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MODELLING THE THERMAL RESISTANCE OF LAYERED STRUCTURES FOR BLOCKING INFRARED RADIATION

V. Glyva[1],
Doctor of Technical Sciences, Professor

N. Burdeina[1],
Doctor of Technical Sciences, Associate Professor

L. Levchenko[2],
Doctor of Technical Sciences, Professor

G. Krasnianskyi[1],
PhD, Associate Professor

Y. Biruk[1],
PhD

M. Dovhanovskyi[1]

[1]*Kyiv National University of Construction and Architecture, Kyiv*

[2]*National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv*

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Ensuring high thermal resistance of building, cladding, finishing and other materials helps to solve the problems of energy efficiency of buildings and energy saving in general. Typically, building and cladding structures have several layers. This makes it difficult to predict their heat transfer. To solve these problems, it is proposed to model the thermal resistance of layered structures. The mathematical functions that should be used in modelling are determined. In particular, the mechanisms of heat transfer due to thermal conductivity and radiant heat transfer are separated. The assumptions and simplifications in the calculations that are acceptable in terms of errors are determined. The use of glass fibres for blocking infrared radiation is theoretically substantiated. The thermal resistance of a layered structure with an arbitrary number of layers and different thermal properties of each layer was modelled. The modelling was carried out using COMSOL tools. Changes in the thermal state of the layered structure in space and time were obtained. The modelling results were verified. Samples of materials based on glass fibre were manufactured and tested using a standard thermal imager. It was found that such a three-layer glass fibre material actually completely blocks infrared radiation at an initial temperature of up to 40 °C. Comparison of the results with the efficiency of a standard thermal insulation product shows that the predominant mechanism for blocking infrared radiation in a glass fibre-based product is the scattering of infrared radiation. This opens up the possibility of using glass fibre fabrics both to increase the thermal resistance of building and finishing materials and to produce infrared camouflage.

Keywords: thermal resistance, modelling, infrared radiation, thermal conductivity.

Introduction

Increasing the thermal resistance of building, finishing and cladding materials is of great importance for solving the problems of energy efficiency of buildings and structures and energy saving in general. To achieve these goals, it is necessary to minimize the intensity of infrared radiation transmission through materials and structures. This is possible by reducing the thermal conductivity coefficients and increasing the material thickness. However, increasing the thickness of the material is not always possible or advisable. Therefore, it is necessary to design structures with low thermal conductivity coefficients. Real building structures, cladding and finishes have a multi-layered structure. Therefore, it is difficult to take into account different constants for each layer. Especially if you need to minimize the overall thickness of the structure. To some extent, this process can be optimized by modelling the processes of heat transfer through a layered structure with different physical parameters of each layer. This requires the development of an error-acceptable mathematical apparatus and the use of modern software tools. Such research is relevant in terms of energy saving and energy efficiency of buildings and structures. In Ukraine, such research is particularly relevant due to the need to develop materials with high thermal resistance for use as infrared camouflage. For laminated materials of small thicknesses, it is particularly important to correctly model the passage of infrared radiation through the material with its maximum blocking in the protective layers.

