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Reduction of Thermal Signature Using Fabrics with Conductive Additives

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The most effective way to reduce the thermal signature is to reduce the emissivity. The goal of our research is to create the material, which can reduce the thermal signature, and make it interflow with environment. The materials and material compositions concealing the thermal signature of the object were developed using aluminium coatings and conductive metalized fibres, i. e. yarns with stainless steel staples or coated with silver.

The analysis of the prepared samples was carried out with equipment consisting of a stand with integrated heating controller imitating the human body. The concealing properties of the samples in the far infrared (FIR) spectral range were evaluated using ThermaCAM Reporter 7.0.

The thermal signature analysis of prepared samples demonstrates that respectable results could be obtained using yarns coated with silver and materials coated with aluminium, but the first one is more flexible and preferable for clothing.

Keywords: camouflage materials, thermal signature, metal fibres, silver coated fibres, far infrared spectral range.

1. INTRODUCTION

Under the rapid development of surveillance and acquisition devices it became imperative to develop camouflage textiles that could protect the soldiers from detection by various sensors in a wide spectral range. Non-detectability or reduced observability is crucial in modern warfare. Especially for peace keeping operations, where positions are more or less known, reduced detectability can be of direct vital importance [1]. To reduce the thermal infrared (IR) signature of a person operating in the open, the thermal signature needs to match the thermal patterns of the background. It is known that the higher the temperature of an object of interest, the grater the intensity of emitted radiation and thus the bigger the resulting image [2, 3]. Herewith resemblances in apparent surface temperatures and their dimensional patterns between the person and background are an essential requirement for effective thermal camouflage.

Thermal imagers have become cheaper and are therefore becoming increasingly more widespread. They are also becoming downsized to fit on personal weapons. Therefore camouflage for soldier can no longer be restricted to visual and near infrared but must include thermal infrared.

Conventionally the detector working ranges at wavelength of 3 μm – 5 μm and 8 μm – 13 μm are used for the lower and upper thermal bands or ‘windows’ respectively. The 3 μm – 5 μm band is most important for high temperature objects, while the 8 μm – 13 μm interval is useful for detecting friction, heated wheels and even human bodies. The 8 μm – 13 μm is the range the seeker can see thermal image of individual warriors [4, 5]. Much research has been done in attempts to produce camouflaging surface coating for these regions and some of this work has concerned textile base [6]. The thermal IR signature of a dressed man can only be changed through appropriate design of the thermal emissivity of the clothing surface and its geometric structure for any given environmental condition and personal physical activity level. Infrared camouflage technologies can be divided into such three categories as changing the infrared transmission characteristics of the atmosphere, controlling the emissivity of the external surface and adjusting the surface temperature of the target [7].

In the 8 μm – 13 μm range objects are detected by the heat energy they emit or reflect. In simple terms the relationship between the amount of emitted radiation and the absolute temperature of the target is governed by Stefan’s law, which states:

$$E = \eta \sigma T^4 , \tag{1}$$

where E is the radiant energy emitted, T is the absolute temperature, η is the emissivity and σ is the constant [4].

According to this equation there are two possibilities to reduce the thermal signature of targets, including human body:

– reduce the temperature of the target – for human targets the thermal signature can be made lower by wearing more insulated clothing, putting on covers, or increasing the external surface area using fur or pile-type structures,

– reduce the emissivity of the target – using shiny, reflective covers.

The second approach is more effective and more up-to-date, because the reduction of temperature by wearing additional clothing or covers adds to the thermal discomfort of the individual [5, 8 – 10]. Also an emissivity reduction is desired, since objects of interest are generally hotter than their surroundings.

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Emissivity is a measure of object radiation energy of efficiency. Textiles have high emissivities between 0.92 and 0.98, whereas shiny metallic surface have emissivities from 0.04 up to 0.12 [5, 11 – 13]. Therefore the emissivity of the target can be reduced by using a shiny reflective cover, although this will obviously interfere with visual camouflage. Practical thermal camouflage screening materials tend to be complex laminates, which include a textile fabric support carrying a film or foil of aluminium or other shiny metal [14 – 18]. However thermal screens are bulky, stiff and impermeable to sweat vapour, which precludes its use in clothing.

The aim of this study was to develop flexible textile materials able to reduce the thermal signature of human targets, using electro conductive metalized fibres and coatings. It is expected that this study could provide an intense understanding of the concealing behaviour of textile fabrics and could help to optimize their structural design for human body protection.

