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Specialised Clothing for Firefighters in Poland – a Comparison of the Latest Set with the One Currently Used

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Abstract
Specialist clothing for firefighters must comply with a number of various standards in terms of e.g. water vapour resistance. The use of different materials and constructional solutions may affect the results of thermal parameters of the clothing. A search for new solutions can lead to ergonomic products. The aim of the article was to show whether there were differences in thermal parameters between the special clothing currently used for firefighters in Poland and clothing that takes into account new materials and trends in the construction of the above-mentioned type of clothing. The research results indicate no difference between the sets of clothing tested in terms of global thermal parameters; however, differences are recorded for values of local thermal insulation and water vapour resistance. These differences are attributable mainly to the construction of the clothing and not to the materials used.

Key words: *firefighter, special clothes, thermal manikin, thermal parameters.*

Introduction

As a firefighters' job is considered as one of the most dangerous professions, appropriate and comfortable protective clothing is essential. The State Fire Service in Poland gives numbers concerning, among other things, fire incidents. Only in 2017, in general, 1196158 firefighters intervened in 125892 incidents, from which 5116 are considered as *medium*, 298 as big, and 70 as large [1]. A medium fire means that objects, parts of objects, chattels, material storages, machines, devices and/or raw materials with an area of (71-300) m^2 or a volume of (351-1500) m^3 are destroyed as a result [2]. Considering the most common materials that burn during incidents (e.g. the maximum diffusion flame temperature, varies from 1027 °C for wood to 1200 °C for methanol [3]), firefighters are exposed to heat stress. The common and frequent exposure to high temperatures can cause extremely high thermal stress and overheating, which are life-threatening regarding their circumstances. These factors make this area of protective clothing interesting for global as well as local producers. The number of the latter in Poland is currently increasing. Besides the obvious functions that thermal clothing fulfils, it also needs to comply with strict standards. All personal protective equipment used by firefighters (including special clothing) is classified as Category III. The result of this process is the EC type-examination certificate, which confirms compliance with the requirements of Directive 89/686/EEC[1)] [4], in particular the EN 469 standard [5]. These requirements are essential when choosing appropriate equipment. Producers, trying to fulfil all of them, offer many different types of clothing. Models of protective clothing differ from each other with respect to their construction, number of layers and, most importantly, the materials that they are made of. The many combinations of different fibres used for thermal clothing imply a great number of fabrics that have protective properties.

Unfortunately, most of them, aside from insulating from outside heat, also do so from the heat produced by humans, causing a disturbance in thermal comfort as well as overheating of the firefighter's organism. The weight of sets also needs to be mentioned, as they are usually quite heavy, which makes the work even more difficult and tough. Optimal protective clothing, therefore, needs to insulate against the outside temperature, highly reduce heat transfer, and be light and comfortable for its user.

Main goal of research

The main goal of the research presented in the article was to show whether there were any differences in thermal parameters between the special clothing currently used for firefighters in Poland (EN_1) and clothing that takes into account new materials and trends in the construction of the above-mentioned type of clothing (EN_2).

The results of our research could answer the question whether the construction or material used in special clothing have an influence on thermal parameters. Indirectly, it could allow to state how to improve new patterns of special clothing.

Material and methods

Research equipment

The study was carried out with a thermal manikin of the Newton type manufactured by Measurement Technology Northwest (USA). The manikin consists of 32 segments (***Figure 1***). The thermal manikin allows simulation of dry heat transfer (thermal insulation) as well as wet heat transfer (evaporative resistance) [6].

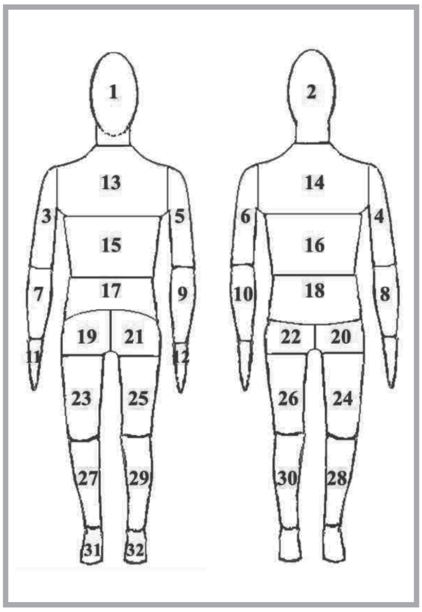

Figure 1. *Scheme of thermal manikin's segmentation (from left: front and back of the manikin).*

__Figure 2.__ Sample of firefighter personal protective clothing (FFPPC) (from left: EN_1, EN_2) with the place with the difference in the construction of the clothes marked.

