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Camouflage Woven Fabric Hooded Cloak for Protection against Thermal Surveillance Imagers

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Abstract:

This article enumerates a number of up-to-date achievements in the field of creating metamaterials that can theoretically be used when manufacturing the means of camouflage for armed forces personnel. A high-performance version of the design of camouflage hooded cloak for protecting servicemen is presented. The presence of slot air flaps for the air exchange via thermal convection between the external environment and the internal cavity of the cloak will prevent the formation of unwanted zones of localized heat concentration with the presence of an elevated temperature on the surface of the cloak fabric in the course of a long period of use. Prototypes of such a design of an invisibility cloak have successfully passed tests during combat operations in Ukraine.

Keywords:

camouflage, thermal cloak, thermal imagers, thermal convection, thermal radiation

1 Introduction

In order to hide heat transfer, thermal radiation, and thermal convection of objects (including persons), various types of heat-protective cloaking devices have been developed over the past 20 years that can make the objects invisible to thermal imagers. This has become possible through the development of optimal heat transfer "transformation optics" [1] and creating various metamaterials.

Elaborating the transformation optics method has led to the emergence of modern concentrators, bending waveguides, rotators, superlenses, hyperlenses, artificial black holes [2], and also to the state-of-the-art achievements of topological photonics. However, optical technologies are unacceptable for camouflaging in certain circumstances, because they cannot hide thermal radiation.

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Various metamaterials have been developed, including metamaterials with electromagnetic properties superior to those of natural materials to a certain extent, and also so-called smart textiles that respond to environmental stimuli [3], which are associated with research in a wide range of so-called smart metamaterials [4].

Today's combat operations in Ukraine differ from all previous ones, which took place in various corners of our world, in the large-scale use of high-tech weapons, armored vehicles, saturation firing weapon systems, and also a large number of aerial drones for reconnaissance purpose, which are equipped with surveillance thermal imagers. Therefore, there was a need to equip units of the Ukrainian Armed Forces with modern means of camouflaging military personnel, equipment, weapons, and objects that are sources of heat radiation against detection by the enemy.

2 Some Remarks about Thermal Metamaterials and Thermal Radiation

Over the past ten years, a fairly large number of studies have been conducted in the field of developing thermal metamaterials and improving the camouflage properties of invisibility cloaks that can hide objects from infrared radiation.

A long-continued study of thermal metamaterials has shown the effectiveness of their application to make invisibility cloaks [5].

Paper [6] has presented a method of active cloaking of objects based on the development of monopole and dipole distribution of the heat source on the boundary of the area to be cloaked.

Paper [7] has presented a thermal cloak that allows switching the direction of heat transfer manipulation, depending on whether the inner layer of the developed cloak is a thermal insulator or a thermal superconductor.

According to paper [8], the thermal visibility of an object can be optimally suppressed under "weak invisibility conditions" for the transient response, which can completely hide the object in a steady state.

According to paper [9], a small object can be made completely invisible to heat diffusion waves by adjusting the heat conductivity of the spherical shell enclosing the object.

Paper [10] has presented the structure of multilayer film for infrared camouflage with heat transfer management, which has a high infrared camouflage performance against the lidar detection in the near-infrared range.

According to paper [11], the electromagnetic invisibility of small objects under several layers of homogeneous materials with appropriate electromagnetic properties has been achieved.

Paper [12] has presented a study on infrared camouflage textile composites with intelligent temperature control, which were produced by different methods. For example, when the bottom layer of the infrared camouflage textile composite is composed of 27% phase-change microcapsules and the surface layer is composed of 20% copper powder, its heating and cooling speed is slowed down. It has excellent heat storage and temperature regulation function, which can reduce the skin surface temperature by more than 6 °C and effectively reduce infrared radiation.

At present, quite a lot of data has been published on the results of the development of various metamaterials capable of converting (absorbing) heat. In such publications, special attention is given to theoretical calculations and conducting computer-simulated tests, and, consequently, to studying the potential of applicability of such materials. However, publications on practical tests (under field conditions when conducting real combat operations) of metamaterials are today a great rarity, or such data are not published by reason of an increased level of their secrecy.