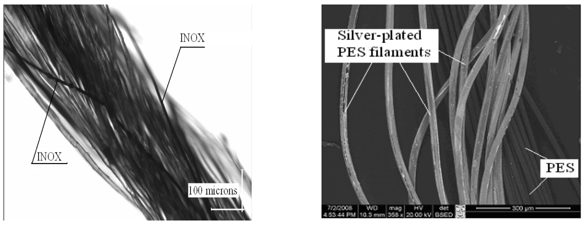
2. MATERIALS AND METHODS OF THE INVESTIGATION

Textile materials exhibit high emission coefficient (0.92 ÷ 0.98) [13]. Therefore materials (coated or using special fibres) with small emission coefficient were incorporated into woven fabrics establishing samples, which may reduce contrast between environment and concealing object (man). The aluminium foil coating (thickness 0.1 mm), S-Shield PES® yarns and Silverflex-170® yarns were used for the sample production. S-Shield PES® yarns consist of Polyester (PES) fibers with stainless steel staples (INOX) – 80 % PES, 20 % INOX; Silverflex-170® yarns consist of two twisted components – Polyester 11.3 tex (f32) filaments and Polyester silver-plated 4.4 tex (f12) filaments.

The investigations of above mentioned conductive yarns were fulfilled by microscopic analysis:

– Microscope Olympus CH-30, objective A Plan 40× (see Fig. 1, a);

– FEI Quanta 200 FEG (scanning electron microscope) (see Fig. 1, b).



a b

Fig. 1. Microscopically longitudinal views of S-Shield PES® yarn (a) and Silverflex-170® yarn, mag. 358× (b)

Experimental investigations were carried out with six woven fabrics, which were produced in Textile institute from conductive fibre or coated with aluminium foil using different production technologies (Table 1).

The stand with integrated heating controller emitting the very similar thermal energy like real human body was constructed (Fig. 2). The stand contains integrated heating controller covered with metal plate, which was hooded with textile material layer (see Fig. 2 (1)). The thermocouple with measuring and recording device (see Fig. 2 (2)) took stand's temperature and the thermacamera (see Fig. 2 (3)) recorded the thermal signature.

Table 1. Specification of the investigated samples

Fabric No.	Description
1	Cotton (35 %) - Polyester (65 %) rip-stop weave woven fabric coated with aluminium foil (warp density – 28 cm^{-1}, weft density – 20 cm^{-1})
2	Polyester plain weave woven fabric with conductive metal fiber, inserted in the fabric in weft direction every 1 cm; fiber content: 99.6 % PES 0.4 % INOX (warp density – 54 cm^{-1}, weft density – 28 cm^{-1})
3	Polyester plain weave woven fabric with conductive metal fiber, inserted in the fabric in weft direction; fiber content: 90 % PES and 10 % INOX (warp density – 54 cm^{-1}, weft density – 28 cm^{-1})
4	Polyester plain weave woven fabric with silver, inserted in the fabric in weft and warp direction every 1 cm; fiber content: 98.5 % PES and 1.5 % silver plated filaments (warp density – 28 cm^{-1}, weft density – 28 cm^{-1})
5	Polyester plain weave woven fabric with silver, inserted in the fabric in weft direction every 0.5 cm, in warp direction 1 cm; fiber content: 97.5 % PES and 2.5 % silver plated filaments (warp density – 28 cm^{-1}, weft density – 28 cm^{-1})
6	Reference sample - white colour Polyester (100 % PES) plain weave woven fabric (no metal) (warp density – 54 cm^{-1}, weft density – 28 cm^{-1})

The adaptive properties of the samples in the far infrared (FIR) spectral range were evaluated using FLIR SYSTEMS ThermaCAM with technical data:

– spectral range: 7.5 μm – 13 μm;

– detector type: Focal Plane Array (FPA), uncooled microbolometer 120×120 pixels;

– accuracy: ±2 ºC or 2 % of reading;

– thermal sensitivity: 0.20 ºC;

– detector image interpolated to 240×240 pixels;

– temperature ranges from –10 ºC up to +350 ºC.