__Table 1.__ Materials used for the clothing ensembles tested (data from the producer).

Layer	EN_1	EN_2
External	64% meta-aramid 35% para-aramid 1% anti-static fibres	70% meta-aramid 28% para-aramid 2% anti-static carbon fibre
Membrane	35% polyurethane 65% para-aramid	50% laminate PTFE 25% meta-aramid 25% para-aramid
Thermal insulation	aramid flame retardant fibres	67% meta-aramid 33% para-aramid
Lining	50% aramid fibre 50% viscose	93% meta-aramid 5% para-aramid 2% anti-static fibres

__Table 2.__ Weight of individual elements of the FFPPC garment.

Layer weight, kg		EN_1	EN_2
Blouse	external layer	1.235	1.860
	thermal insulation and lining layer	0.826	
Pants	external layer	0.618	1.216
	thermal insulation and lining layer	0.547	

__Table 3.__ Microclimate parameters in the climatic chamber during testing of the thermal insulation of the clothing ensembles (mean values with standard deviation for two microclimate meters).

Clothing ensemble FFPPC		t_a, °C	V_a, m/s	RH, %
EN_1	test_1	12.4 ± 0.1	0.35 ± 0.05	46 ± 1
	test_2	12.4 ± 0.1	0.35 ± 0.05	48 ± 1
EN_2	test_1	12.4 ± 0.1	0.38 ± 0.05	45 ± 1
	test_2	12.4 ± 0.1	0.39 ± 0.05	47 ± 1

__Table 4.__ Microclimate parameters in the climatic chamber during testing of the evaporative resistance of the clothing ensembles (mean values with standard deviation for two microclimate meters).

Clothing ensemble FFPPC		t_a, °C	V_a, m/s	RH, %
EN_1	test_1	12.3 ± 0.1	0.38 ± 0.05	69 ± 1
	test_2	12.2 ± 0.1	0.39 ± 0.05	68 ± 1
EN_2	test_1	12.2 ± 0.1	0.40 ± 0.05	62 ± 1
	test_2	12.2 ± 0.1	0.40 ± 0.05	62 ± 1

The tests were done in a climatic chamber (Weiss). Microclimate parameters like air temperature (t_a), air velocity (V_a) and relative humidity (RH) were controlled by two microclimate meters: Indoor Climate Analyzer from B&K and INNOVA.

Tested clothing

Two sets of special clothing (Fire-Fighters Personal Protective Clothing – FFPPC) intended for firefighting and similar actions, such as rescue and disasters, were used. One of them (EN_1) is currently used in Poland (***Figure 2***), while the other is a new design (EN_2) meeting the requirements of EN 469 [5] while using the latest trends. The EN_2 garment has a high-quality membrane and perforated reflective tapes. Such types of tapes do not stop water from evaporating, therefore the clothing ability to "breathe" is enhanced. Furthermore, perforated reflective tapes affect the mass of the clothes. The clothing has an EC type examination certificate and the CNBOP-PIB Certificate of Approval[2)].

The clothes tested differed in terms of the materials used for each layer of the structure. A summary of materials used for the clothing ensembles tested is shown in ***Table 1***.

Individual layers of the firefighter special clothing differed mainly in the percentage of each aramid isomer and the materials used in the lining layer.

The above sets of clothing also differed in mass. Detailed information is provided in ***Table 2***.

The EN_2 set was 150g lighter than the EN_1. Lighter clothing, being a lower burden for the user; which improves ergonomics and comfort of use.

