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MODELING OF INFRARED RADIATION PROPAGATION THROUGH THERMAL INSULATION SURFACES

Abstract. The development of materials for blocking infrared radiation, provided there are several layers with different thermophysical characteristics, requires large amounts of experimental research. Therefore, it is advisable to automate this process. This is possible due to the modeling of heat flow through the layered material. **The purpose of the research** is a modeling of the passage heat flow through a material made of layers different thermophysical properties and verification of the modeling results. **Results of the research**: Modeling of the passing heat flow through a layered structure with different thermophysical properties of individual layers was carried out. An air gap of small thickness was assumed between the layers of materials. Changes in the temperature of the outer layer were determined depending on the time of heat passing through the layered structure. The obtained dependences of temperature changes of each layer in time and space. The obtained easy-to-use graphical dependencies are suitable for the designing a protective material with the required properties. The temperature gradient between the heat source and the outside space was taken into account. The modeling results were verified using a calibrated infrared radiation detector. It was established that the application of modeling allows to choose the thermophysical characteristics of individual layers the material, which ensure the temperature of the outer layer and is equated to the temperature of the environment. A comparison of the manufactured material with known analogues showed that it has better protective properties with a smaller thickness. **Conclusions:** The application of the modeling heat flow propagation through a layered structure with different thermophysical properties of individual layers allows designing protective materials depending on operating conditions.

Keywords: modeling; infrared radiation; insulation surfaces; design protective materials.

Introduction

Infrared radiation is thermal radiation. Therefore, a lot of attention is paid to determining the patterns of its distribution through various materials. Research in this field is carried out in several directions: providing thermal insulation of buildings, protecting people from thermal effects and developing infrared camouflage.

Creating heat-insulating clothing is the most difficult task. This is explained by the fact that the heat flow passes through several layers with different physical characteristics. In fact, the tasks of creating heat-insulating clothing and infrared camouflage are direct and inverse tasks.

Therefore, the same approaches can be used for their development. But even with the presence of all the necessary physical data - thermophysical properties of materials, temperature gradients, the development of protective structures requires the creation and testing of a large number of experimental samples to obtain an acceptable result.

Therefore, at the first stage of development, it is advisable to model heat transfer processes through layers of materials, in particular, in the presence of air gaps under certain conditions. Such modeling will allow to reduce the time of development and the expenditure of funds for the implementation of the project.

Analysis of research and publications

Most of the research on modeling heat transmission processes is aimed at solving the problems of energy saving and increasing the energy efficiency of buildings. In the study [1], the modeling of heat transmission by a material with a variable phase composition was carried out. In the work, a model of laminar flow molten material was developed using ANSYS. But such material is not suitable for the production of protective clothing, that is, the developed model cannot be used for such purposes. The work [2] is devoted to the optimization of heat flows in finishing materials from the point of view of creating comfortable conditions for people. In particular, non-stationary thermal processes in one layer of material, which is not inherent in layers of clothing, are considered. Materials with phase changes are very promising for solving thermal insulation problems [3–5], but the current technological level does not allow their use for moving objects and in conditions of variable mechanical loads. The results of 3D modeling of the phase change process [6] can be partially used. But such material has a very high cost and is not stable under long-term operation. In the review [7], all the advantages and disadvantages of materials with a phase change during operation are given. From the point of view of product design, it can be concluded that even with the correct modeling of the heat transmission processes in such materials, the production of mobile protective equipment from them is unpromising. Materials produced using nanotechnologies have high thermal insulation performance [8]. But their thermophysical properties, which must be included in the calculations, are not reference data. This is due to different particle concentration and their spatial distribution. This excludes the calculation method of predicting the protective properties without conducting experiments and making a large number of test samples Similar problems arise when calculated predicting the efficiency of materials on the basis of microstructures [9, 10]. It is difficult to determine the correct mathematical apparatus for such materials [11]. In addition, for heterogeneous structures, problems arise regarding the experimental determination of the necessary constants [12].

Known works on designing clothing to block infrared radiation [13, 14] are somewhat outdated. The main drawback of these studies is the consideration of specific materials, which does not allow obtaining a generalized model of heat transmission. In addition, it does not take into account the presence of air gaps between individual layers of material (clothing), which are necessarily present in real products and operating conditions.

It is advisable to develop a model that considers layers with different thermophysical properties, with air gaps between them. This will provide an opportunity to design clothes to protect people from external thermal influences and prevent the leakage of infrared radiation from the space under the suit.

Presentation of the main material

In the model considers the process of the passing a heat flow from a heated body through three layers of material. There is an air gap between the body and each layer.