Fig. 2. Equipment for thermal signatures analyses: 1 – stand with integrated heating controller, which imitates the human body, 2 – thermocouple with a measuring and recording device, 3– thermacamera

The distance between the thermacamera and samples was 50 cm. The samples were observed using thermacamera in particular time intervals (i. e. the thermal views were fixed immanently after covering the stand with sample and after 5 minutes). After more than 5 minutes it is necessary to observe the heated sample due to stabilization of temperature of sample. The adaptive properties, such as thermal images and temperature, of the samples in the FIR spectral range were evaluated using software ThermaCAM Reporter 7.0. The accuracy of temperature measurements is 0.1 ºC. The effectiveness of thermal signature reduction was evaluated calculating the differences of seeming temperature ΔT of sample laid on heated test stand T_{mat} and temperature of heated stand – T_h, according to equation:

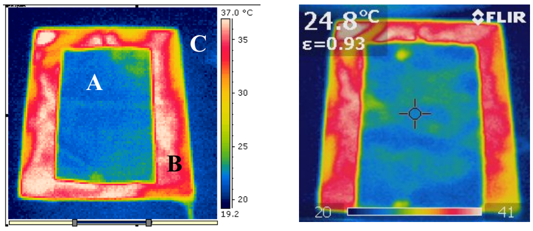
$$\Delta T = T_h - T_{mat}\,. \qquad (2)$$

The bigger this difference the better concealing effectiveness of investigated material in the FIR spectral range.

3. RESULTS AND DISCUSSION

The camouflage materials must provide concealing properties during all wearing period. These properties in the visible, NIR and FIR spectral ranges mostly depend on spectral characteristics of surface colour and particularly on spectral reflectance in these ranges.

After literature analysis [5, 19] it was estimated that one of the most perspective way of creating newly thermo camouflage materials is based on decreasing of emission of concealed object in FIR spectral range. Therefore, in this study it was chosen such a way for developing experimental objects.



a b

Fig. 3. The thermal images of sample No. 1 (1 layer) laid on heated test stand, with indicated seeming temperatures: a – the view of sample on the heated stand; b – the view of sample on the heated stand after 5 min

The results of investigation of thermal signature of materials are presented in Figs. 3, 4 and 5. The point of seeming temperature measurement is ringed and the dark background observable around the heated stand is the local environment. The best concealing effect – the least difference between the thermal signature of the target (in this case – heated stand with fabric) and the local background, is gained in cases of No. 1 (see Fig. 3), when the textile material is coated with a layer of aluminium foil, and this correlates with data obtained by other authors [10]. From Fig. 3 it is seen that sample No. 1 conceals the heated stand (Fig. 3, a, point B) very well, i. e. the colour of covering material (Fig. 3, a, point A) is near the environment colour (Fig., 3, a, point C). Even good effect is achieved after keeping the sample No. 1 on the heating stand for the 5 min long – the temperature of object is 24.8 ºC (Fig. 3, b). Such type of coatings may provide good concealing properties in FIR range, however textile material became deficient in flexing, glittering and cannot