Thermal parameters of FFPPC

Thermal insulation R_{ct}

Thermal insulation tests of the clothes selected (R_{ct}) were conducted in accordance with the EN ISO 15831:2004 [7] and EN 342:2004 [8] standards. During the tests, the thermal manikin was wearing a special fabric skin, and its surface temperature was set at 34.0 °C.

According to EN ISO 15831:2004 [7], the permitted error between measurements is 4%.

The insulation tests were carried out in an environmental chamber with the parameters set as follows: air temperature (t_a) 12 °C, relative humidity (RH) 45%, and air velocity (V_a) 0.4 m/s. The tests were done in steady-state conditions, and the thermal parameters in the climatic chamber were controlled by microclimate meters (***Table 3***).

Evaporative resistance R_{et}

The evaporative resistance of the clothing ensemble (R_{et}) was tested on a thermal manikin wearing a special fabric skin. The test conditions complied with the ASTM F2370-15 standard [9]. During the tests, the manikin surface temperature for most segments was 34.0 °C and the sweat rate – 400 ml/(h · m^2). According to ASTM F2370-15 [9], the permitted error between measurements was 10%.

As required, they corresponded to the 'non-isothermal conditions' under the same conditions as for dry heat exchange. The thermal parameters in the climatic chamber were controlled by microclimate meters (***Table 4***).

Results

Results from the thermal insulation and evaporative resistance tests performed for the clothing selected are presented below.

Total thermal insulation

A summary of the total thermal insulation (calculated by two mathematical methods [6, 7]: the thermal insulation was calculated by two mathematical methods: serial (R_{ct_serial}) – as the sum of the thermal insulation calculated for individual segments, and parallel ($R_{ct\_parallel}$) – treating the thermal manikin as a whole (as one segment), is shown in ***Table 5***.

In order to find out whether the use of other materials affected the thermal resistance, despite the approximate final R_{ct} value, the local thermal insulation (R_{cti}) was calculated for selected segments of the manikin where the clothing tested had a direct influence on the manikin, such as the head, face, hands and feet (***Figure 3***).

The percentage difference (PD) measured by the local R_{cti} was calculated (according to ***Equation (1)***) for selected segments of the manikin for 2 sets of clothing.