An overview of literary sources

Modern research on modelling heat transfer processes is carried out mainly for the purpose of energy supply and diagnostics of metal structures. In [1], the modelling of thermoacoustic devices for use in the field of renewable energy was carried out. Study [2] deals with heat transfer processes in thermal control systems for energy storage devices. The modelling was carried out with a small error, but the considered heat transfer processes cannot be used to simulate the penetration of infrared radiation through solid layered structures. Study [3] deals with changes in the thermal state of a material. Changes in heat flux due to the evolution of the microstructure of metals are modelled. The advantage of this work is the consideration of several approaches to modelling. Paper [4] considers a model of heat flow changes on defects in the form of material points, which is not acceptable for considering heat flow penetration through continuous thin structures. For materials that can potentially be used as finishing materials and infrared camouflage, the main requirement is ease of use. Paper [5] presents the results of studies of the temperature field distribution in a film coated with an alloy of germanium, antimony, and tellurium. This material is quite effective, but has a high cost. The material described in [6] has almost similar characteristics. The basis of this material is polyurethane with the addition of antimony and tin oxide. But it has a complex manufacturing technology. In addition, the manufacturability of its application is low. A common disadvantage of all heterogeneous materials with a uniform distribution of inhomogeneities in the matrix is the inability to use modelling methods to design a protective material with the required properties. The modelling of protective materials with high thermal resistances suitable for blocking infrared radiation is somewhat outdated [7, 8]. At least, the distribution of the thermal field obtained as a result of modelling is questionable. To a certain extent, the shortcomings of modelling heat transfer processes are due to the imperfection of the calculation apparatus [9]. Analysis of available sources leads to the conclusion that layered materials with different thermophysical parameters are the most promising for blocking infrared radiation. Therefore, it is advisable to develop models that characterize changes in the thermal resistance of layered materials with different initial data, as well as to verify the modelling results.

Presentation of the main material

The amount of heat transferred through a unit area of a homogeneous material is defined as:

$$q=-\lambda\frac{dT}{dx}=\frac{T_1-T_2}{1/\alpha_1+d/\lambda+1/\alpha_2}, \tag{1}$$

where λ – thermal conductivity of the material, $\frac{dT}{dx}$ – temperature gradient in the thickness of the material, T_1 – temperature of the inner surface of the material, T_2 – temperature of the outer surface of the material, d – material thickness, α_1, α_2 heat exchange coefficients of the inner and outer surfaces with the environment.

In this case, the thermal resistance of the material:

$$R=\frac{1}{\alpha_1}+\frac{d}{\lambda}+\frac{1}{\alpha_2}, \tag{2}$$

For multi-layer structures:

$$R=\frac{1}{\alpha_1}+\sum_{i=1}^{n}\frac{d_i}{\lambda_i}+\frac{1}{\alpha_2}. \tag{3}$$

Parameters α_1, α_2 are constant for certain environments. That is, increasing the thermal resistance of a layered structure is possible only by increasing the thickness of the material, layers of materials, and reducing thermal conductivity.

Therefore, it is advisable to model the thermal resistance of layered structures with any number of layers using these parameters.

The heat transfer process is defined by Eq:

$$\frac{\partial T}{\partial t}=\lambda_x\frac{\partial^2 T}{\partial x^2}, \tag{4}$$

where T – temperature, t – time, λ_x – is the thermal conductivity coefficient in the x direction.

However, in real conditions, the heat transfer process consists of two components: thermal conductivity and radiation.

The contribution of thermal conductivity to heat transfer is determined by the *N* component [10]:

$$N = \frac{\lambda k}{4\sigma T^3}, \tag{5}$$

where *T* – is the absolute temperature of the inner surface of the material.

The contribution of radiation to the heat transfer process is more difficult to determine. This is because the radiative heat transfer equations do not have exact solutions. Therefore, to solve more specific problems, it is necessary to apply some reasonable assumptions and simplifications.

The smaller the value of *N*, the smaller the contribution of thermal conductivity.

The radiation transfer equation does not have exact solutions. However, in specific problems, with appropriate simplifications, solutions are possible. In the following, we will assume that the shielding material is a grey medium, and the absorption coefficient k does not depend on the wavelength of radiation between two grey and diffuse plane-parallel surfaces. In general, these assumptions are not physically feasible.

For example, E-glass is used for the manufacture of glass fibre, the absorption spectrum of which is continuous in the wavelength range of 8–10 μm, which corresponds to infrared radiation. Therefore, such assumptions are correct.

