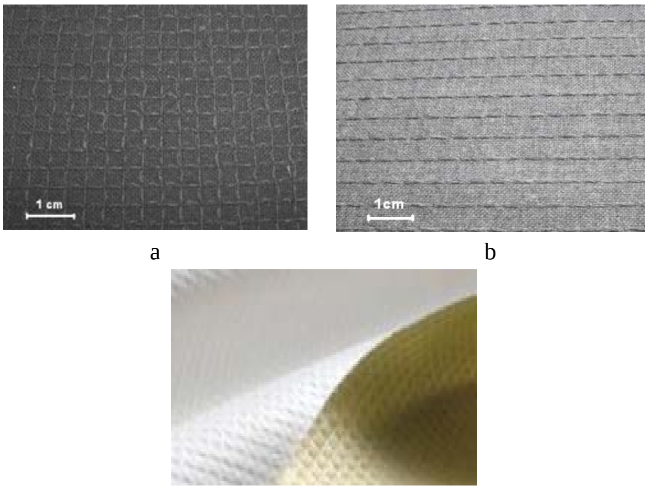
*Corresponding author. Tel.: +370-37-308660; fax.: +370-37-308668.
E-mail address: *grineviciute@lti.lt* (D. Grinevičiūtė)

of surface relief (three-dimensional) structure of textile materials on functional properties of the system. One of the goals was to determine differences of functional properties of surface relief textile fabrics in multilayer systems and typical flat structure of common fabrics, used in manufacture of firefighters clothing [2].

MATERIALS AND METHODS

To compose the multilayer system three and four layers fabric compositions were chosen which consisted of: outer shell, moisture and thermal barrier and lining layers.

In order to investigate the influence of surface relief of textile materials on their protective and comfort properties, a relative rating of surface relief was defined. The rate was determined after measuring thickness of the fabric in its' highest and lowest peaks of the surface structure elements. According to this, three types of surface structure were defined: flat (when thickness rate is 1.0), small relief (the rate 1.2 ÷ 1.5), and relief (the rate >1.5). Some examples of relief structures are presented in Fig. 1.



a b

c

Fig. 1. Surface structure of fabrics: outer layer O4-1 (a), thermal lining L1-2 (b), moisture barrier MB1-1 (c)

Relief identification of multilayer systems structures was performed taking into account structures of the fabrics composing particular systems.

Outer shell

Outer shell must stop flame spread to inner layers and has to be resistant to mechanical treatments. To secure higher resistance to heat and mechanical treatments, meta-aramid fibre together with high-strength para-aramid fibre is usually used. In order to evaluate the influence of different structure of outer shell on functional properties of multilayer system, different fabric constructions – single layer and two layers – were produced (fabrics groups O1 – O3), also new commercially available fabric structure (based on patented Ti-technology) O4-1 was investigated. Outer shell fabric characteristics are presented in Table 1.

Lining

In multilayer system a thermal insulation layer is usually used in combination with lining material. The thermal barrier must limit the increase of temperature inside the clothing, while lining secures a good sliding over firefighter's clothing.

In this research the range of different single layer lining fabrics of flat plain weave surface (L1-1) and three-dimensional plain weave structure (fabrics L1-2, L1-3, L1-4, Table 2) were created. Three-dimensional structure on the surface of the fabric was obtained due to the higher linear density weft yarns being periodically introduced in the fabric.

For the comparison of mechanical parameters of different lining materials additional commercially available fabric structures were evaluated (fabrics L2-1 and L3-1, Table 2).

Thermal and moisture barrier

In order to avoid heat transfer from outer layer to inner ones a thermal barrier layer is necessary. For the investigation of thermo isolative layer commercially available advanced technology para-aramid fabrics (TB1-1, TB1-2) were chosen.

For the development of multilayer system hydrophilic and bicomponent membranes, produced applying different technologies and having different surface relief (MB1-1, MB1-2) were chosen. Structure parameters of thermal and moisture barrier layers are presented in Table 2.