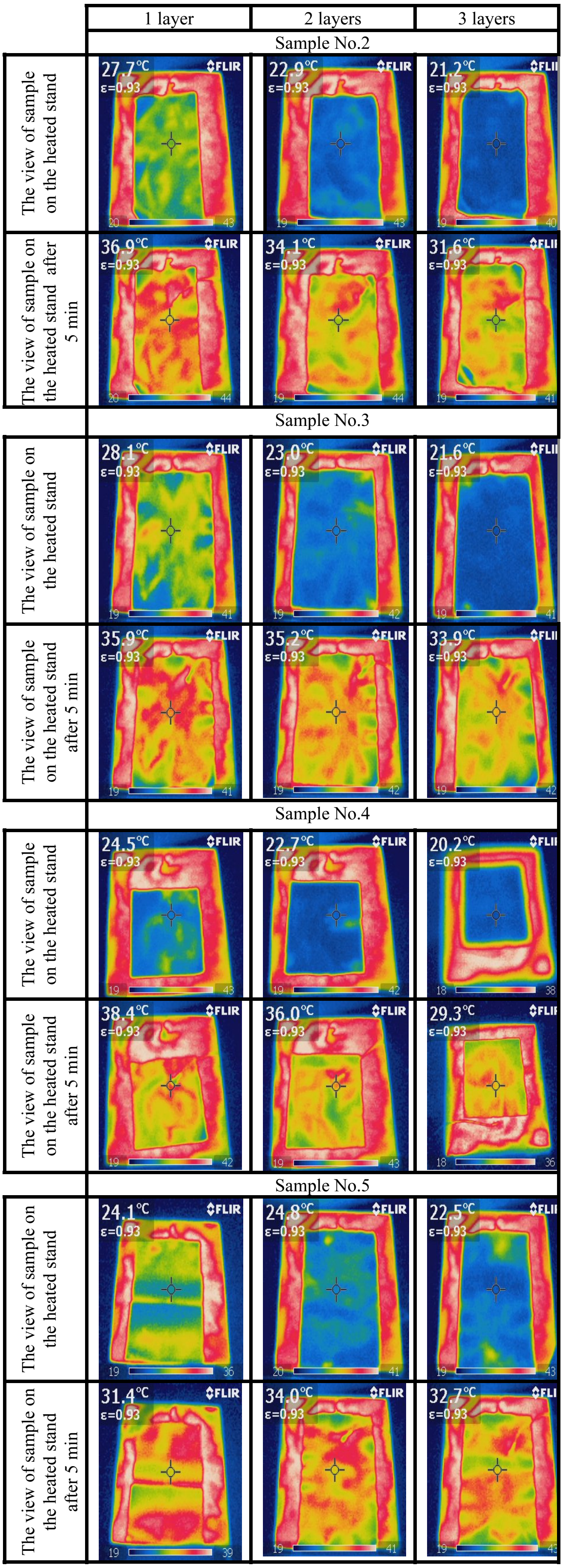


Fig. 4. The thermal images of samples No. 2 – 5 laid on heated test stand, with indicated seeming temperatures

be used as camouflage material in the visible and near IR (NIR) spectral range.

Whereas fabrics with incorporated conductive fibres may be easy printed or dyed with particular dyes and camouflage view may be given in wide spectral range. Therefore for further investigations fabrics with metal fibres and silver coated PES filaments - samples No. 2, 3, 4 and 5, were chosen. For comparison of results the reference fabric (sample No. 6) without conductive fibres was investigated. The investigation of thermal images (Figs. 4 and 5) and seeming temperatures (Fig. 6) of these samples showed that used conductive fibres provide obvious effect comparing with reference sample No. 6, which is produced only from polyester fibres. The results show (Fig. 6) that increasing the amount of conductive fibres in both cases (metal fibres or silver coated filaments) have insignificant influence on the reduction of thermal signature.

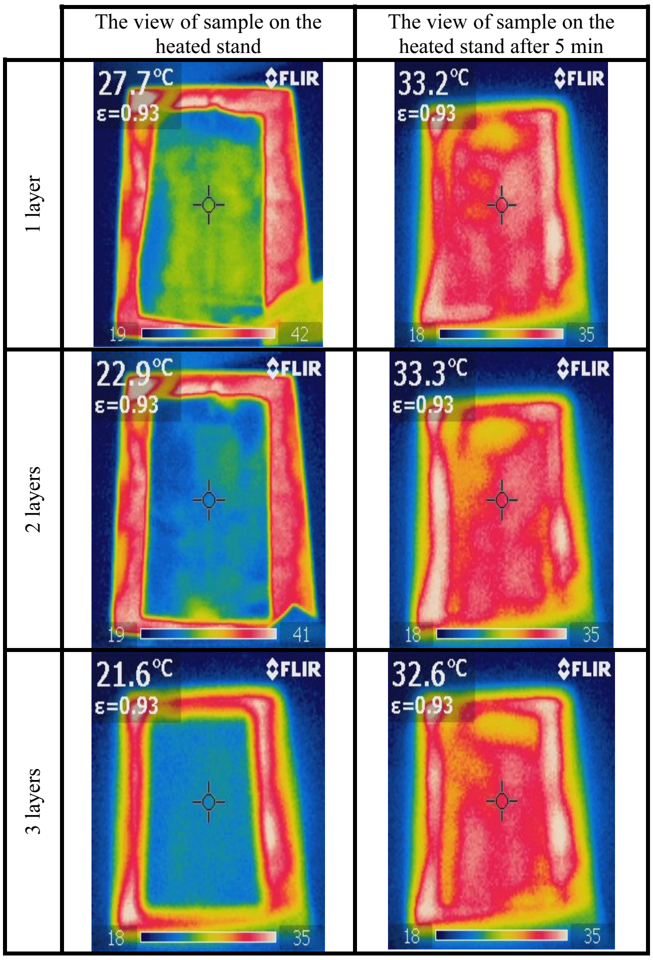


Fig. 5. The thermal images of sample No. 6 (1 layer) laid on heated test stand, with indicated seeming temperatures

The more important is the type of conductive additives used – the better results were obtained with silver coated PES filaments beside the metal (stainless steel) fibres. This can be explained by different emissivity of the metal component – silver has lower emissivity than stainless steel [12, 19]. The best results gained with the sample No. 4 – fabric containing polyester filaments coated with silver.