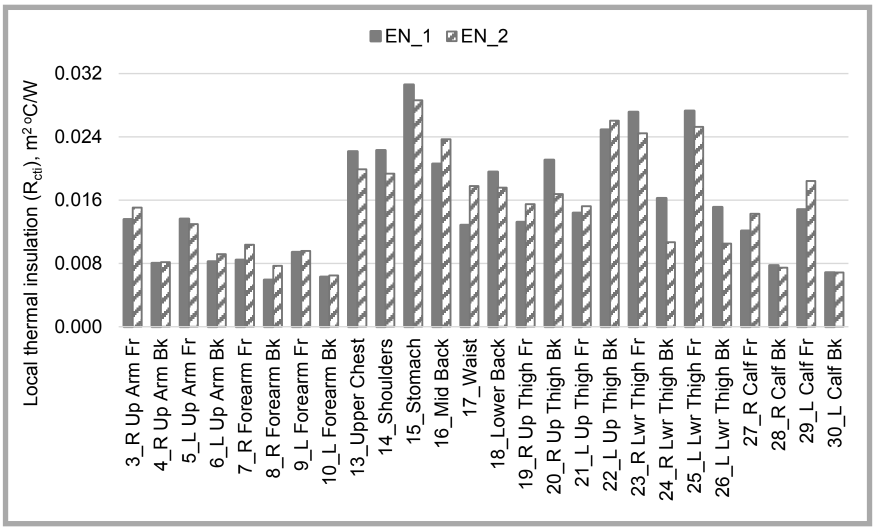

Figure 3. *Local thermal insulation (R_{cti}) for selected segments.*

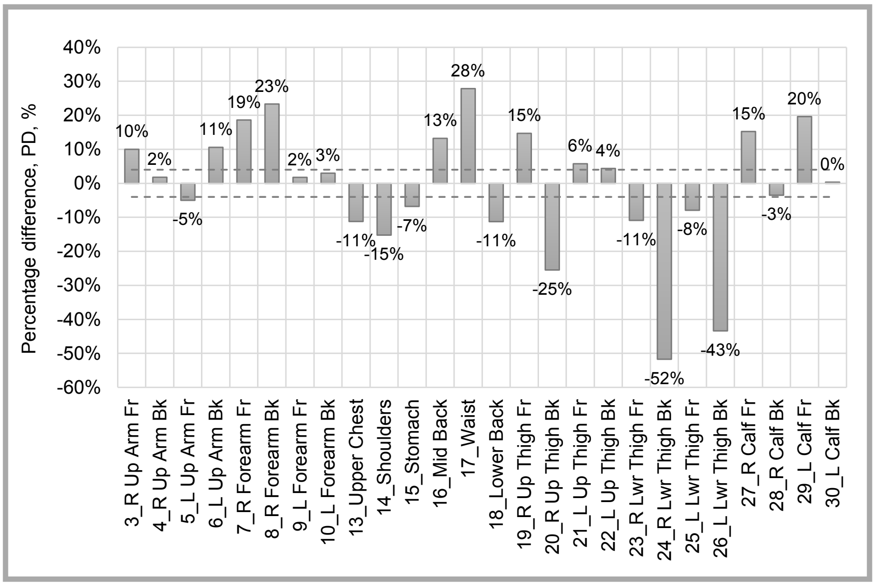

Figure 4. *Percentage difference (PD according to* ***Equation (1)****) in local thermal insulation R_{cti} between the ensembles tested.*

Table 5. *Total insulation (R_{ct}) of the special clothes: mean values with standard deviation (SD).*

Clothing ensemble	test_1	test_2	mean value ± SD
R_{ct_serial}, m^2 °C/W			
EN_1	0.420	0.424	0.422 ± 0.003
EN_2	0.416	0.424	0.420 ± 0.006
$R_{ct\_parallel}$, m^2 °C/W			
EN_1	0.262	0.263	0.263 ± 0.001
EN_2	0.272	0.273	0.272 ± 0.001

$$PD = \frac{R_{cti}(EN\_2) - R_{cti}(EN\_1)}{R_{cti}(EN\_2)} \cdot 100\% = \left(1 - \frac{R_{cti}(EN\_1)}{R_{cti}(EN\_2)}\right) \cdot 100\% \qquad (1)$$

where:

PD – percentage difference, %

$R_{cti}(EN\_1)$ – local thermal insulation for selected segments of the manikin for ensemble 1, m^2 °C/W

$R_{cti}(EN\_2)$ – local thermal insulation for selected segments of the manikin for ensemble 2, m^2 °C/W.

The difference (PD values) is shown in ***Figure 4***.

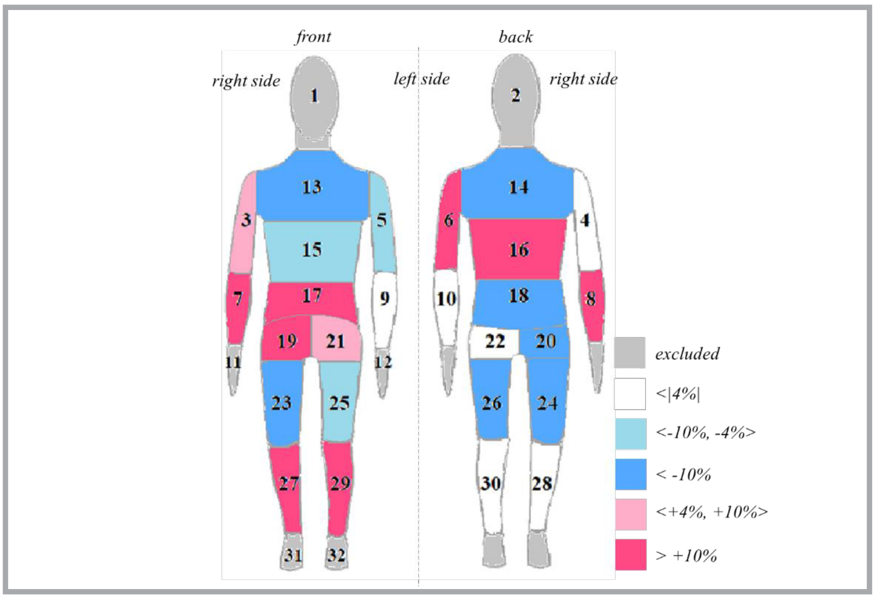

***Figure 5.** Percentage difference (PD) in local thermal insulation R_{cti} between the ensembles tested on the thermal manikin.*