The intensity of the radiation passing through the medium is reduced by absorption. At the same time, the medium heats up and becomes a source of thermal radiation itself. Thus, along with a decrease in intensity due to absorption, there is an increase in intensity due to intrinsic radiation. In this case, with one-dimensional radiation transfer along the x-axis perpendicular to the material, the following equation can be written for the change in intensity I in a layer of medium with thickness *dx* within the framework of the approximation under consideration:

$$dI = (-kI + J)dx, \tag{6}$$

J – is the radiation energy emitted by a unit volume of the medium in a unit solid angle per unit time.

It is known that under conditions of thermodynamic equilibrium, in this case, due to the non-isothermal nature of the medium, there is a thermodynamic equilibrium for each elementary volume.

$$J = KI^0, \tag{7}$$

I^0 – is the radiation intensity of an absolutely black body at the temperature of the medium.

Taking into account (7) from (6) for the radiation intensity I_2 after passing through a layer of medium with a thickness *h*, the integration results in the following:

$$I_2 = I_1 e^{-kh} + I_R, \tag{8}$$

I_1 – radiation intensity at the input of the medium; I_R – is the intensity of the intrinsic radiation of the medium arising in elementary volumes of length dx and attenuated by elementary volumes on the path from *x* to *h*, where $0 \le x \le h$:

$$I_R = \int_0^h kI^o(x) e^{-\int_x^h k dx'} dx. \tag{9}$$

Considering the relation between intensity and flux density of hemispherical radiation of an absolutely black body E^0

$$I^0 = \frac{E^0}{\pi}, \tag{10}$$

In accordance with the Stefan-Boltzmann law, we have:

$$I^0(x) = \frac{E^0(x)}{\pi} = \frac{\sigma T^4(x)}{\pi}, \tag{11}$$

where *T*(*x*) – temperature in the medium layer with coordinate *x*.

It follows from (11) that in order to integrate (9), it is necessary to know the explicit form of the dependence *T*(*x*). As a first approximation, we will use the linear dependence $T^4(x)$, which occurs in the case of an optically dense medium. (κh>>1) [10]:

$$T_x^4 = T_1^4 - bx, \tag{12}$$

b – constant.

Then, substituting (11) into (9), taking into account (12), we find:

$$I_R = \frac{k\sigma}{\pi}\int_0^h (T_1^4 - bx)e^{-k(h-x)}dx = \frac{k\sigma}{\pi}(T_1^4\int_0^h e^{-k(h-x)}dx - b\int_0^h xe^{-k(h-x)}dx) = \\ = \frac{\sigma}{\pi}(T_1^4(1-e^{-kh}) - b(h - \frac{1}{k}(1-e^{-kh}))). \tag{13}$$

And finally, expressing I_1 and I^2 in terms of the surface temperatures of the shielding material:

$$I_1 = \varepsilon\frac{E_1^0}{\pi} = \varepsilon\frac{\sigma T_1^4}{\pi},\ I_2 = \varepsilon\frac{E_2^0}{\pi} = \varepsilon\frac{\sigma T_2^4}{\pi}, \tag{14}$$

ε – degree of blackness of surfaces; E_1^0 і E_2^0 – radiation flux densities of an absolutely black body at surface temperatures, and taking into account that under conditions of thermodynamic equilibrium on the basis of Kirchhoff's law, the degree of blackness of the surface is equal to its absorption capacity α:

$$\varepsilon = \alpha = 1 - e^{-kh}, \tag{15}$$

From (7), after substituting (13)–(15), we obtain the following simple transformations:

$$T_2^4 = T_1^4(1+e^{-kh}) - \left(\frac{bh}{1-e^{-kh}} - \frac{1}{k}\right). \tag{16}$$