Table 1. The structure parameters of outer shell fabrics

Fabric code	Characteristic					
	Content	Weave type		Structure periodicity	Area density, g/m^2	Thickness, mm
		Face	Back			
O1-1	75 % meta-aramid 23 % para-aramid 2 % carbon fibre	Twill 2/1		-	199	0.54
O2-1		Plain rip-stop		4 mm × 4 mm*	190	0.45
O2-2				6 mm × 6 mm*	195	0.47
O2-3				8 mm × 8 mm*	196	0.47
O3-1		Twill 1/3		1/1**	276	0.72
O3-2		Twill 1/3		2/2**	270	0.73
O3-3		Basket 1/3	Broken twill 1/3	2/1**	266	0.71
O3-4	58 % meta-aramid 41 % para-aramid 1 % carbon fibre	Twill 1/3		1/1**	270	0.69
O3-5		Twill 1/3		2/2**	279	0.72
O4-1	89 % meta-aramid 9 % para-aramid 2 % carbon fibre	Plain rip-stop	Grind*	4 mm × 4 mm*	220	0.88

* – interval of a crosshatch pattern; ** – face to back weft yarn ratio.

Table 2. Structure parameters of lining, thermal and moisture barrier fabrics

Fabric code	Characteristic				
	Content	Weave (structure) type		Area density, g/m^2	Thickness, mm
		Face	Back		
L1-1	50 % meta-aramid / 50 % viscose FR	Plain		140	0.35
L1-2	50 % meta-aramid / 50 % viscose FR	Plain with insertion of higher density weft yarns*	Plain	150	0.72
L1-3	42 % meta-aramid / 42 % viscose FR 16 % para-aramid		Plain	155	0.74
L1-4	41 % meta-aramid / 52 % viscose FR 7 % para-aramid		Plain	151	0.73
L2-1	75 % meta-aramid / 25 % viscose FR	Plain		110	0.30
L3-1	100 % meta-aramid	Combined (patterned)	Combined	130	0.38
Nonwoven fabrics					
TB1-1	100 % para-aramid	Flat perforated needlefelt		95	1.53
TB2-1	100 % para-aramid	Relief 3D spunlace felt	Flat	80	1.21
MB1-1	Textile: 100 % meta-aramid, para-aramid Membrane: 100 % bicomponent ePTFE/PU	Relief 3D	Flat	140	1.35
MB2-1	Textile: 50 % melamine resin / 25 % para-aramid / 25 % meta-aramid Membrane: 100 % hydrophilic PES	Flat		110	0.87

* 8 mm interval of a higher density weft insertion.

Multilayer system structures

Multilayer fabric systems for firefighter's protective clothing were arranged considering the area density and thickness of the separate fabrics. In order to achieve the aim relief outer shell was created and lining structures with periodically segmented air layer, which together with other recent relief moisture barrier and thermal insulation textile materials were used to compose the multilayer system.

EXPERIMENTAL

Before composing multilayer systems separate fabrics were tested according to special requirements based on fabric functional properties in accordance with EN 469 +AC:2005 standard (performance level 2):

- tensile and tearing strength were determined according to standards EN ISO 13934-1:1999 and EN ISO 13937-2:2000 employing universal tensile testing machine Zwick;
- resistance to surface wetting was performed according to a standard EN ISO 4920:2012 when spraying water at a distance of 150 mm to the specimen with inclination of 45°. Surface wetting was determined according to spray rating scale;
- air permeability was determined according to a standard EN ISO 9237:1995 when test surface area was 20 cm^2 and pressure drop 100 Pa;
- dimensional change was determined according to a standard EN ISO 5077:2008 5 washing cycles at 60 °C (EN ISO 6330:2012);
- resistance to water penetration was determined applying a hydrostatic pressure method (EN 20811:1992) and measuring the pressure of water column until penetration occurs on the opposite side of the fabric. The rate of the pressure increase of the water was 60 cm ±3 cm head of water per minute.

Protective properties of multilayer systems were determined after pre-treatment procedure (5 washing and drying cycles according to the standard EN ISO 6330:2012 procedure 2A at 60 °C):

- radiant heat transmission of 40 kW/m^2 ($RHTI_{24}$, $RHTI_{24-12}$) according to the standard EN ISO 6942:2002;
- heat transmission on exposure to flame of 80 kW/m^2 (HTI_{24}, HTI_{24-12}) according to the standard EN 367:1992,
- water vapour resistance R_{et} according to the standard EN 31092:1993.

The coefficient of variation of experimental values varied in between 0.52 % – 6.19 %.