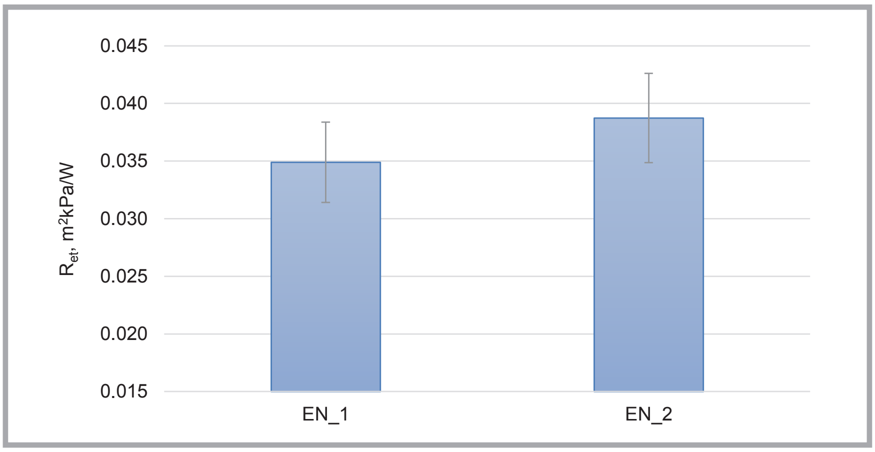

***Figure 6.** Average evaporative resistance R_{et} values together with the permitted 10% error of measurement.*

The PD values could inform as to which segment possessed significant differences, and the PD 'sign' shows where the higher value was obtained. For a percentage difference > 0%, higher local thermal insulation values were recorded for EN_2, for a percentage difference < 0% – higher local thermal insulation values were recorded for EN_1. The differences obtained are marked schematically in ***Figure 5***.

Differences of > |4%| (where the difference is significant) were recorded on many segments. Higher values of local thermal insulation for EN_2 were recorded mainly on segments located on the front of the manikin at hip level (17_waist, 19-21_upper thighs ((front)), shank (27-29_calf ((front)) and on the back (16_midle back). On the other hand, higher values of local thermal insulation for EN_1 were recorded mainly on the front of the manikin on the chest and abdomen (13_upper chest, 15_stomach), and on the back of the manikin on the shoulder and hips (14_shoulder, 18_lower back, 20_upper thigh ((back)).

***Table 6.** Mean values of the evaporative resistance R_{et} of the ensembles, tested with standard deviation (SD).*

Clothing ensemble, R_{et}, m^2kPa/W	test_1	test_2	mean value ± SD
EN_1	0.0351	0.0347	0.0349 ± 0.0003
EN_2	0.0371	0.0394	0.0383 ± 0.0016

Also, on the segments located at thigh level (23-26_thigh ((front and back)), the differences in local thermal insulation are due to the difference in the length of the jacket of the special clothing. For EN_1, it covers a larger proportion of the thighs than for EN_2.

According to the manufacturer, EN_2 uses materials with a basis weight lower than 500 g/m^2, therefore for the above-mentioned set of clothing. the thermal insulation should be lower. For the construction of clothing, however, material with very high resistance to mechanical damage was used to reinforce, among others, the arms, elbows, knees, leg pockets and sleeve pockets. Therefore, the above-mentioned areas have higher local thermal insulation values for EN_2. The differences recorded may also be related to the fitting of the clothing tested to the manikin's body, as well as to the type of membrane used in the clothing. It should be noted, however, that globally the thermal insulation values of the entire products EN_1 and EN_2 are similar to each other.