From the samples No. 2 – 6 the fabrics' packets were constructed consisting of one, two and three layers of material. The influence of tested fabric layers on seeming temperature was investigated and the results of differences of seeming temperatures Δ*T* of separately examined material are presented in Fig. 6.

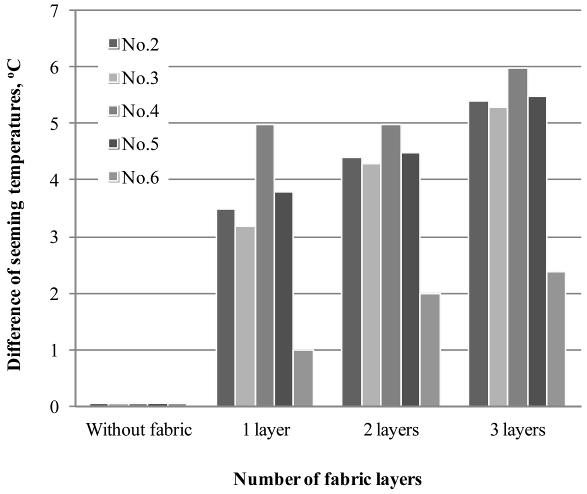


Fig. 6. Difference of temperatures Δ*T* vs fabric layers

Especially concealing effect is observable when fabric consists of three layers. The analysis described above shows that, by adding the layer for each sample, a satisfactory effect of infrared camouflage can be achieved when people wear the proposed cloth prototype.

In Fig. 7 counted differences of temperatures (Δ*T*) for all investigated samples are presented.

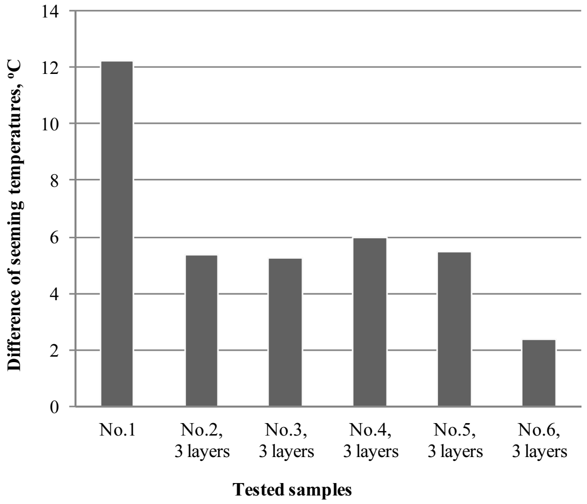


Fig. 7. Difference of seeming temperature Δ*T* vs fibre nature and amount of layers

From Fig. 7 it can be found that the smallest difference of seeming temperature is obtained between human body and body covered with reference sample (sample No. 6). The concealing effect of sample No. 6 is 80 % less compared with material coated with aluminium foil (sample No. 1). Herewith sample No. 1 is not particularly suitable for clothing construction due to its rigidity. There is a data in the literature that in order to improve effect of infrared camouflage, the thicknesses of fabric layers can be increased [9]. Therefore, in order to achieve better concealing effect three layers of fabrics were used. The usage of three layers can be clarified by heat and mass transfer phenomenon, i. e. the greater thicknesses of the three layers would lead to a lower target temperature. According to the Fourier's law, if the thickness of any one of the front layers is increased, less amount of heat can be transferred via the sensible heat transfer. Thus, the front three layers need bigger thicknesses to suppress the sensible heat transfer. Optimal reduction of thermal signature can be reached using fabrics with silver or metal additives (samples No. 2 – 5).

Analysis of the thermal signatures of the investigated fabrics showed that comparatively good background matching could be obtained using fabrics containing conductive silver additives (samples No. 4 and No. 5). For evaluation of concealing properties of selected samples in FIR spectral range their thermal images and seeming temperature curves obtained by software were analyzed. In Fig. 8 the comparison of thermal images of sample with silver coated filaments – No. 4, and reference sample – No. 6, is presented.