RESULTS AND DISCUSSION

Outer shell

Test results of outer shell fabrics are listed in Table 3. It was determined that changes in interval of crosshatch pattern of fabrics group O2 had no influence on fabric structure characteristics (thickness and area density). Considering physical and mechanical characteristics of these fabrics, only slight difference in most of the characteristics was noticed. The exception was only the tearing strength, which is one of the most important characteristics of the outer shell and which ensures proper protective performance of the garment under the influence of mechanical effects. As it was expected, decreasing interval of a crosshatch pattern, tearing strength has gradually increased. It can be also mentioned that the denser was crosshatch pattern the slight increase in tensile strength and decrease in tensile elongation was obtained. According to these results fabric O2-1 with highest resistance to mechanical treatments was chosen for further investigations.

From the analysis of double-layer fabrics properties (fabrics group O3) it can be seen, that increasing the face to back weft yarn ratio, the values of area density slightly decreased. However, the most significant influence upon mechanical characteristics had the content of back yarn system. Para-aramid fibres, inserted as the back yarn system, increased the tensile strength twice and decreased the elongation at break (Table 3, fabrics O3-4, O3-5).

Considering these results the thickest and lightweight fabric O3-4 with the highest strength characteristics was selected for further investigations in a structure of multilayer system.

Considering results of mechanical characteristics fabric O4-1 that have double-weave construction and a lightweight grind on the back side was also selected for further investigation of multilayer systems.

Lining, thermal and moisture barrier

Test results of the lining, thermal and moisture barrier layers are presented in Table 4. As it was expected analysis of results of L1 fabrics group showed that higher linear density yarns periodically introduced in the weft yarn system (L1-2, L1-3, L1-4) increased the thickness of the fabric roughly twice and slightly changed the weight of the fabric comparing to L1-1 (area density increased up to 10.7 %). The content of thicker yarns had no influence on the structure properties of the fabrics, but significant differences were fixed in physico-mechanical properties – significant changes in fabric tensile properties in weft direction. Values of tensile strength have increased gradually, whereas tensile elongation decreased. Such results could predict lower comfort properties of the whole garment because of restricted freedom of movement. It was also achieved that integration of higher linear density yarns into system enhanced the air permeability of the fabric.

However, as it was noted before, a hydrophilic lining could also enhance the process of moisture transfer. According to this, for further investigations fabric L1-2 was selected, as the fabric with the best complex of properties. For multilayer structures investigations L2-1 and L3-1 – contemporary structures stitched with thermal barrier layer – were also chosen. For the evaluation of multilayer systems commercially available thermal (TB) and moisture barrier (MB) fabrics with different relief surface were chosen.

The arrangement of multilayer systems

Seven multilayer systems were arranged combining different new created materials for outer shell and lining together with advanced commercially available thermal and moisture barrier layers composed of fabrics with different area density and thickness (Table 5). The selection was performed according to initial mechanical parameters determined in previous investigation. Three fabrics for outer shell were chosen with following parameters: area density (190, 220, 270 g/m^2), thickness (0.45, 0.88, 0.69 mm) and structure relief (small relief, relief and flat) respectively. Lining fabrics for this study were also selected with different area density (110, 130, 150 g/m^2), thickness (0.30, 0.38, 0.72 mm) and structure relief (small relief, relief and flat) respectively.

According to the content of aramid fibre in the fabric, multilayer systems may be divided into two groups: fabrics

Table 3. Characteristics of outer shell fabrics

Fabric code	Tensile strength, N		Elongation at break, %		Tear strength, N		Air permeability, dm^3/m^{2}s	Resistance to surface wetting, class	Dimensional change, %	
	Warp	Weft	Warp	Weft	Across warp	Across weft			Warp	Weft
O1-1	1283	1076	16.0	9.2	52	43	133	4	–1.0	–0.5
O2-1	1046	1075	20.8	9.8	117	94	152	4	–2.5	0
O2-2	1037	1038	20.7	10.2	102	79	122	4	–2.0	–0.5
O2-3	1057	907	21.9	10.6	89	71	106	5	–2.5	0
O3-1	1503	1734	21.3	8.4	122	93	331	4	–3.0	0
O3-2	1489	1698	21.0	8.2	130	94	277	4	–3.0	0
O3-3	1500	1712	21.5	8.4	91	98	121	5	–3.0	0
O3-4	1511	3414	21.0	4.7	134	160	429	4	–2.0	0
O3-5	1495	3387	21.4	4.6	153	186	530	4	–2.5	0
O4-1	1300	1100	40.0	30.0	115	105	140	4	–1.5	–0.5

