Characteristics of Specialised Firefighter Clothing Used in Poland – the Thermal Parameters

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Abstract

This paper describes the characteristic thermal parameters of firefighters’ personal protective clothing (FFPPC) used in Poland. The total thermal insulation and evaporative resistance of three different types of FFPPC were measured and used on a thermal manikin. Next, the results were compared. Based on the analyses and calculations of the test results, it was shown that FFPPC provides a barrier to the heat exchange between the user and the surrounding environment. Differences in the local thermal insulation can be triggered not only by the material used but they can also be attributable to clothes fitted on the manikin. The biggest differences can be noted on the segments forming part of the manikin’s trunk. No difference was found in the evaporative resistance between the clothes tested. In order to examine further the impact of the materials used on thermal parameters of protective clothing, it is necessary to carry out an analysis of the impact of individual layers.

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

In order to protect not only others but also themselves, firefighters must be fully concentrated on their tasks, otherwise they run a risk of making mistakes during a firefighting operation. The optimal conditions for such a type of work could be ensured by so-called thermal comfort, characterised by the thermally neutral state of the body. Comfort is influenced by two types of factors: environmental and individual. Firefighters have no influence on environmental factors i.e. they have to work in the conditions which they find on site. They can, however, influence one of the individual factors, namely their protective clothing. Inappropriate protective clothing during an operational situation can cause an increase in body temperature, leading to an increased frequency of cardiac contractions, or the increased working of sweat glands. Firefighters may be more prone to mistakes when feeling a lack of thermal comfort.

In normative documents there is no requirement regarding the value of the thermal insulation of special clothing. There is only information about the value of the evaporative resistance [3].

Material and methods

Test apparatus


The thermal manikin allows the simulation of dry heat transfer (thermal insulation) as well as wet heat transfer (evaporative resistance) [5]. A general scheme of the division of the
The study was carried out in a climatic chamber (WEISS) equipped with microclimate meters (Indoor Climate Analyzer, from B&K and INNOVA) to monitor the thermal conditions during testing of the special clothing for firefighters selected.

**Clothing**

Three sets of special clothing (FFPPC) intended for firefighting and similar actions, such as rescue and disasters, were used, two of which (EN_1 and EN_2) are currently used in Poland (Figure 2). The tests sets are in compliance with the EN 469 [3] standard (second level of protection (Xf-2, Xr-2, Y-2, Z-2)).

FFPPC has a multilayer construction [6, 11], a schematic diagram of which is shown in Figure 3 [2, 3, 6, 10, 11].

As seen from the outside environment, the special clothing consists of:
- an external fabric layer;
- a membrane;
- a thermal insulation layer;
- lining.

The outer (external layer) is the first layer of protection, providing protection against flame, heat, chemicals and mechanical injuries. This layer is usually impregnated. The moisture barrier (a membrane) protects against water and other liquids, like chemicals and bloodborne pathogens. The thermal insulation layer protects the firefighter’s body against environmental heat. The inner liner (lining) protects against direct contact of the human skin with the thermal barrier [11].

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 firefighters’ special clothing differed mainly in the percentage of each aramid isomer and the materials used in the lining layer.

**Thermal parameters of FFPPC**

*Thermal insulation.* Thermal insulation tests of the clothes selected were conducted in accordance with the EN ISO 15831:2004 [7] and EN 342 [8] standards. Thermal insulation is described by
Insulation is the sum of insulations calculated for particular segments [7]:

\[ R_i = I_i = \sum f_i \left( \frac{t_{si} - t_a}{H_{si}} \right) \]

where:
- \( t_{si} \) – temperature on the surface of \( i \)-segment of manikin, °C;
- \( t_a \) – air temperature in climatic chamber, °C;
- \( H_{si} \) – sensible heat loss from \( i \)-segment of manikin, W/m²;
- \( f_i \) – part of total surface area which contains \( i \)-segment of manikin.

In the case of the parallel model, thermal insulation is the insulation relating to the whole body of the manikin [7]:

\[ R_i = I_i = \frac{\sum f_i A_i}{\sum H_{si}} \]

where:
- \( A \) – total surface area of manikin, m².

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

Insulation tests were carried out in an environmental chamber with the parameters set as follows: air temperature 12 °C, relative humidity 45% and air velocity 0.4 m/s. The thermal parameters in the climatic chamber were controlled by microclimate meters (Table 2).