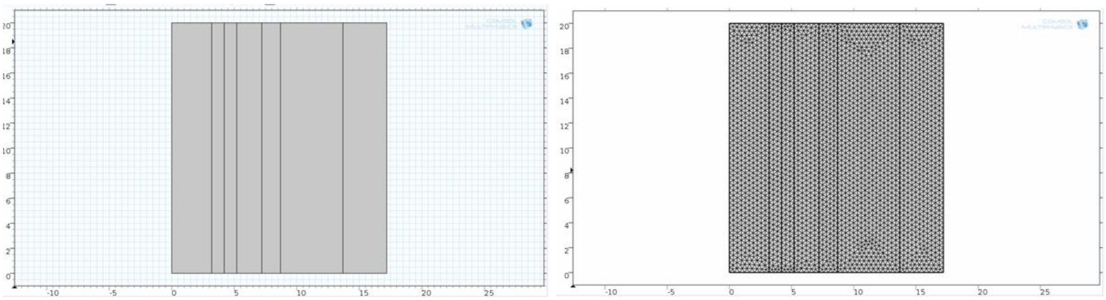
In other words, we have obtained a relation that can be conveniently used to select a protective material.

It should be noted that in the limiting approximation of an optically dense medium, at large values of k, this expression becomes a known linear dependence:

$$T_2^4 = T_1^4 - bh. \tag{17}$$

The choice of glass fibre as a material that shields infrared (thermal) radiation is due to its low thermal conductivity and significant absorption of infrared radiation in the 8–14 μm spectral range, which is the operating range of most thermal imagers. Indeed, the chemical composition of the E-glass fibre used to make the glass fibre fabric offered as a shielding material includes, in particular, 53–55 % SiO_2, 17–21 % CaO, and 5–10 % B_2O_3. The vibration frequencies of the Si–O bonds cover almost the entire range from 600 to 1100 cm^{-1}, the Ca–O bonds are in the range of 700–1400 cm^{-1}, and the B–O bonds are in the range of 1300–1400 cm^{-1}. This leads to the presence of intense absorption bands in the wavelength range of interest.

On the basis of the defined relations, the thermal resistance of a material with an arbitrary number of layers with different thermal and physical characteristics was modelled. The modelling was carried out using an explicit difference scheme. The temperature value was determined at the centres of the difference cells. The computational domain of the difference scheme is shown in Fig. 1.