The development of military technologies allows unmanned aerial systems to perform reconnaissance tasks using modern devices for recording electro-optical, thermal, radar images, for detecting light and determining the distance. In this connection, there is a need for the practical development of effective solutions of camouflage to counteract technical surveillance equipment being used by modern reconnaissance units. Aerial reconnaissance using thermal imagers passively detects an object's thermal radiation regardless of the time of day, making the selection of effective countermeasures more challenging.

However, the thermal radiation of an object and its background will be the same if the temperature difference between the object and its ambient background is small, or if the emissive power of an object and its ambient background are similar [13].

The widespread use of infrared detection and surveillance equipment in military units makes combat camouflage of various targets extremely important. It is especially significant for preserving the lives of personnel, who are the primary targets for every enemy. In this connection, infrared camouflage being used by personnel must be portable, reliable, and multifunctional.

Camouflage clothing must comply with military standards, be safe for the human body, comfortable to wear, resistant to washing, and capable of maintaining its functionality over time under varying temperatures and environmental stressors. An important factor is the low cost, which makes it possible to organize the mass production of camouflage clothing [3].

3 Results of the Tests Conducted

The difference between camouflage textile cloaks that are offered by various developers lies in the diversity and composition of the layers of woven fabrics being used with the impregnation of individual layers of fabric with a special polymer solution. Those specific layers absorb or significantly complicate the penetration of heat through the camouflage material into the environment. By changing the structure of textile materials at the expense of mixing them with other compounds or by means of applying functional polymer coatings to their surfaces, the properties of the infrared radiation of the fabric itself can be significantly changed. For example, it is possible to change the overall emissivity of the fabric or reduce the difference in infrared radiation between the fabric and the background of the environment in order to achieve the desired result of camouflage of the object itself.

The majority of known developments of inexpensive camouflage cloaks based on woven fabric rest on the physical principles of the presence of high thermal resistance, maximum reflection, and partial absorption of thermal energy in the materials. Some scientists offer their own compositions of the polymer solution for impregnating camouflage woven fabric [14].

In consequence of the sudden expansion of the combat zone in Ukraine, an urgent need to develop an inexpensive and effective version of the invisibility cloak design for Ukrainian servicemen has arisen.

To satisfy this need, the first step was to select layer materials [15] for a new composition of camouflage woven fabric [16] that would meet all the requirements on camouflage clothing for servicemen (see Fig. 1).

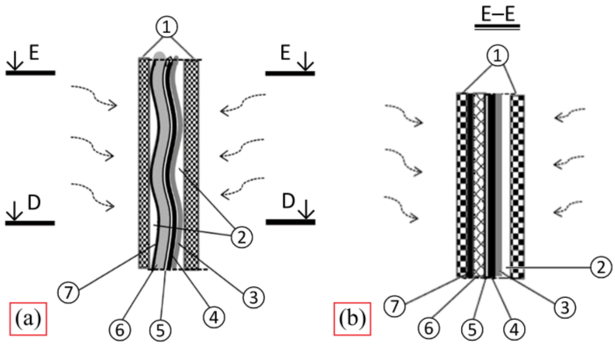

Fig. 1 Camouflage multilayer woven fabric: *(a) cross-section; (b) and (c) longitudinal sections along two cut lines* D–D *and* E–E*; 1 double-sided camouflage fabric “winter” and “summer”; 2 closed air cavities; 3 heat-resistant fabric; 4 solid aluminium film; 5 polyethylene terephthalate coating (PET coating); 6 wave-shaped heat-insulating porous material; 7 absorbent polymer composite coating*

The camouflage woven fabric is formed by two outer layers 1 (see Fig. 1) which can be made of woven or non-woven fabric. The external surface of the inner and outer layers has a light or dark camouflage coloration depending on the winter or summer season. Between the layers 1, closed air cavities 2 of a complex geometric configuration in the form of a segment with a linear dimension of measurement in the plane at the base up to 50 mm and a height of up to 5 mm are formed, which emerge at the expense of wavy heat-insulating surface of layer 6. The wave-shaped porous heat-insulating material 6 has a low heat transfer coefficient and contains multifaceted closed air cavities inside. This can be, for example, foamed polyethylene or another material with a hollow structure. In so doing, the cavities have a multifaceted prismoidal closed structure filled with air and are formed between the outer layer 1 and the thermal layer 3. The thermal layer 3 can be made, for example, of “Aluholst PET”.