**Evaporative resistance.** The evaporative resistance of the clothing ensemble (\( R_{et} \)) was tested with the thermal manikin wearing a special fabric skin (Figure 2). The test conditions complied with the ASTM F2370-10 standard [8]. There is no an European equivalent of this standard, which describes the measurement of evaporative resistance (\( R_{et} \)) on a thermal manikin. The manikin surface temperature for most segments was 34.0 °C and the sweat rate – 400 ml/h/m² (Figure 4).

**Table 1. Materials used for the tested clothing ensembles.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>EN_1</th>
<th>EN_2</th>
<th>EN_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>External</td>
<td>64% meta-aramid, 35% para-aramid, 1% anti-static fibres</td>
<td>75% meta-aramid, 23% para-aramid, 2% anti-static fibres</td>
<td>94% meta-aramid, 5% para-aramid, 1% anti-static fibres</td>
</tr>
<tr>
<td>Membrane</td>
<td>65% para-aramid, 35% polyurethane</td>
<td>50% meta-aramid, coating 100% polyurethane</td>
<td>95% meta-aramid, 5% para-aramid</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>aramid, flame retardant fibres</td>
<td>65% meta-aramid, 20% para-aramid, 15% polyethylene</td>
<td>100% para-aramid</td>
</tr>
<tr>
<td>Lining</td>
<td>50% aramid fibre, 50% viscose</td>
<td>100% cotton flame retardant</td>
<td>93% meta-aramid, 5% para-aramid, 2% P140 (carbon fibre)</td>
</tr>
</tbody>
</table>

**Table 2. Microclimate parameters in the climatic chamber during testing of the thermal insulation of the clothing ensembles.**

<table>
<thead>
<tr>
<th>Clothing ensemble</th>
<th>( t_a ) °C</th>
<th>( V_a ) m/s</th>
<th>RH %</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN_1</td>
<td>test_1</td>
<td>12.4±0.1</td>
<td>0.35±0.05</td>
</tr>
<tr>
<td></td>
<td>test_2</td>
<td>12.4±0.1</td>
<td>0.35±0.05</td>
</tr>
<tr>
<td>EN_2</td>
<td>test_1</td>
<td>12.4±0.1</td>
<td>0.42±0.05</td>
</tr>
<tr>
<td></td>
<td>test_2</td>
<td>12.4±0.1</td>
<td>0.42±0.05</td>
</tr>
<tr>
<td>EN_3</td>
<td>test_1</td>
<td>12.4±0.1</td>
<td>0.41±0.05</td>
</tr>
<tr>
<td></td>
<td>test_2</td>
<td>12.4±0.1</td>
<td>0.41±0.05</td>
</tr>
</tbody>
</table>

All calculations were based on the heat loss method, defined as [9]:

\[ R_{et,heat,p} = \frac{P_a - P_{et}}{\sum (A_i \times H_{si})} \]

where:
- \( R_{et,heat,p} \) – total clothing evaporative resistance calculated by the heat loss method kPa · m²/W;
- \( P_a \), \( P_{et} \) – water vapour pressure on the whole fabric skin surface and in ambient air, respectively, kPa;
- \( H_{si} \) – segmental evaporative heat loss, W/m²;
- \( A \), \( A_i \) – total sweating surface area and segmental sweating surface area, respectively, m²;
- \( i \) – number of segments of the sweating thermal manikin (\( i = 1, 2, \ldots, n \)).

The water vapour pressures at the fabric skin surface and in the ambient air were calculated by Antoine’s equation:

\[ p_a = \exp \left( 18.956 - \frac{4030.18}{t_a + 235} \right) \times RH_a \]

\[ p_{et} = \exp \left( 18.956 - \frac{4030.18}{t_{et} + 235} \right) \times RH_{et} \]
where:
\( t_{sk}, t_a \) – temperatures at the wet fabric skin surface and in ambient air, respectively, °C;
\( RH_{sk}, RH_a \) – relative humidity at the wet fabric skin surface and in ambient air, respectively, % (assuming that \( RH_{sk} \) on the saturated wet fabric skin surface was 100%).

According to ASTM F2370-10 \[9\], the error permitted between measurements is 10%.

As required, they corresponded to ‘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 3).