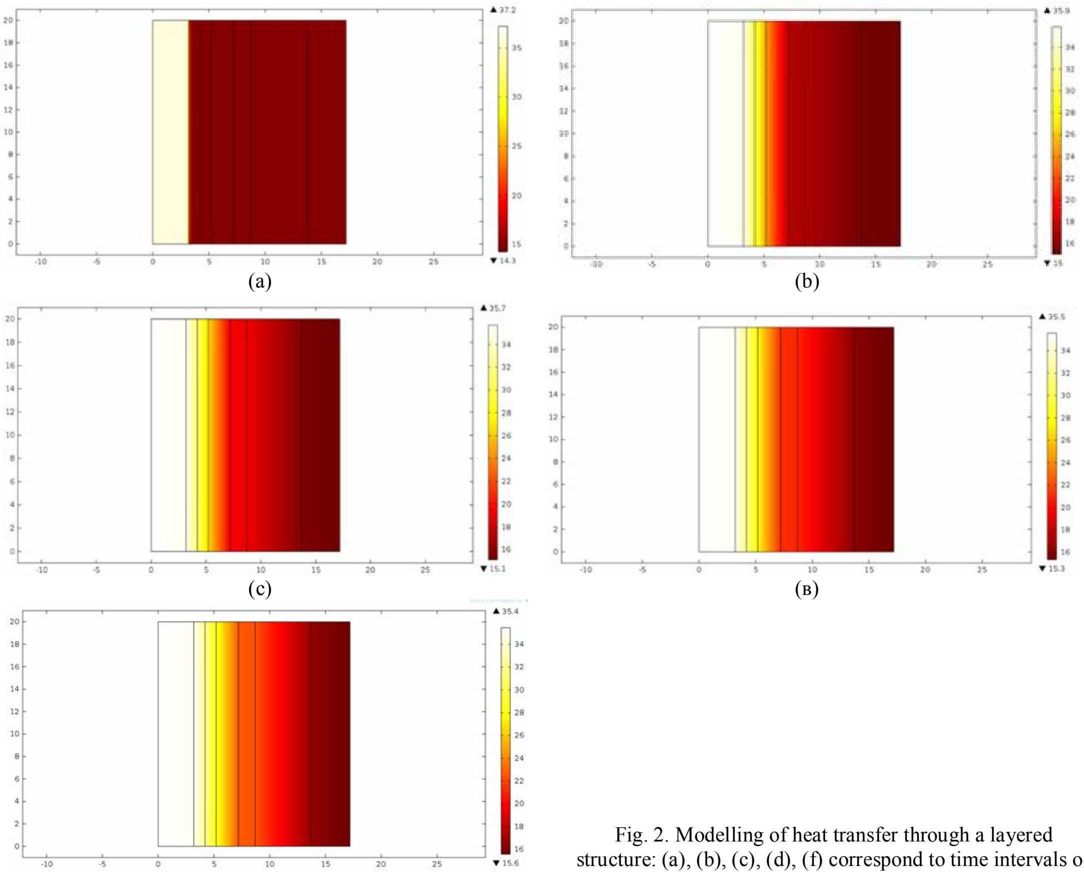


(a) (b)

Fig. 1. Calculated area of the difference circuit. The ordinate axis is the distance in centimeters, the abscissa axis is the distance in millimeters (a) – material diagram with several layers of material; (b) – finite element mesh

The results of modelling heat transfer through the layered structure are shown in Fig. 2.

In this model, the initial temperature was assumed to be around 40°C (left). The outside temperature is 15°C (right). It can be concluded that the above method can be used to estimate the thermal resistance of any layered structure, provided that the thermal characteristics of each layer are known.



(a) (b)

(c) (в)

(f)

Fig. 2. Modelling of heat transfer through a layered structure: (a), (b), (c), (d), (f) correspond to time intervals of 0, 1, 2, 3, 4 hours. The temperature scale is on the right

Since the main (outer) layer was assumed to be made of glass fibre, a glass fibre sample was made to verify the modelling results. The second and third layers were made of two different textile materials.

The tests were carried out using a professional thermal imager UNI-T UTi120S.

Fig. 3 shows the original photo of the object in the infrared region of the electromagnetic spectrum.

In Fig. 4 shows a photo of an object protected by a layered structure based on glass fibre.

As can be seen from the figures above, the transmission of infrared radiation through the test sample is minimal.

It is important to separate the mechanisms of inductive and conductive heat transfer. That is, the resistance to heat transfer due to thermal conductivity and radiant heat transfer. The results obtained were compared with the efficiency of a standard European-made thermal blanket sample (Fig. 5).

Comparing the data of Fig. 5 and Fig. 4, it can be concluded that the glass fibre-based structure is more effective than the thermal insulation coating. That is, the main mechanism of thermal protection in glass fibre is the scattering of infrared radiation in the glass fibres.

Fig. 3. An object in the infrared region of the electromagnetic spectrum

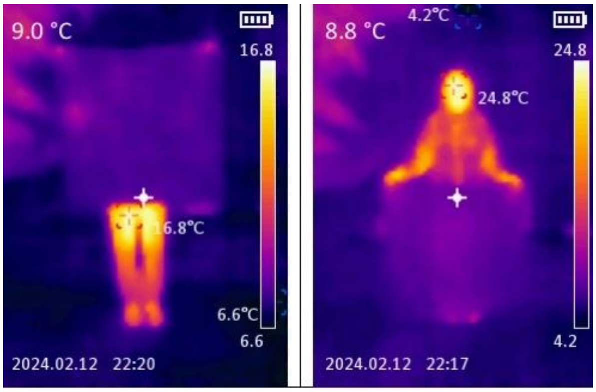


Fig. 4. Thermal protection efficiency of a layered structure based on glass fibre