The outer surface of the heat-insulating layer 3, impregnated with a special salt solution to protect against short-term exposure to open fire and high temperatures, contains the polymer composite coating 7 with a low reflection coefficient on the side of the outer layer 1 to absorb radio waves. For example, electrically conductive ferrite-polymer composites (e.g., RAM) can be used as such a material.

The outer surface of the thermal layer 3 on the side of contact with the heat-insulating layer 6 comprises the impermeable aluminum coating 4, which is laminated with the transparent protective PET coating 5. Its reverse surface is separated from the camouflage layer 1 along the inner side, as is the surface of the camouflage layer 1 along the outer side from the heat-insulating layer 6, by air cavities 2. The stable existence of the cavities 2 is ensured by the formation of a wavy surface of the heat-insulating layer 6 and the thermal layer 3, in so doing, both outer camouflage layers 1 are connected to each other along their peripheral boundaries.

Thus, at the first stage of the research, a novel composition of camouflage multilayer woven fabric was designed and proposed, which provides a high thermal resistance to infrared radiation and significantly reduces the movement of heat flow through it into the external environment.

The reduction in heat transfer through a multilayer surface–that is, heat transfer rate–is determined by the equation of heat transfer through a multilayer wall:

$$\dot{Q} = \frac{T_1 - T_2}{\sum \frac{d_i}{k_i A_i}} \tag{1}$$

where $\dot{Q}$ = the heat transfer rate [W]; T_1 and T_2 = the temperatures on the outer surfaces of the wall [K]; d_i = the layer thickness [m]; k_i = the thermal conductivity coefficient of the layer [W/(m·K)]; A_i = the surface area of the layer [m²].

Calculations were made for layers with the following characteristics:

- Camouflage woven fabric, ≈1 mm in thickness, 0.05 W/(m·K) in thermal conductivity coefficient.
- Aluminum film, 0.1 mm in thickness, 205 W/(m·K) in thermal conductivity coefficient.
- Thermal insulation with air cavities, 5 mm in thickness, 0.03 W/(m·K) in thermal conductivity coefficient.
- Camouflage woven fabric, ≈1 mm in thickness, 0.05 W/(m·K) in thermal conductivity coefficient.

Using Eq. (1) for heat transfer through a multilayer wall, we determined the heat transfer rate through its surface of 1 m² in area at the maximum temperature of the camouflage woven fabric along the inner side of +300.15 K (+27 °C) and the temperature of the camouflage woven fabric along the outer side of +273.15 K (0 °C). For comparison, the heat transfer through a single-layer woven fabric 7.1 mm in thickness (as equal to the total thickness of the multilayer woven fabric) was calculated. The reduction in heat transfer from inside to the external environment through 1 m^2 of the developed multilayer fabric (i.e., heat flux) amounted to Q = 31.7 (W/m^2).

Therefore, at a temperature of the camouflage fabric along the inner side of +300.15 K (+27 °C) and the camouflage fabric along the outer side of +273.15 K (0 °C), the use of the developed camouflage multilayer woven fabric reduces the surface heat flux by 31.7 W/m² in comparison with conventional camouflage clothing of the same thickness for servicemen.

Tab. 1 presents the changes in heat transfer through a specified multilayer fabric surface (1 m²) under various usage conditions.

Tab. 1 Heat transfer indicators of the developed multilayer camouflage fabric

Temperature along the inner side of multilayer fabric, [°C]	**Ambient temperature, [°C]**	**Heat flux through multilayer fabric, [W/m^2]**
27	+20	42.94
27	0	190.10
27	−20	288.34

The obtained heat flux values in Tab. 1 confirmed that an increase in the temperature difference between the inner and outer surfaces reduces the camouflage properties of the multilayer woven fabric over time. Thus, based on Eq. (1), it was suggested that the thermal camouflage of an object only at the expense of the use of a multilayer camouflage woven fabric has a time limit, and the duration of the camouflage depends on the temperature difference inside the camouflage cloak and the external environment.