### Results

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

#### Total thermal insulation

A summary of the total thermal insulation (calculated by two mathematical methods and with the permissible 4% measurement error) is shown in Figure 5.

The mean value of the total thermal insulation of the clothing ensembles tested is 0.419 ± 0.012 m²°C/W. The \( R_{ct} \) resulting in both the serial and parallel calculations are within the 4% permissible measurement error (Figure 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 tested clothing had a direct influence (Figure 6).

For most segments no significant differences in the local thermal insulation were noted (Figure 7).

Differences in the local thermal insulation of the clothing ensembles were recorded mainly on the trunk of the manikin (Figure 8).

The percentage difference measured by the local \( R_{cti} \) was calculated on selected segments of the manikin for 3 sets of clothing. A difference of >4% is shown in Table 4.

#### Table 3. Microclimate parameters in the climatic chamber during testing of the evaporative resistance of the clothing ensembles.

<table>
<thead>
<tr>
<th>Clothing ensemble</th>
<th>( t_a ), °C</th>
<th>( V_u ), m/s</th>
<th>RH, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN_1 test_1</td>
<td>12.3 ± 0.1</td>
<td>0.38 ± 0.05</td>
<td>69 ± 1</td>
</tr>
<tr>
<td>test_2</td>
<td>12.2 ± 0.1</td>
<td>0.39 ± 0.05</td>
<td>68 ± 1</td>
</tr>
<tr>
<td>EN_2 test_1</td>
<td>12.2 ± 0.1</td>
<td>0.38 ± 0.05</td>
<td>41 ± 1</td>
</tr>
<tr>
<td>test_2</td>
<td>12.2 ± 0.1</td>
<td>0.39 ± 0.05</td>
<td>64 ± 1</td>
</tr>
<tr>
<td>EN_3 test_1</td>
<td>18.2 ± 0.1</td>
<td>0.43 ± 0.05</td>
<td>50 ± 1</td>
</tr>
<tr>
<td>test_2</td>
<td>18.2 ± 0.1</td>
<td>0.38 ± 0.05</td>
<td>62 ± 1</td>
</tr>
</tbody>
</table>

#### Table 4. Absolute percentage difference in the local thermal insulation \( R_{cti} \) between the ensembles tested.

<table>
<thead>
<tr>
<th>Segments/ensemble</th>
<th>(EN_1 – EN_2)</th>
<th>(EN_1 – EN_3)</th>
<th>(EN_2 – EN_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Chest</td>
<td>12%</td>
<td>33%</td>
<td>19%</td>
</tr>
<tr>
<td>Shoulders</td>
<td>0%</td>
<td>59%</td>
<td>58%</td>
</tr>
<tr>
<td>Mid Back</td>
<td>2%</td>
<td>16%</td>
<td>19%</td>
</tr>
<tr>
<td>Waist</td>
<td>34%</td>
<td>19%</td>
<td>22%</td>
</tr>
<tr>
<td>Lower Back</td>
<td>12%</td>
<td>21%</td>
<td>8%</td>
</tr>
<tr>
<td>R Up Thigh Fr</td>
<td>31%</td>
<td>34%</td>
<td>5%</td>
</tr>
<tr>
<td>R Up Thigh Bk</td>
<td>50%</td>
<td>39%</td>
<td>7%</td>
</tr>
<tr>
<td>L Up Thigh Fr</td>
<td>16%</td>
<td>27%</td>
<td>13%</td>
</tr>
<tr>
<td>L Up Thigh Bk</td>
<td>67%</td>
<td>34%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Out of the segments selected, only the shoulders and middle back showed no differences between EN_1 and EN_2.

The reason for the differences may lie in the material used and lack of precision in fitting of the clothing to the manikin. The biggest differences, which most probably resulted from poorly fitting clothing, were found in the following segments: the upper thigh (front, back, right, left), waist, lower back and middle back. The size of clothes were fitted to the manikin’s dimensions. Theoretically, all clothes should have had the same size, but in practice there were differences.

Evaporative resistance

Evaporative resistance tests of the clothing ($R_{et}$) were carried out for an assumed intensity of sweating equal to 400 ml/h·m$^2$ (Figure 4). A summary of the evaporative resistance of the tests is shown in Figure 9.

$R_{et}$ values for the individual sets of special clothing were similar (Figure 9). The maximum difference between the results was <10%, i.e. below the permissible error between evaporative resistance tests [8] (Figure 9).