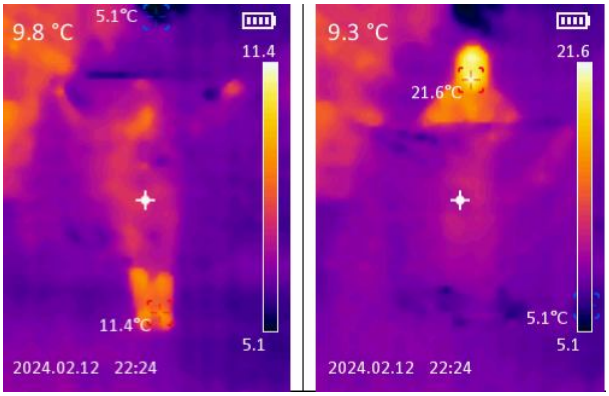


Fig. 5. Thermal protection efficiency of a thermal blanket

It can also be concluded that the design of layered structures to block infrared radiation by modelling thermal resistance has an acceptable agreement with the experiment.

Conclusions

1. The theoretical foundations and mathematical functions for modelling the thermal resistance of layered structures for blocking infrared radiation are developed. The limits of application of mathematical functions for calculating the processes of thermal energy transfer due to thermal conductivity and radiant heat transfer are shown. The use of glass fibre for blocking infrared radiation is substantiated.
2. The thermal resistance of layered structures was modelled using COMSOL tools. It is shown that this toolkit is suitable for designing thermal protection for any purpose. Correct modelling requires data on the thermal and physical characteristics of the materials of each layer of the layered structure. The results obtained allow us to determine the dynamics of heat transfer processes in space and time.
3. The simulation results were verified using a three-layer structure based on glass fibre. Comparison of theoretical and experimental results shows their acceptable convergence. It is determined that the predominant mechanism of blocking infrared radiation in glass fibre is scattering of radiation even by a thin layer of material. This opens up the possibility of using glass fibre-based materials as infrared camouflage.

REFERENCES

1. *Umar Nawaz Bhatti, Salem Bashmal, Sikandar Khan, Rached Ben-Mansour.* Numerical modeling of standing wave thermoacoustic devices–A review: Modélisation numérique des dispositifs thermoacoustiques à ondes stationnaires–Une revue//International Journal of Refrigeration,V. 146, 2023, p. 47-62, https://doi.org/10.1016/j.ijrefrig.2022.09.024.
2. *Yahya Sheikh, Mohammad O. Hamdan, Said Sakhi.* A review on micro-encapsulated phase change materials (EPCM) used for thermal management and energy storage systems: Fundamentals, materials, synthesis and applications.// Journal of Energy Storage, V. 72, Part C, 2023, 108472, https://doi.org/10.1016/j.est.2023.108472.
3. *Łach Ł, Svyetlichnyy D.* 3D Model of Heat Flow during Diffusional Phase Transformations. // Materials. 2023; 16(13):4865. https://doi.org/10.3390/ma16134865
4. *Nairn, J.A.*Modeling heat flow across material interfaces and cracks using the material point method. // Comp. Part. Mech. 6, 133–144 (2019). https://doi.org/10.1007/s40571-018-0201-z
5. *Qu, Y., Li, Q., Cai, L. et al.* (2018). Thermal camouflage based on the phase-changing material GST.// Light Sci Appl 7, 26. https://doi.org/10.1038/s41377-018-0038-5
6. *Jeong, SM., Ahn, J., Choi, Y.K. et al.* (2020). Development of a wearable infrared shield based on a polyurethane–antimony tin oxide composite fiber. // NPG Asia Mater 12, 32. https://doi.org/10.1038/s41427-020-0213-z
7. *Foda E, Sirén K.* A new approach using the Pierce two-node model fordifferent body parts. // International Journal of Biometeorology. 2011. № 55(4). P. 519–532.
8. *Davoodi F, Hasanzadeh H, Zolfaghari S. A, Maerefat M.* Developing a new individualized 3-node model for evaluating the effects of personal factors on thermal sensation. // Journal of Thermal Biology. 2017. № 69. P. 1–2.
9. *Potter A. W, Blanchard L. A, Friedl K. E, Cadarette B. S, Hoyt R. W.* Mathematical prediction of core body temperature from environment, activity, and clothing: The heat strain decision aid (HSDA). // Journal of Thermal Biology. 2017. №64. P. 78–85.
10. *E.M. Sparrow, R.D. Cess* (2017). Radiation Heat Transfer. Augmented Edition. Routledge, 361 p. http://doi.org/10.1201/9780203741382