The heat conduction equation is used for modeling:

$$\frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}, \quad (1)$$

where T is temperature, t is time, x is distance, λ is thermal conductivity of the material in the X direction.

The thermophysical parameters of the source of heat energy and all layers through which the heat flow passed were included in the calculations.

The modeling was carried out on the example of the passage of heat from the human body through the skin, two layers of clothing and thermal protection material. Real indicators of human skin l_s - skin thickness, C_s, ρ_s, λ_s - its heat capacity, density and thermal conductivity were taken into account.

The air layer parameters, C_a, ρ_a, λ_s and the air layer thickness L_1 were taken into account.

Accordingly, the parameters of the three layers d_1, x_1, C_1,ρ_1; L_2, d_2,λ_2, C_2, ρ_2; L_3, C_3, ρ_3, d_3. The outside air temperature is 15 °C.

The coefficient of thermal conductivity a_n for each layer of material was determined as:

$$a_n = \frac{\lambda_n}{\rho_n C_n}. \quad (2)$$

The following boundary conditions are set for the modeling equation of thermal conductivity (1):

- a temperature value of 36°C is set on one outer surface (left);

- on the other - outer surface (right) the temperature value is set to 15°C.

The boundary condition in terms of time has the following form:

$$T_{n-1} = T_n, \quad (3)$$

where T_n is the temperature in the last calculation cell, T_{n-1} is the temperature in the previous calculation cell.

The initial condition at $t=0$, T=36°C is accepted in the entire calculation area.

A rectangular difference grid is used for calculations. The temperature value is determined in the centers of the difference cells. For the numerical solution of the modeling equation (1), an explicit difference scheme is used.

$$T_i^{n+1} = T_i^n + \Delta t \cdot a_1 \frac{T_{i+1}^n - T_i^n}{\Delta x^2} + \\ + \Delta t \cdot a_2 \frac{-T_i^n + T_{i-1}^n}{\Delta x^2}, \quad (4)$$

$$a_1 = \frac{2(a_{i+1} \cdot a_i)}{a_{i+1} + a_i}, \quad (5)$$

$$a_2 = \frac{2(a_{i-1} \cdot a_i)}{a_{i-1} + a_i}. \quad (6)$$

Dependencies (4) and (5) are used to calculate the value of the temperature conductivity coefficient at the boundary of layers with different thermophysical parameters. A total of 50 calculation nodes to the *Ox* axis, grid step 7.7/50 mm.

In the calculations, the two inner layers had the thermophysical properties of common textile materials, the outer (protective) layer had the characteristics of a solid fiberglass product.

Modeling was performed using the COMSOL package [15, 16]. The geometric characteristics of the surface are a rectangle with a height of 20 mm and a length that is the sum of the thicknesses of all layers. In Fig. 1 shows the layout of material layers and the finite element mesh.

Changes in temperature and heat flow in the total thickness of the material were determined (Fig. 2).

The results shown in Fig. 2 make it possible to determine the time intervals during which heat leaks from the layered material to the outside.

To select the materials of individual layers of protective clothing, temperature changes in individual layers at certain time intervals were determined (Fig. 3).

The generalized model of temperature distribution in the body of the material depending on the layer (point) and time of heat transfer is shown in Fig. 4.

The level of thermal insulation clothing is one of the basic factors influencing the visualization of the infrared field of an object - the body.

Accepting an initial temperature on the surface of the body of 36°C and a 4-layer model of human clothing under conditions of a load of 120 W, we can observe the blocking of infrared radiation on the second layer of clothing. The model takes into account not only the coefficients of thermal conductivity of clothing materials, but also air.

It should be noted that under the conditions of increasing the load to 400 W, the amount of heat in the undersuit space will accumulate.