Evaporative resistance

Evaporative resistance shows how easily water vapour can diffuse through the material. There are three classes of water vapour permeability [10]: 1^{st} R_{et} > 0.040 m^2kPa/W, 2^{nd} 0.020 m^2kPa/W < R_{et} ≤ 0.040 m^2kPa/W and 3^{th} R_{et} ≤ 0.020 m^2kPa/W. Membranes with high evaporative resistance (1^{st} class membrane) are unfit for a long wear. hence, the wearing time has to be restricted.

In our research, evaporative resistance tests of the clothing (R_{et}) were carried out for an assumed intensity of sweating equal to 400 ml/(h · m^2). A summary of the evaporative resistance of the tests is shown in ***Table 6***.

R_{et} values for individual sets of special clothing were similar (***Figure 6***). The maximum difference between the results was < |10%|, i.e. below the permissible error between evaporative resistance tests [9].

The clothing layer which has a big impact on the evaporative resistance is the membrane.

In our research, the membrane used (EN_1: 65% para-aramid, 35% polyurethane ((PU)); EN_2: 50% laminate PTFE 25% meta-aramid, 25% para-aramid; see

Table 1), as well as other layers of the clothing did not significantly affect the evaporative resistance.

The local evaporative resistance (R_{eti}) was calculated for selected segments of the manikin where the clothing tested had a direct influence on the manikin, such as the head, face, hands and feet (***Figure 7***).

The results obtained, shown in ***Figure 7***, highlighted that on some segments differences in R_{eti} occurred. The percentage difference (PD) measured by local R_{eti} was calculated (according to ***Equation (2)***) for selected segments of the manikin for 2 sets of clothing.

$$PD = \frac{R_{cti}(EN\_2) - R_{cti}(EN\_1)}{R_{cti}(EN\_2)} \cdot 100\% = \left(1 - \frac{R_{cti}(EN\_1)}{R_{cti}(EN\_2)}\right) \cdot 100\% \qquad (2)$$

where:
PD – percentage difference, %
R_{eti}(EN_1) – local thermal insulation for selected segments of the manikin for ensemble 1, m^{2}kPa/W
R_{eti}(EN_2) – local thermal insulation for selected segments of the manikin for ensemble 2, m^{2}kPa/W.

The difference in PD values is shown in ***Figure 8***.

For a percentage difference > 0%, higher local thermal insulation values were recorded for EN_2, while for a percentage difference < 0%, higher local thermal insulation values were recorded for EN_1. The differences obtained are marked schematically in ***Figure 9***.

On many segments, the differences were > |10%|, mainly on the back of the manikin.

Despite the use of a better membrane, higher values of local water vapour resistance for EN_2 were reported mainly on segments located on the back (14_shoulders, 16_middle back, 18_lower back) and on the front of the manikin at hip height (17_waist, 19-21_upper thighs ((front)). However, it must be borne in mind that additional reinforcing material was used in the EN_2 clothing structure, which also affects the evaporative resistance. On the other hand, higher values of local water vapour resistance for EN_1 were recorded mainly on the back of the manikin on the thighs (22_upper thigh, 24-26_lower tights ((back)) and at abdominal height (15_stomach).