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Глива В.А., Бурдейна Н.Б., Левченко Л.О., Краснянський Г.Ю., Бірук Я.І., Довгановський М.О.

МОДЕЛЮВАННЯ ТЕРМІЧНОГО ОПОРУ ШАРУВАТИХ СТРУКТУР ДЛЯ БЛОКУВАННЯ ІНФРАЧЕРВОНИХ ВИПРОМІНЮВАНЬ

Забезпечення високого термічного опору будівельних, облицювальних, оздоблюваних та інших матеріалів сприяє вирішенню задач енергоефективності споруд та енергозбереження в цілому. Зазвичай будівельні і облицювальні конструкції мають декілька шарів. Це ускладнює прогнозування їх теплопередачі. Для вирішення цих задач запропоновано здійснення моделювання термоопору шаруватих структур. Визначено математичні функції, які доцільно застосувати при моделюванні. Зокрема відокремлені механізми теплопередачі за рахунок теплопровідності й променевої теплопередачі. Визначено прийнятні за похибками припущення й спрощення у розрахунках. Теоретично обгрунтовано застосування скловолокон для блокування інфрачервоних випромінювань. Здійснено моделювання термічного опору шаруватої структури з довільною кількістю шарів та різними теплофізичними властивостями кожного шару. Моделювання здійснювалося із застосуванням засобів COMSOL. Отримано зміни теплового стану шаруватої структури у просторі і часі. Проведено верифікацію результатів моделювання. Було виготовлено зразки матеріалів на основі склотканини й випробувано їх з використанням стандартного тепловізора. Встановлено, що такий тришаровий матеріал на основі склотканини фактично повністю блокує інфрачервоне випромінювання за вихідної температури до 40 °C. Порівняння отриманих результатів з ефективністю стандартного теплоізоляційного виробу свідчить, що переважним механізмом блокування інфрачервоного випромінювання у виробі на основі скловолокон є розсіювання інфрачервоного випромінювання. Це відкриває можливість для застосування склотканин як для підвищення термічного опору будівельних та оздоблювальних матеріалів, так і для виготовлення інфрачервоного камуфляжу.

Ключові слова: термічний опір, моделювання, інфрачервоне випромінювання, теплопровідність.

Glyva V.A., Burdeina N.B., Levchenko L.O., Krasnianskyi G.Y., Biruk Y.I., Dovhanovskyi M.O.

MODELLING THE THERMAL RESISTANCE OF LAYERED STRUCTURES FOR BLOCKING INFRARED RADIATION

Ensuring high thermal resistance of building, cladding, finishing and other materials helps to solve the problems of energy efficiency of buildings and energy saving in general. Typically, building and cladding structures have several layers. This makes it difficult to predict their heat transfer. To solve these problems, it is proposed to model the thermal resistance of layered structures. The mathematical functions that should be used in modelling are determined. In particular, the mechanisms of heat transfer due to thermal conductivity and radiant heat transfer are separated. The assumptions and simplifications in the calculations that are acceptable in terms of errors are determined. The use of glass fibres for blocking infrared radiation is theoretically substantiated. The thermal resistance of a layered structure with an arbitrary number of layers and different thermal properties of each layer was modelled. The modelling was carried out using COMSOL tools. Changes in the thermal state of the layered structure in space and time were obtained. The modelling results were verified. Samples of materials based on glass fibre were manufactured and tested using a standard thermal imager. It was found that such a three-layer glass fibre material actually completely blocks infrared radiation at an initial temperature of up to 40 °C. Comparison of the results with the efficiency of a standard thermal insulation product shows that the predominant mechanism for blocking infrared radiation in a glass fibre-based product is the scattering of infrared radiation. This opens up the possibility of using glass fibre fabrics both to increase the thermal resistance of building and finishing materials and to produce infrared camouflage.