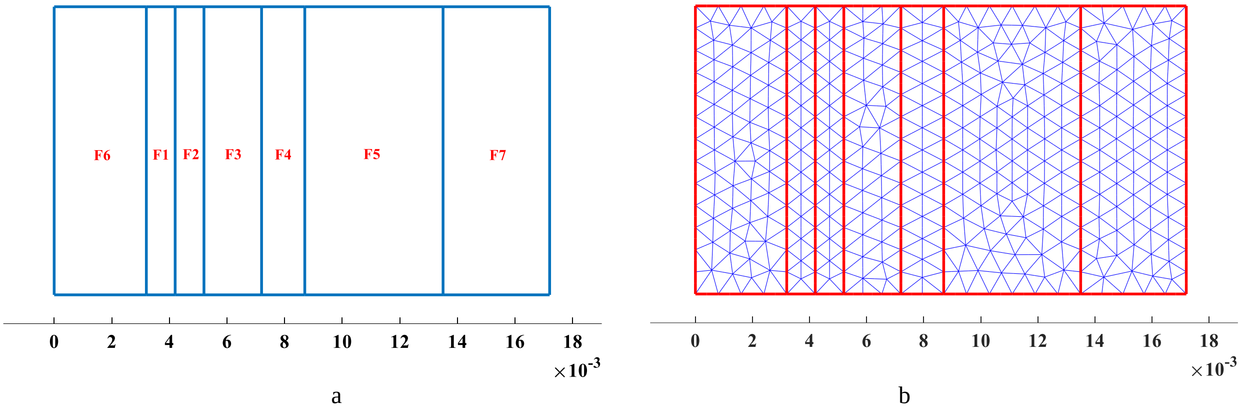


Fig. 1. Geometry of the calculation area: a – F6 – human skin, F1, F3, F5 – layers of air, F2, F4, F7 – textile materials; b – geometry breakdown by finite element mesh

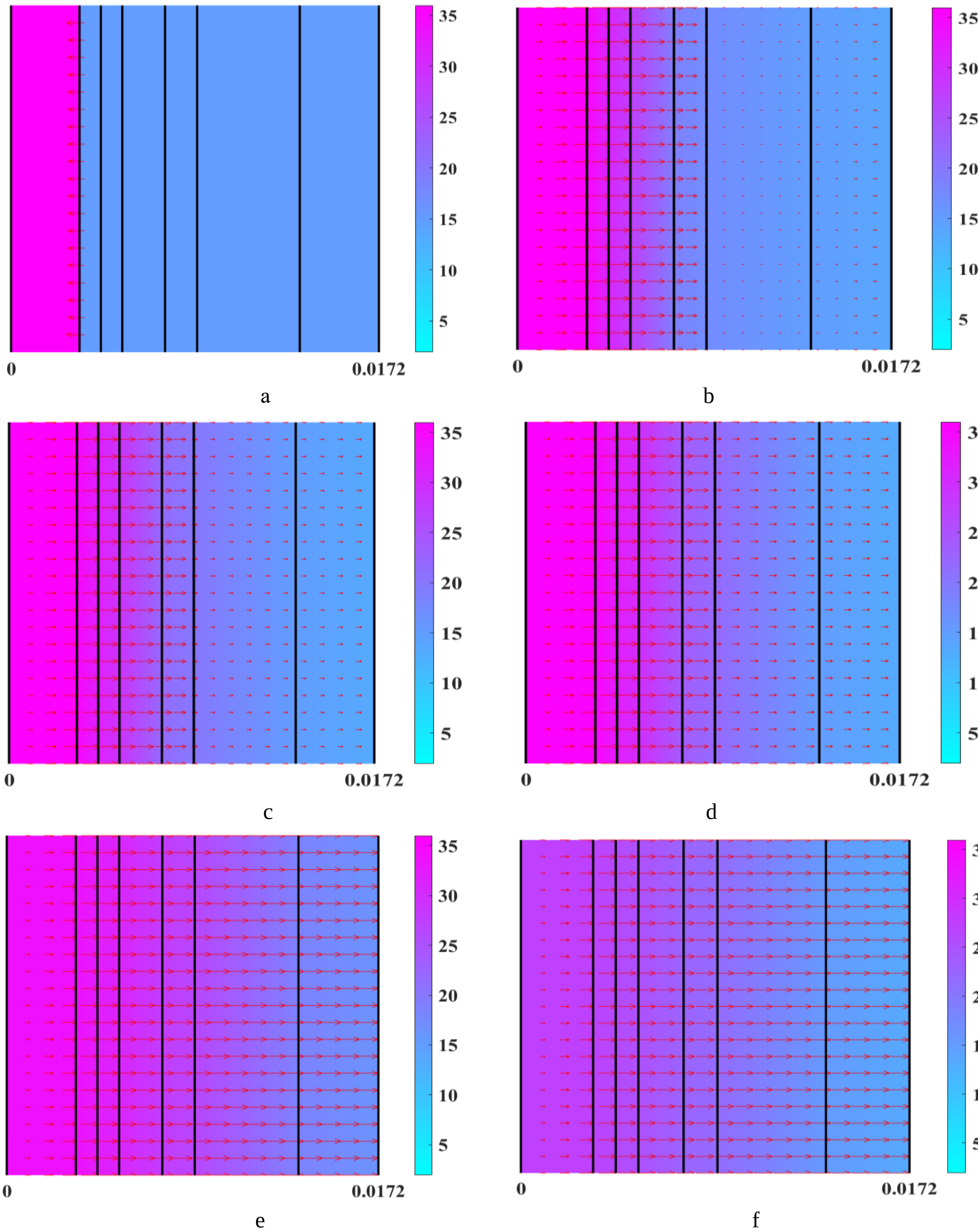


Fig. 2. Fields of temperature distribution and heat flow in the thickness of the material at different time intervals: a – 0 c, b – 12 c, c – 24 c, d – 36 c, e – 48 c, f – 60 c.