Table 4. Characteristics of lining, thermal and moisture barrier fabrics

Fabric code	Tensile strength, N		Elongation at break, %		Tear strength, N		Air permeability, dm^3/m^{2}s	Resistance to water penetration, kPa	Dimensional change, %	
	Warp	Weft	Warp	Weft	Across warp	Across weft			Warp	Weft
L1-1	645	526	16.3	15.0	46	43	1325	–	–2.0	+2.0
L1-2	653	655	14.7	14.3	46	65	1517	–	–2.0	+1.5
L1-3	660	702	15.5	13.6	48	94	1514	–	–2.0	+2.5
L1-4	652	772	13.6	8.1	46	73	1531	–	–2.0	+2.0
L2-1	608	496	25.1	26.9	37	35	1380	–	–1.0	+1.5
L3-1	869	726	30.1	23.6	93	102	953	–	–1.0	+1.0
TB1-1	27	49	61.6	73.1	18	19	1507	–	–1.6	–0.6
TB2-1	247	169	51.7	70.1	60	43	1242	–	–0.5	–0.5
MB1-1	541	342	46.1	73.4	109	54	–	89.3	–0.5	–0.5
MB2-1	181	149	43.3	65.7	33	37	–	95.0	–0.8	–1.0

containing 70 % – 75 % of aramid fibre (systems 1 – 4) and fabrics containing 80 % – 85 % of aramid fibre (systems 5 – 7) (Table 5). Such principle of classification according to aramid quantity is based on a possibility to form lighter structures, i. e. fabrics systems with lower aramid content (systems 1 – 4) have lower area density (480 – 560 g/m^2), and this enables to create multilayer systems with advanced wear properties only decreasing system weight.

Table 5. The arrangement of multilayer systems

System No.	Fabric code	Surface relief*	Structure type	Area density, g/m^2	Content of aramid fibres in a system, %
1	O2-1/MB1-1/L1-2	S/R/R	Relief	480	69.0
2	O4-1/MB1-1/L1-2	R/R/R	Relief	510	70.8
3	O3-4/MB1-1/L1-2	F/R/R	Relief	560	73.6
4	O2-1/MB2-1 TB1-1+L2-1	S/F/F	Flat	510	76.2
5	O3-4/MB2-1 TB1-1+L2-1	F/F/F	Flat	590	79.5
6	O2-1/MB1-1 TB2-1+L3-1	S/R/R	Relief	540	86.4
7	O3-4/MB1-1 TB2-1+L3-1	F/R/R	Relief	620	88.3

* F – flat; S – small relief; R – relief.

It should be also noted that multilayer structures in both groups were composed of fabrics with flat and relief surface structure. Noticeably smoother surface was obtained in systems 4 and 5. Thickness of multilayer structures varied in between 2.5 mm ÷ 3.5 mm.

After pre-treatment procedure it was determined that the thickness of the systems No. 1 – 4 have increased approx. 30 % – 50 %, also higher thickness increase values were obtained in fabrics systems with relief structures. The results obtained in the second group (systems No. 5 – 7) showed less significant increase of fabrics thickness (24 %). This tendency was determined in multilayer systems formed of different surface structures: smooth as well as relief (Fig. 2).

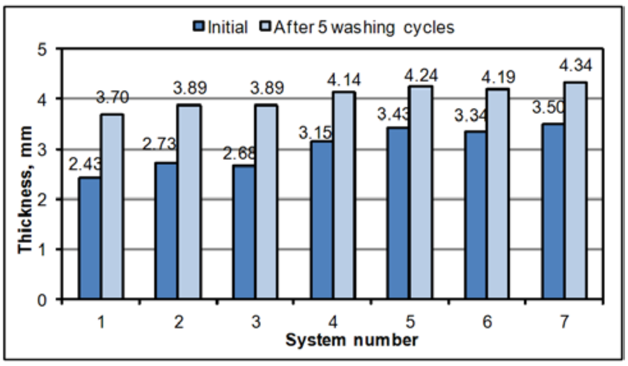


Fig. 2. Comparison of system thickness before and after washing procedure

Analysis of multilayer systems

Test results of protective and comfort properties of created relief and flat surface structure multilayer systems are presented in Figs. 3 – 6. According to test results protective properties of all seven multilayer systems met the requirements of the standard EN 469 +AC: $HTI_{24} \geq 13.0$ s, $HTI_{24\text{-}12} \geq 4.0$ s; $RHTI_{24} \geq 18.0$ s, $RHTI_{24\text{-}12} \geq 4.0$ s; $R_{et} \leq 30.0$ m^{2}Pa/W.