It does not matter what combination of camouflage woven fabric layers the camouflage means will be made of, over time the object will be decamouflaged. This is due to the fact that over time, heat concentration zones will appear, and the camouflage object will be detected by technical means of thermal observation. The Eq. (1) of heat transfer cannot be revoked, but if the process conditions are changed, then the period of preservation of camouflage properties can be significantly increased, and this was the task of the second stage of our research.

At the second stage of the research, the basic design of camouflage hooded cloak [17] was created from the camouflage multilayer woven fabric, thanks to which a serviceman can regulate the temperature conditions on the inner side at the expense of the presence of slot air flaps for convective heat transfer between the external environment and the internal cavity of the camouflage cloak and, therefore, the displacement of a part of the heated air. The sizes of the openings of these flaps are regulated depending on the ambient temperature (see Fig. 2).

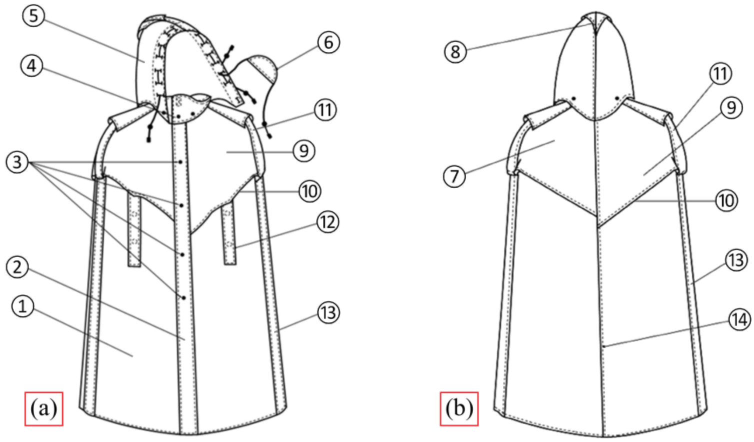

Fig. 2 The basic design of camouflage hooded cloak: (a) front view, (b) back view

The cloak is made of camouflage multilayer woven fabric and can have an additional layer of the outer camouflage such as the KIKIMORA type or the SITKA type (see Fig. 3).

The camouflage hooded cloak ① has a straight silhouette with a central front placket ② that contains fasteners ③ (e.g., buttons, zippers, snaps, strings, etc.). At the top, the placket ② goes over to a stand-up collar ④, to which the hood ⑤ with the mask ⑥ is attached using fasteners ③. The hood ⑤ is made of two side parts with a shaped underside that continues at the back. The junction of the hood with the stand-up collar ④, at the expense of the made shape of the lower part of the hood ⑤, ensures the passage of air through the ventilation flap ⑦ and the shaped flap ⑧, which, in its turn, ensures the ventilation both in the cavity of the hood ⑤ and, in combination with the flaps located below, the ventilation in the vertical direction of the cloak ①. The stand-up collar ④ is made in the form of a sewn-on yoke-pelerine ⑨ that in contacting with the lower part of the cloak ① forms the slot flaps ⑩. The shoulder ventilation flaps-epaulets ⑪ are located on the yoke-pelerine ⑨. The lower part of the cloak contains plackets-flaps ⑫, through which a person, if necessary, sticks out his arms. The plackets of side seams ⑬ and the central rear plackets ⑭ form closed air cavities.

Fig. 3 View of the camouflage hooded cloak (PNM-1) made of camouflage multilayer woven fabric: (a) front view; (b) side view; (c) back view; (d) cloak version with additional outer camouflage layer of the KIKIMORA type; (e) cloak version with additional outer camouflage layer of the SITKA type

Prolonged use of conventional camouflage gear made from multilayer woven fabric without ventilation flaps results in uneven air heating inside the garment, leading to the formation of localized hotspots on the fabric surface (see Fig. 4). In this connection, the camouflage properties of the camouflage means are reduced, which increases the risk of detection of the camouflaged object (person) by thermal imaging devices of surveillance and reconnaissance.