The membrane used (EN_1: 65% para-aramid, 35% polyurethane; EN_2: 50% melamine 50% meta-aramid, 100% polyurethane coating, EN_3: 95% meta-aramid, 5% para-aramid; see Table 1) and other layers of clothing did not significantly affect the evaporative resistance.
**Discussion and summary**

The thermal parameters of specialised firefighters’ clothing, such as the thermal insulation and evaporative resistance, were measured. Based on the analysis and calculations of the test results, it was shown that special clothing for firefighters provides a barrier to the 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 obtained from the tests is 0.419 ± 0.012 m²·K/W. The best-fitting clothes were found to be on the upper chest and shoulders of the manikin. The biggest differences, which most probably resulted from the non-adherent clothing, were found for the following segments: the upper thigh, waist, lower back and middle back. The materials used for the EN 1 and EN 2 ensembles did not affect the local value of thermal insulation $R_{clo}$. The materials used for EN 3 provided a lower level of protection than fabrics used in EN 1 and EN 2. The local values of thermal insulation were lower than in the other ensembles tested.

The similar results of thermal insulation were obtained by Zhu et al. [12]. The thermal insulation of a material structure consisting of aramid (outer shell), a PTFEE (polytetrafluoroethylene) membrane (moisture barrier) and para-aramid fibre (thermal barrier) was equal to 0.404 m²·K/W. According to Zhu et al. [12], the effect of the thermal barrier material is stronger than that of the outer shell material.

It should be noted that this value applies only to firefighters’ clothing. Under real conditions, appropriate underwear is put under the outer layer in addition to other equipment, such as gloves, boots, a balaclava and a helmet, which increase the total thermal insulation of the entire set for firefighting operations. On the one hand, FFPPC should provide complete protection from heat exposure (then a high value of thermal insulation is indicated). On the other hand, the use of highly insulating clothing hampers the exchange of heat produced by the human (metabolic heat) to the environment, proving that it is very difficult to ensure thermal comfort and protection performance at the same time [11].

Not only the heat transfer affects firefighters’ sense of comfort but also moisture transfer, the latter being a very important process, associated with the evaporation, condensation, absorption and desorption of moisture [11]. If the materials used are not appropriately selected, the sweat will condensate on the skin and accumulate on the inner layer of clothing, thus leading to a wetness sensation and increase in the wearer’s discomfort. The parameter describing moisture transfer is the evaporative resistance ($R_e$) [9]. According to the EN 469 standard [3], the critical value for $R_e$, 0.030 m²·K/Pa/W, below which the clothing meets the requirements of the second level of protection. The mean value of the evaporative resistance of the clothing tested was $0.037 \pm 0.002$ m²·K/Pa/W, exceeding the critical value. It needs to be pointed out that according to EN 469 [3], $R_e$ should be measured with a sweating skin model (a hot plate), but the test was performed on one piece of the multilayer fabric. In the present research, $R_e$ was measured on a full-size thermal manikin, and the manikin’s tests were more similar to real conditions of use. The results could be different if various measuring equipment were used. It should also be pointed out that a single sample of fabric is arranged differently on the measuring surface than on the entire set of clothing.

There was no difference in $R_{ev}$ between the clothes tested. The membranes used for testing purposes and other layers of clothing did not significantly affect the evaporative resistance value. Perhaps the use of a higher class membrane would show a significant difference in the $R_{ev}$ value.

For a material structure consisting of aramid (outer shell), para-aramid fibre (thermal barrier) and a PTFEE membrane (moisture barrier), the evaporative resistance $R_{ev}$ was equal to 0.048 m²·K/Pa/W [12]. The higher class membrane changed the value of $R_{ev}$.

In order to further examine the impact of the materials used on the thermal parameters of the clothing, it is necessary to analyse the impact of individual layers. Furthermore, it would also seem helpful to perform separate analyses of individual clothing layers to find out which part of the structure should be improved.

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**References**


3. EN 469: Protective Clothing for Firemen.


6. Ordinance the Ministry of the Interior and Administration 30 November 2005 on the uniforms of the fire brigade of the State Fire Service (Dz. U. 2006 no. 4, item 25)


8. EN 342, Protection against Cold Environment.


10. EN 15614. Protective Clothing for Firefighters. Laboratory Test Methods and Performance Requirements for Wildland Clothing.