Comparing comfort properties, i. e. water vapour resistance R_{et}, of multilayer systems with lower aramid content (systems 1 – 4) better performance was obtained of systems 1 – 3 which have lower area density as well as relief structure (Fig. 3). Results of comfort properties of systems 5 – 7 (80 % – 85 % of aramid) revealed that relief structure of fabric layers also played important role in better parameters of air permeability and water vapour transport (systems 6 and 7, Fig. 4).

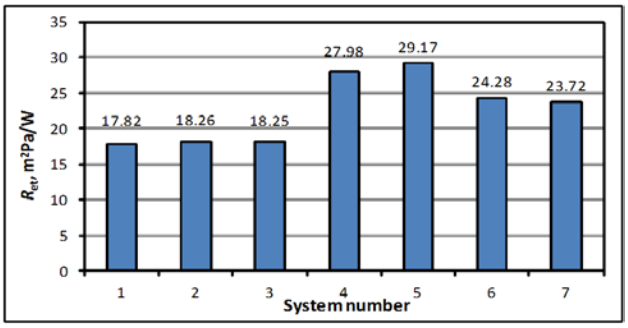


Fig. 3. Results of water-vapour resistance of multilayer systems

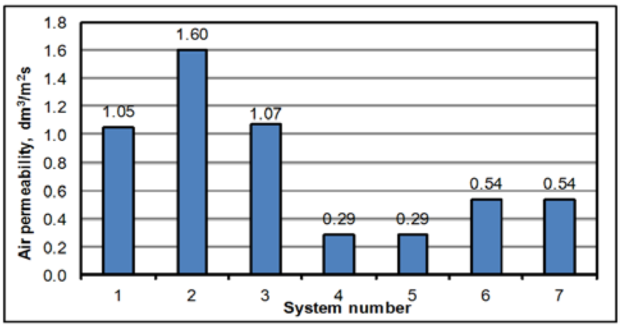


Fig. 4. Results of air permeability of multilayer systems

Analysis of protective properties of two structures (systems 2 and 4, Table 5) having the same area density (510 g/m^2) showed that their protective properties were comparable but relief system 2 showed better comfort properties (water vapour resistance) than the flat system 4 (18.26 m^{2}Pa/W – system 2 and 27.98 m^{2}Pa/W – system 4). Besides, the thickness of system 2 was 15 % lower than the system 4.

In study [14] it was found that moisture barrier has significant effect on protective properties of multilayer system. It must be noted that in system 2 a bicomponent membrane was used as a moisture barrier. The same fabric with bicomponent membrane was used in systems 1 and 3 containing lower quantity of aramid fibre and in systems 6 and 7 containing 80 % – 85 % of aramid fibre. Comparing results presented in Fig. 3 it is evident that water-vapour resistance of relief systems 6 and 7 was achieved lower (16.7 % and 18.7 %, respectively), comparing to the flat system 5 with incorporated hydrophilic membrane (29.17 m^{2}Pa/W). It comes to a conclusion that comparing systems which have the same area density (2 and 4), properties of thermal resistance (Figs. 5, 6) of relief system

Table 6. Results of comparison of protective properties of multilayer systems for firefighters clothing

System No.	Structure type	Area density, g/m^2	Heat transmission on exposure to flame, s		Radiant heat transmission, s	
			HTI_{24}	HTI_{24-12}	$RHTI_{24}$	$RHTI_{24-12}$
6	Relief	540	19.30	5.8	22.70	6.83
6 [2]	Flat	540 [2]	16.50	4.0	21.30	6.30
5	Flat	590	24.23	6.7	25.43	6.90
5 [2]	Flat	630 [2]	24.20	6.0	32.10	8.80

2, containing bicomponent membrane in moisture barrier layer, were superior than flat system 4, containing hydrophilic membrane, but water-vapour resistance of relief system 2 was approx. 35 % better than the same parameter of flat system 4. It can be predicted that integration of bicomponent membrane into a multilayer system could ensure superior wear properties.