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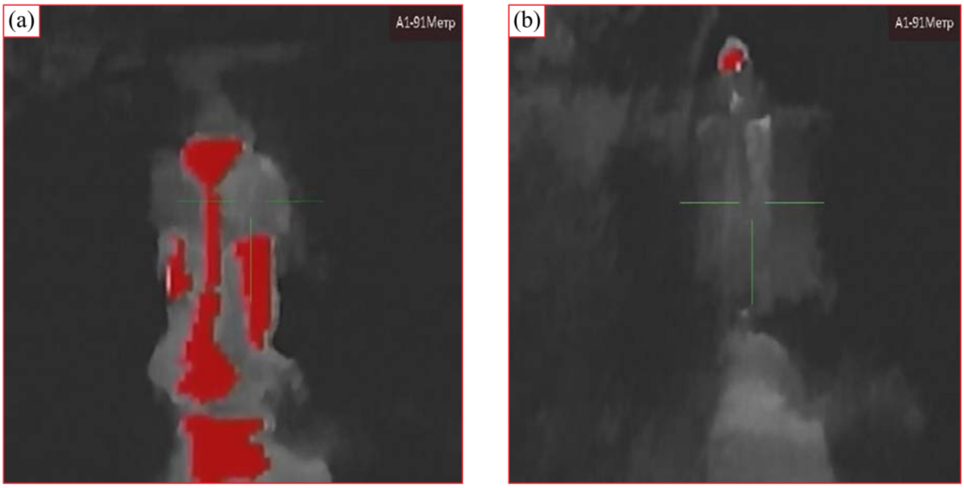

Fig. 4 Thermal images of serviceman after 30 minutes *of surveillance: (a) conventional design (without ventilation flaps); (b) developed design with ventilation flaps*

The newly developed design of the camouflage hooded cloak (see Fig. 2) with ventilation flaps 7 and 8 ensures the air exchange between the external environment and the internal cavity of the cloak. The air exchange occurs by thermal convection both in the vertical and horizontal directions through the removal of air heated from the human body from the internal cavity of the cloak into the environment. This ensures the absence of formation of zones of local heat concentration with an increased surface temperature of the cloak fabric. The opening of the slot flaps is adjusted depending on the ambient temperature so that the air exchange intensity is imperceptible to thermal imaging devices of surveillance.

Enhancing the protection of the camouflaged object is possible by increasing the camouflage properties of the cloak and by simulating a natural landscape. The slot flaps are located at an acute angle to the vertical to imitate tree or bush branches that can be recognized in thermal images (see Fig. 5).

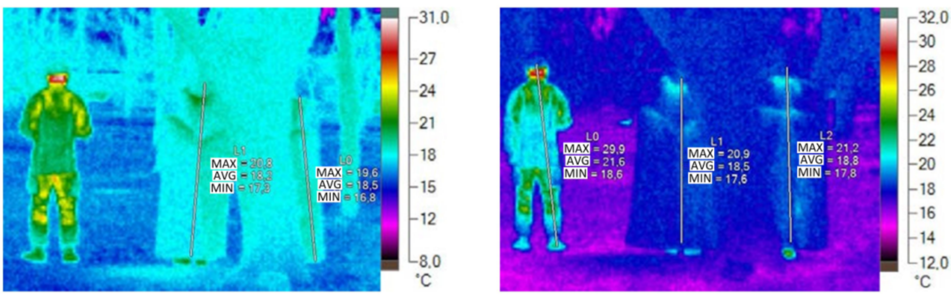

Fig. 5 Thermal images of servicemen in the proposed design of the PNM-1 camouflage hooded cloak from a distance of 10 m, *where MAX, AVG, and MIN are temperature values of exterior surface taken with thermal imager while testing*

Prototypes of this invisible cloak design were tested in the combat zone in 2023 in eastern Ukraine in various military units. Fig. 6a shows a thermal image of three servicemen. The first one from the left is a serviceman who is covered with the PNM-1 camouflage hooded cloak of a patented design with ventilation flaps for thermal convection of air. The image of this serviceman was taken using an unmanned aerial vehicle of the DJI Mavic 3T type from a distance of 63 m. Fig. 6b shows a thermal image of one serviceman. This image was taken with an AGM Rattler TS19-256 device from a distance of 50 m. Information about the tests carried out even appeared in *Newsweek Magazine* [17].