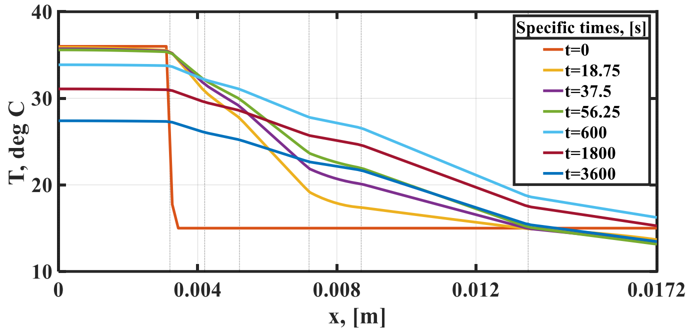


Fig. 3. Temperature sections of the surface – distribution of temperatures in certain time intervals

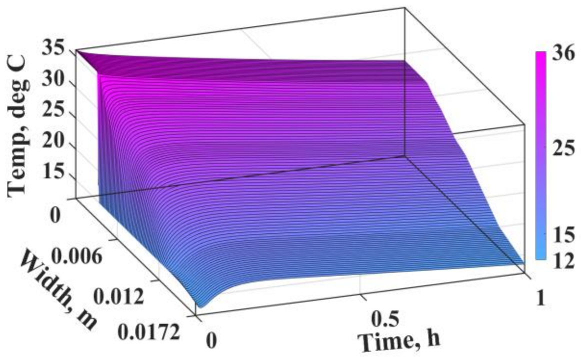
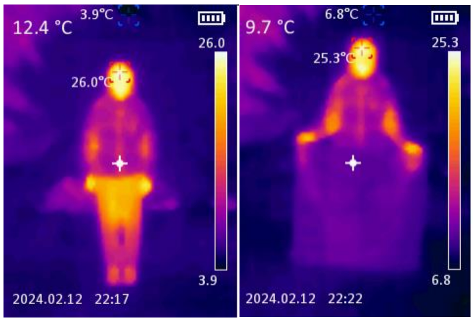


Fig. 4. Distribution of temperatures depending on the coordinate in the body of the material and the time of heat transfer



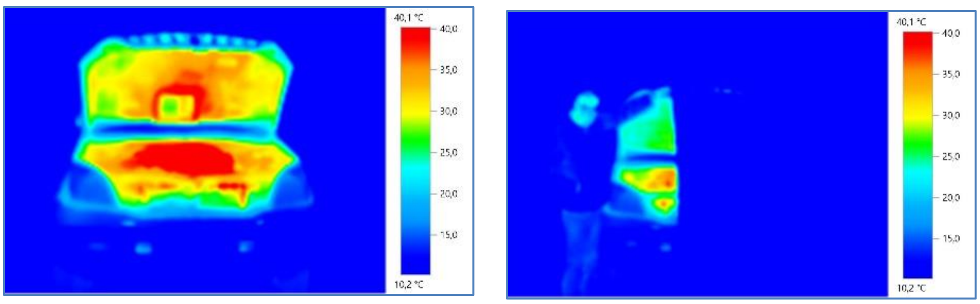
a b

Fig. 5. Effectiveness of using a protective coating based on fiberglass: a – image of a person in infrared rays, b – image of a person protected by material in infrared rays

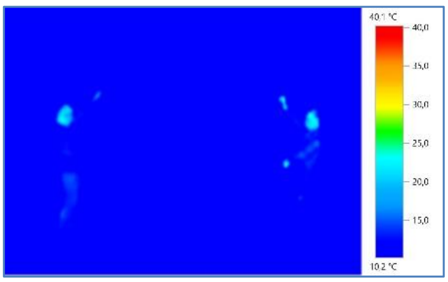
Given that real materials with known thermophysical properties were chosen for the simulation, the results of the study were verified. This was implemented by the method of field measurements using thermal imagers UNI-T UTi120S and Testo 8821-2 Profi 0563 0881 V6.