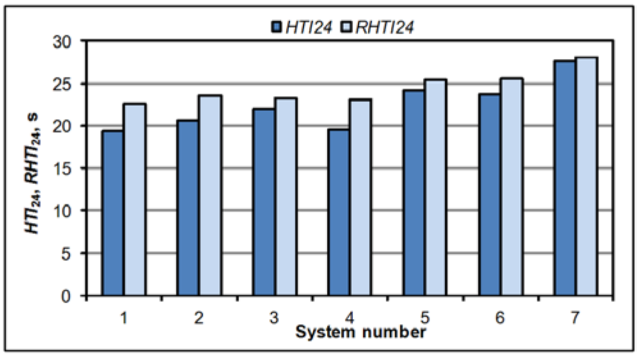


Fig. 5. Results of radiant heat transmission and heat transmission on exposure to flame of multilayer systems to reach temperature increase of 12 °C

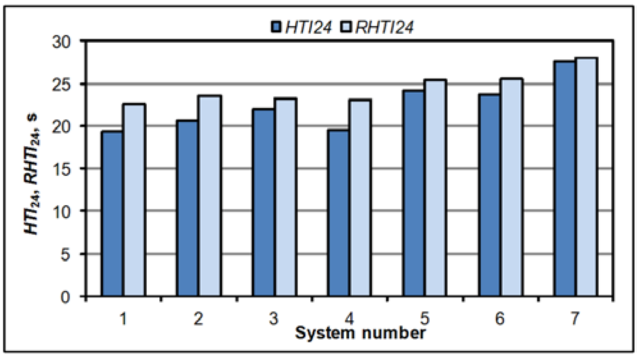


Fig. 6. Results of radiant heat transmission and heat transmission on exposure to flame of multilayer systems to reach temperature increase of 24 °C

In this study comparison of the achieved tests results with investigations performed by other researchers [2] was performed. For the objects of investigation two structures 6 (relief) and 5 (flat) were chosen. Relief multilayer system 6, having the most relevant area density (540 g/m^2) and fabrics combination, was compared with a typical structure of common flat fabrics used in contemporary firefighter's clothing system 6 [2]. Comparative analysis of parameters of created multilayer systems and typical structures of firefighters clothing are presented in Table 6. As it can be seen protective properties of relief structure were achieved superior than of typical flat structure of common fabrics (especially heat transmission on exposure to flame parameter HTI_{24}).

With some presumption protective properties of flat system 5 (590 g/m^2) could be compared to test results of typical structure of common fabrics 5 [2] with area density 630 g/m^2 (Table 6). These systems are similar for their structure, still the difference is that for thermal barrier in system 5 flat perforated needlefelt having lower area density was used, whereas thermal barrier in study [2] was created of heavier and non-perforated fabric. According to data presented in study [17] that perforated thermal barrier fabric ensures analogous protective properties as a non-perforated one with approx. 30 % higher area density, theoretically it can be assumed that protective performance of system 5 (590 g/m^2) is almost the same as of typical heavier firefighter's system (630 g/m^2) [2]. Although results presented in Table 6 show that these both systems met requirements of the standard EN 469 +AC: 2005 it must be mentioned that structure with incorporated perforated thermal barrier layer had lower level of radiant heat transmission.

CONCLUSIONS

During the investigation it was determined that structure of a separate fabric layer had a direct influence on protective and comfort properties of a multilayer system of firefighter's garment. Following this it can be stated that:

1. Proper protective performance of the whole garment under the influence of mechanical effects can be ensured using an outer shell material with narrow interval of crosshatch pattern in rip stop fabric structures.
2. Fabric strength and resistance to mechanical factors characteristics can be improved using two-layer fabrics for outer shell layer.
3. Pre-treatment (washing) procedure has direct influence on structural changes of multilayer system: thickness of relief fabrics significantly increased comparing to flat ones, though forming air gaps in the system.
4. Heat protective properties of the multilayer system may be improved using thermal lining with relief structure hereby creating air gaps in the system.
5. Multilayer systems formed of lower area density fabrics having surface relief, ensure the required level of protection, additionally improving comfort properties.
6. Comparative analysis of parameters of created multilayer systems and typical structure of common fabrics for firefighters clothing showed that protective properties (especially heat transmission on exposure to flame) of relief structures of the same area density and similar structure were superior comparing to

typical flat structure of common fabrics used for contemporary firefighters clothing.