For additional comfort of the serviceman when it is impossible or dangerous to use traditional heating means (a stove or an open fire), the cloak has metal fasteners to clamp the hem of the cloak to imitate a sleeping bag.

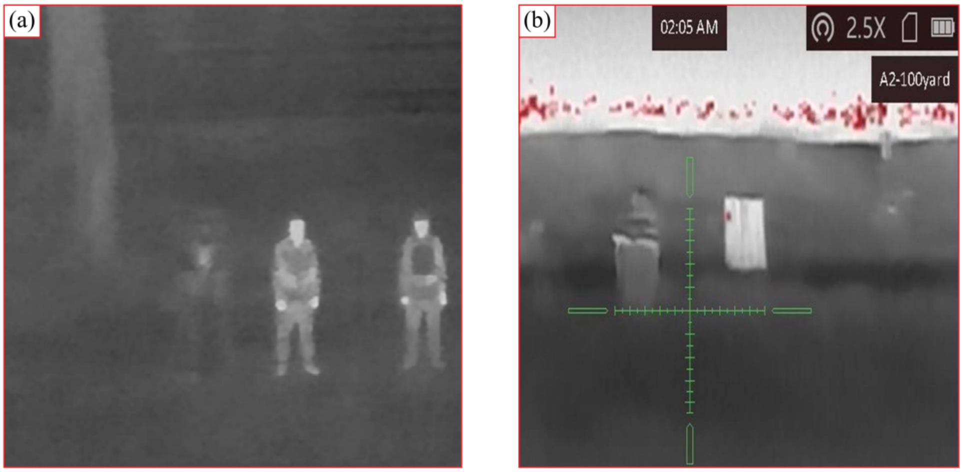

Fig. 6 Thermal images of servicemen covered with the PNM-1 camouflage hooded cloak of a patented design with ventilation flaps for the thermal convection of air

4 Conclusion

The PNM-1 camouflage hooded cloak is compact, light enough to move (up to 2.5 kg in weight), and is a multifunctional product that has the following features:

- A high level of camouflage for a serviceman in imitation of the landscape of the environment with natural vegetation (bushes, trees) and artificial structures or equipment against thermal imagers of surveillance and reconnaissance when using unmanned aerial vehicles from a distance of more than 30 m, regardless of weather conditions.
- A reliable protection against the negative impact of electromagnetic high-frequency radiation on the human body, for example, when using electronic warfare equipment at the expense of the presence of a conductive (aluminum-based) layer.
- A high level of comfort for a serviceman at low ambient temperatures. When it is impossible or dangerous to use traditional heating means—a stove or an open fire—the cloak replaces a sleeping bag.
- A high mechanical strength from accidental damage by tree branches, bushes, shrubs or sharp gusts of wind; a high wind resistance and a high water resistance at the expense of the laminated top layer of the PET coating.

- A high fire resistance at the expense of impregnation with a special salt solution. The multilayer fabric does not support the combustion process absolutely, which provides the protection of outerwear and human body from burns and damage by open fire during explosions of projectiles, mines, etc.

Thus, it is proposed to use the developed camouflage hooded cloak as additional equipment for servicemen performing tasks in a combat zone, such as:

- Special forces groups.
- Sabotage and reconnaissance units.
- Fire support sniper teams.
- Engineer combat groups for covert mine-laying and mine-clearing.
- Sentries at posts of support structures (trenches) directly on the front line.
- Guard and patrol groups for the protection of military facilities and property.
- Sentries at the checkpoints of logistics supply routes or at the points of covert surveillance in the frontier zone of the state border, who serve in the open air far from protective structures from bad weather.
- Electronic warfare teams.

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