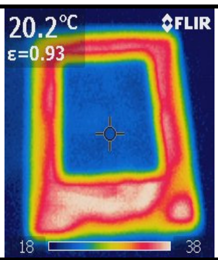
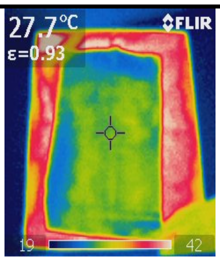
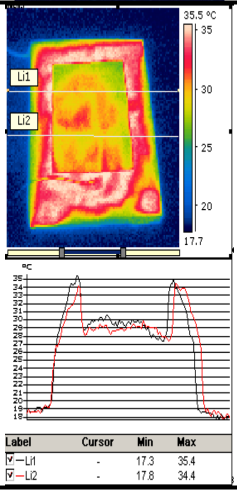
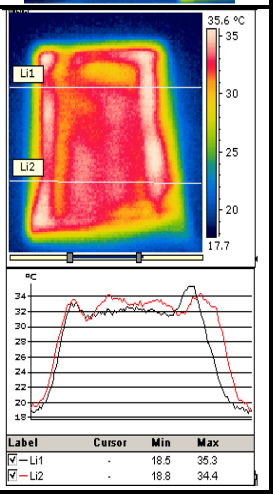
Description of image	Identification code of sample	
	Sample No. 4	Sample No. 6
Thermal image of sample at the moment when laid on the heated stand		
Thermal image of sample after 5 min when laid on the heated stand and temperature variation along lines Li1 and Li2		

Fig. 8. Thermal images of sample No. 4 and reference sample – No. 6

As it can be seen, the efficiency of sample No. 4 is obvious.

The temperature curves indicating the surface temperature in the level of drawn line on thermo signatures (including environment, heated test stand without sample and with sample), were recorded just after putting samples on the heated stand and after 5 minutes.

It is seen from the Fig. 8, seeming temperature of sample No. 4 at the moment when the sample was laid on the heated stand it is obviously lesser than of sample No. 6. The seeming temperature of both tested samples after 5 minutes of laying on the heated stand distinctly increases. The lighter is the places on the images; the higher is the seeming temperature of the sample.

The line Li1 and Li2, drawn in the Fig. 8 shows the temperature variations in the samples. We can observe that over the full length of the lines the seeming temperatures of samples is almost constant, i. e. the seeming temperature remains the same over all area of sample.

In Fig. 9 the view of thermal signatures of concealing and non-concealing object (human) is presented. It is seen form the image taken by thermovisor in natural environmental conditions, that man with ordinary outfit is brightly visible, i. e. the seeming temperature is high (close to 27 ºC) while man with output, produced from sample No. 4 is very underlying (the seeming temperature is about 20 ºC).

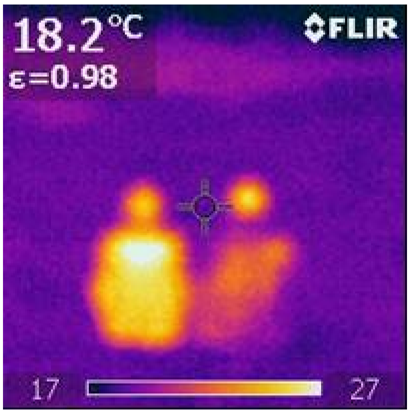


Fig. 9. Objects taken by thermovisor in natural environmental conditions: man with ordinary outfit (body in the left) and man with concealing outfit produced from sample No. 4 doubled layered fabric

4. CONCLUSIONS

Summarizing the experimental results of thermal signatures it is seen that prepared samples with conductive fibres allow decreasing of thermal signature contrast of concealing object with environment, the reached ΔT confirmed obtained results. The seeming temperature of the body covered with one layer of investigated fabrics having in their structure conductive yarns can be minimized about 10 %, whereas, the temperature of the sample coated with aluminium foil can be reduced over 30 %.

Though the continuous metalized surface of fabric provides better thermal signature in case of sample No. 1, when textile material is coated with a layer of aluminium foil, however for the future investigations samples prepared with conductive fibres are more promising.

The experimental results also showed that bigger amount of metal or silver additives do not improve concealing properties of the fabrics considerably, i. e. it is enough to insert the metal or silver yarns into fabric every 1 cm to obtain better concealing effect. It is possible to reduce the thermal signature of clothing using respective optimal amount of special conductive fibres in fabric and latter also has an economical effect. More important is the type of metal – the lower emissivity of the metal used the better concealing properties of the target, i. e. investigated fabrics with silver additives showed 30 % better concealing results comparing with the fabrics containing stainless steel additives. By adding the layer for each sample, a satisfactory effect of infrared camouflage can be achieved when people wear the proposed cloth prototype.

The image of objects, used in investigations, taken by thermovisor in natural environmental conditions confirmed that ordinary outfit doesn't conceals the body at all compared with output, produced from fabric with silver additives, i. e. sample No. 4 – the temperature of such a sample can be reduced over 30 %.

Acknowledgments

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