REFERENCES

1. **Fanglong, Z., Weiyuan, Z., Minzhi, C.** Investigation of Material Combinations for Fire-fighter's Protective Clothing on Radiant Protective and Heat-Moisture Transfer Performance *Fibres & Textiles in Eastern Europe* 1 2007: pp. 72 – 75.
2. **Rossi, R. M., Bolli, W., Stämpfli, R.** Performance of Firefighters' Protective Clothing after Heat Exposure *International Journal of Occupational Safety and Ergonomics (JOSE)* 14 (1) 2008: pp. 55 – 60.
3. **Horrocks, A. R.** Textiles for Protection. Thermal (Heat and Fire) Protection. Woodhead Publishing Limited, 2005: 784 p.
4. **Kutlu, B., Cireli, A.** Thermal Analysis and Performance Properties of Thermal Protective Clothing *Fibres & Textiles in Eastern Europe* 13 (3) 2005: pp. 58 – 62.
5. **Holmer, I.** Protective Clothing in Hot Environments *Industrial Health* 44 2006: pp. 404 – 413.
6. **Bivainytė, A., Mikučionienė, D., Kerpauskas, P.** Investigation on Thermal Properties of Double-Layered Weft Knitted Fabrics *Materials Science* (*Medžiagotyra*) 18 (2) 2012: pp. 167 – 171.
7. **Barauskas, R., Valasevičiūtė, L., Jurevičiūtė, A.** Computational Analysis and Experimental Investigation of Heat and Moisture Transfer in Multilayer Textile Package *Materials Science* (*Medžiagotyra*) 15 (1) 2009: pp. 80 – 85.
8. **Oh, A.-G.** The Measurement of Water Vapour Transfer Rate Through Clothing System with Air Gap Between Layers *Heat and Mass Transfer* 44 (4) 2008: pp. 375 – 379.
9. **Li, X.-H. Lu, Y.-H., Li, J., *et al.*** A New Approach to Evaluate the Effect of Moisture on Heat Transfer of Thermal Protective Clothing under Flashover *Fibres and Polymers* 13 (4) 2012: pp. 549 – 554.
10. **Holmes, D. A.** Textile for Survival. Woodhead Publishing Limited, Cambridge, 2000. http://dx.doi.org/10.1533/9781855738966.461
11. **Barker, R. L., Guerth-Schacher, C., Grimes, R. V., Hamouda, H.** Effect 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 – 31.
12. **Keiser, C., Becker, C., Rossi, R. M.** Moisture Transport and Absorption in Multilayer Protective Clothing Fabrics *Textile Research Journal* 78 (7) 2008: pp. 604 – 613.
13. **Brzezinski, S., Malinovski, G., Nowak, T., *et al.*** Structure and Properties of Microporous Polyurethane Membranes Designed for Textile-Polymeric Composite Systems *Fibres & Textiles in Eastern Europe* 12 2005: pp. 53 – 58.
14. **Cui, Z., Zhang, W.** Study of the Effect of Material Assembly on the Moisture and Thermal Protective Performance of Firefighters Clothing *Fibres & Textiles in Eastern Europe* 17 2009:pp. 80 – 83.
15. **Ogulata, R. T., Mezarcioz, S.** Total Porosity, Theoretical Analysis, and Prediction of the Air Permeability of Woven Fabrics *Journal of the Textile Institute* 103 (6) 2012: pp. 654 – 661.
16. **Jin, L., Hong, K.-A., Nam, H. D., Yoon, K. J.** Effect of Thermal Barrier in Thermal Protective Performance of Firefighter Garments *Journal of Fibre Bioengineering and Informatics* 4 (3) 2011: pp. 245 – 252.
17. **Fourmeux, J.** Fireproof Thermally Insulating Barrier, a Method of Fabricating such as Barrier, and a Garment Comprising at Least One Such Barrier as Internal Insulation. USP No. US 6743498, 2001.