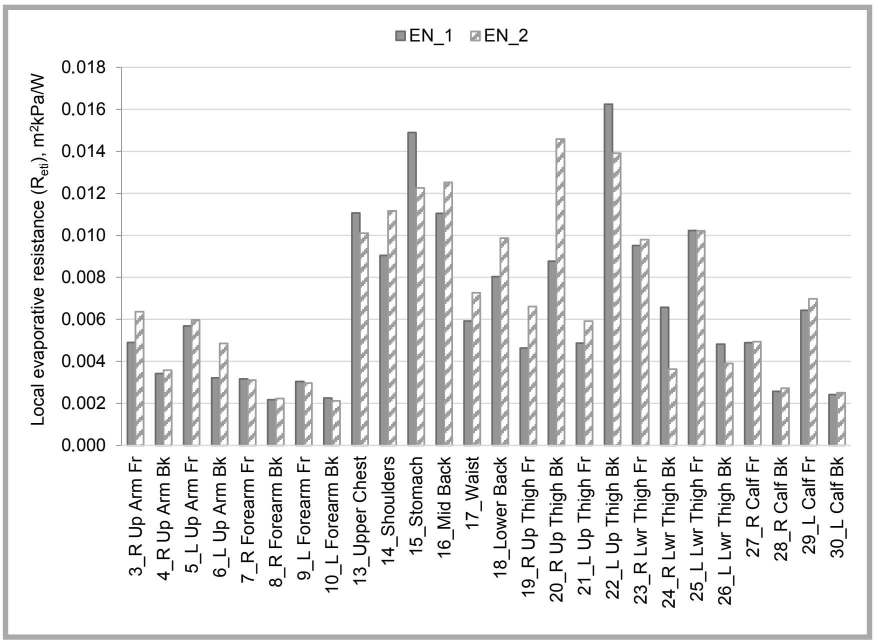

Figure 7. *Local evaporative resistance (R_{eti}) for selected segments.*

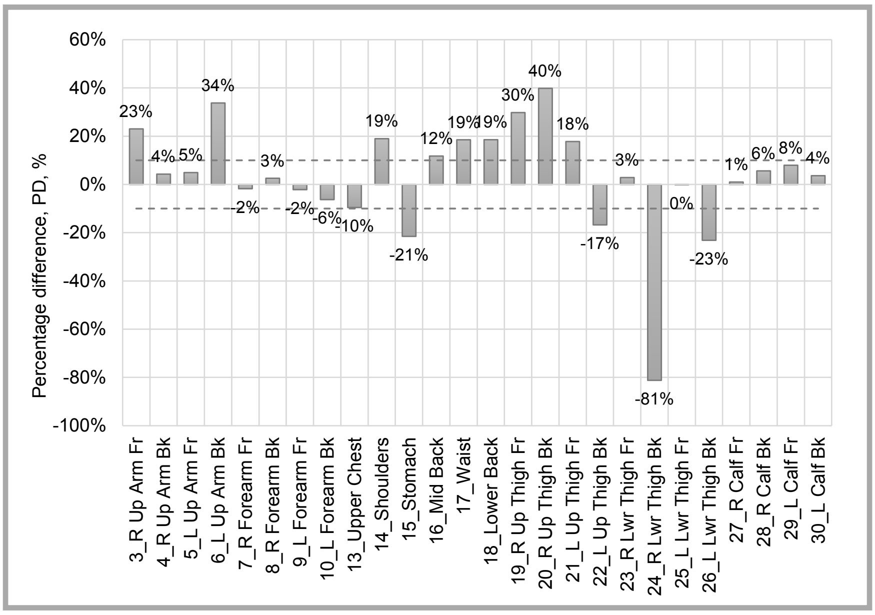

Figure 8. *Percentage difference (PD according to **Equation (2)**) in evaporative resistance R_{eti} between the ensembles tested.*

Disscusion and summary

The thermal parameters of the specialised firefighter clothing presented herein, such as the thermal insulation and evaporative resistance, were measured. Based on the analysis and calculations of the test results, it has been shown that the special clothing for firefighters provides a barrier to heat exchange between the user and the surrounding environment.

According to the normative requirements, there are no limit values for the thermal insulation of such a type of clothing. This is due to the fact that clothing intended for firefighters should be used regardless of weather conditions. The mean value of the clothing's total thermal insulation and evaporative resistance obtained from the tests are (0.421 ± 0.004) m^2 °C/W and (0.0366 ± 0.0022) m^{2}kPa/W. The research has shown that the clothing construction has a greater influence on local values of thermal parameters of the clothing when materials with similar properties are used.