In Fig. 5 shows an image of a person in infrared rays and a person protected by an absorbent material based on fiberglass. Shown in Fig. 5 data indicate that the protection of the heated object is acceptable.

In this case, the task of providing infrared camouflage of a person was considered. Complete blocking of infrared radiation is impractical. The low visibility of the object is ensured by the blurring of the thermal signature against the background of the surrounding environment. The complete blocking of infrared radiation makes it noticeable, especially when using detectors with infrared illumination. Determination of efficiency and protection with a larger temperature gradient and complete blocking of infrared radiation was carried out (Fig. 6.)



a b



c

Fig. 6. An image of an SUV with an open hood in the infrared range:
a – without protective coating; b – with partial overlapping of the object; c – with a complete overlap of the object

The obtained result makes it possible to optimize the ratio of thermophysical properties of individual layers of the clothing material and the protective layer from the point of view of heat leakage from the human body or human protection from external thermal influences.

Analysis of the results shown in fig. 1–3 allows us to conclude that at least with a temperature gradient between the human body and the external environment of 20 □C when using fiberglass material, the temperature of the outer layer does not exceed the temperature of the external environment.

This opens up the prospect of using such a material not only for maintaining the temperature regime of a person, but also for the manufacture of infrared camouflage. Verification of the modeling results heat flow propagation through a layered material with a protective layer showed that it is possible to design structures with the required efficiency for blocking infrared radiation with an acceptable error using the method of modeling heat flow propagation.

Conclusions

1. The calculation apparatus for modeling the spread of heat flow through several layers of material is defined. Calculations were made based on the thermal conductivity ratios, taking into account the thermophysical characteristics of each layer and the air layers between them. In each separate layer, the coefficient of thermal conductivity was determined based on the coefficient of thermal conductivity, density and heat capacity of the material. A rectangular difference grid was used for calculations. For the numerical solution of the modeling equation, an explicit difference scheme was used.

2. Models of changes in the temperature field in the layered material at certain time intervals were obtained and visualized. Temperature sections of the surface are obtained - the distribution of temperatures on the layers of the multilayer material in certain time intervals. This makes it possible to optimize the choice of materials in terms of their thermophysical properties for each layer.

3. Modeling the passage of heat flow from the human body to the outside with the use of an outer layer of fiberglass shows that the use of such a material is acceptable not only for maintaining the temperature regime of the human body, but also for the development of infrared camouflage.

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Моделювання поширення інфрачервоного випромінювання крізь теплоізоляційні поверхні

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Анотація. Розроблення матеріалів для блокування інфрачервоного випромінювання за умови наявності кількох шарів з різними теплофізичними характеристиками потребує великих обсягів експериментальних досліджень. Тому доцільно автоматизувати даний процес. Це можливо за рахунок моделювання проходження теплового потоку крізь шаруватий матеріал. **Метою дослідження є** провести моделювання проходження теплового потоку крізь матеріал, виготовлений з шарів різних теплофізичних властивостей і провести верифікацію результатів моделювання. **Результати дослідження.** Проведено моделювання проходження теплового потоку крізь шарувату структуру з різними теплофізичними властивостями окремих шарів. Між шарами матеріалів передбачався повітряний проміжок малої товщини. Визначалися зміни температури зовнішнього шару у залежності від часу проходження тепла крізь шарувату структуру. Отримані залежності зміни температури кожного шару у часі і просторі. Отримані зручні у застосуванні графічні залежності, придатні для проєктування захисного матеріалу з потрібними властивостями. Враховувався градієнт температури між джерелом тепла і зовнішнім простором. Проведено верифікацію результатів моделювання з використанням каліброваного детектора інфрачервоного випромінювання. Встановлено, що застосування моделювання дозволяє обрати теплофізичні характеристики окремих шарів матеріалу, які забезпечують температуру зовнішнього шару, яка прирівнюється до температури навколишнього середовища. Порівняння виготовленого матеріалу з відомими аналогами показало, що за меншої товщини він має кращі захисні властивості. **Висновки:** Застосування моделювання поширення теплового потоку крізь шарувату структуру з різними теплофізичними властивостями окремих шарів дозволяє проектувати захисні матеріали у залежності від умов експлуатації. За такого підходу можливо отримати матеріал малої товщини з високими захисними властивостями. Це надає можливість проектувати матеріали для вирішення задач теплового захисту на інфрачервоного камуфляжу.

Ключові слова: моделювання; інфрачервоне випромінювання; теплоізоляція поверхонь; проектування захисних матеріалів.