Similar results were obtained by Zhu et al. [11]. The thermal insulation for a material construction consisting of an aramid (outer shell), a PTFE (polytet-

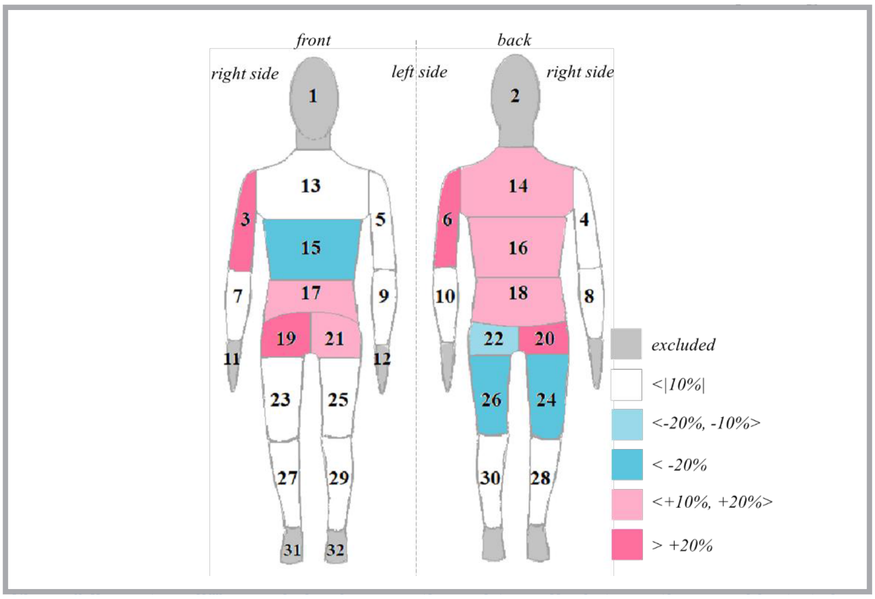

***Figure 9.** Percentage difference in local evaporative resistance R_{eti} between the ensembles tested on the thermal manikin.*

rafluoroethylene) membrane (moisture barrier), and a para-aramid fibre (thermal barrier) was equal to 0.404 m^2 °C/W. According to Zhu et al. [11], the effect of the thermal barrier material is stronger than that of the outer shell material. For the aforementioned firemen's clothing set, the evaporative resistance R_{et} was equal to 0.048 m^2kPa/W [11].

According to the EN 469 standard [5], the critical value for R_{et} is < 0.030 m^2kPa/W. The mean values of the evaporative resistance of the clothing tested were higher than the critical value. It needs to be pointed out that according to EN 469 [5], R_{et} should be measured with a sweating skin model (a hot plate), whereas the test here was performed on one piece of the multilayer fabric. In the present research, R_{et} was measured on a full-size thermal manikin, and the tests thereon were more similar to real conditions of use. The clothing sets under examination meet the requirements of EN 469 [5].

Polyurethane and PTFE membranes are characterised by similar parameters: both have a diameter of pores small enough not to let water particles through, while still being bigger than the vapour (sweat) particle. Polyurethane coatings show outstanding resistance to abrasion combined with good resistance to water and solvents, as well as offering good flexibility. They also have better resistance to mechanical damage than PTFE. However, after some time of use, the PU membrane starts to peel off, thus losing its water proofing abilities [12].

In our research, the differences in R_{eti} observed may result not so much from the type of membrane used but from the material to which it was applied. The PU and PTFE membranes have similar properties; however, it should be remembered that the vapour resistance of breathable membranes and coatings is applied [12]. The differences observed may also result from matching the clothing tested to the manikin's body. The EN_2 jacket was shorter and better adhered to the measuring surface of the manikin. However, globally, the water vapour resistance values of the entire EN_1 and EN_2 products are similar. According to [12] the vapour resistance of breathable membranes and coatings is influenced by the fabric substrate to which they are applied. Considering the great effort during firefighters' work, particular analysis should be dedicated to water vapour permeability. Appropriate material used for protective clothing can significantly reduce thermal discomfort while keeping the basic properties of thermal insulation as well as chemical and mechanical resistance.

Acknowledgements

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Editorial notes

1) Directive 89/686/EEC is repealed (with effect from 21 April 2018) by Regulation (EU) 2016/425 for personal protective equipment.

2) CNBOP-PIB – Scientific and Research Centre for Fire Protection – National Research Institute is a Scientific Unit in Poland with the mission of ensuring the public safety of the Country in terms of fire protection, crisis management, civil protection and civil defence.

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