Keywords: thermal resistance, modelling, infrared radiation, thermal conductivity.

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Глива В.А., Бурдейна Н.Б., Левченко Л.О., Краснянський Г.Ю., Бірук Я.І., Довгановський М.О. **Моделювання термічного опору шаруватих структур для блокування інфрачервоних випромінювань** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА. 2024. – Вип. 113. – С. 329-336. – Англ.

Розроблено теоретичні засади і проведено моделювання термічного опору шаруватих структур з довільною кількістю шарів та різними теплофізичними властивостями кожного шару для блокування інфрачервоних випромінювань. Це дозволяє застосовувати матеріали на основі скловолокна як для підвищення термічного опору будівельних, облицювальних та оздоблювальних матеріалів, так і для виготовлення інфрачервоного камуфляжу.

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The theoretical foundations and modelling of the thermal resistance of layered structures with an arbitrary number of layers and different thermal properties of each layer to block infrared radiation have been developed. This makes it possible to use glass fibre-based materials both to increase the thermal resistance of construction, cladding and finishing materials and to produce infrared camouflage.

Fig. 5. Ref 10.

Автор (науковий ступінь, вчене звання, посада): доктор технічних наук, професор, завідувач кафедри фізики КНУБА, ГЛИВА Валентин Анатолійович

Адреса робоча: 03037 Україна, м. Київ, проспект Повітряних сил, 31, Київський національний університет будівництва і архітектури

Робочий тел.:+38(044) 241-54-40

E-mail: glyva.valentin@gmail.com

ORCID ID: https://orcid.org/0000-0003-1257-3351

Автор (науковий ступінь, вчене звання, посада): доктор технічних наук, доцент, професор кафедри фізики КНУБА, БУРДЕЙНА Наталія Борисівна
Адреса робоча: 03037 Україна, м. Київ, проспект Повітряних сил, 31, Київський національний університет будівництва і архітектури
Робочий тел.:+38(044) 241-54-40
E-mail: burdeina.nb@knuba.edu.ua
ORCID ID: https://orcid.org/0000-0002-2812-1387

Автор (науковий ступінь, вчене звання, посада): доктор технічних наук, професор, професор кафедри цифрових технологій в енергетиці Національного технічного університету України «Київський політехнічний інститут імені Ігоря Сікорського», ЛЕВЧЕНКО Лариса Олексіївна
Адреса робоча: 02000 Україна, м. Київ, вул. Політехнічна, 6
Робочий тел.:+38(044) 204-80-90
E-mail: larlevch@gmail.com
ORCID ID: https://orcid.org/0000-0002-7227-9472

Автор (науковий ступінь, вчене звання, посада): кандидат фізико-математичних наук, доцент кафедри фізики, КРАСНЯНСЬКИЙ Григорій Юхимович
Адреса робоча:03037 Україна, м. Київ, проспект Повітряних сил, 31, Київський національний університет будівництва і архітектури
Роб. тел.+38(044) 241-54-40
E-mail: krasnianskyi.giu@knuba.edu.ua
ORCID ID: https://orcid.org/0000-0002-2421-1270

Автор (науковий ступінь, вчене звання, посада): доктор філософії, доцент кафедри фізики, БІРУК Яна Ігорівна
Адреса робоча:03037 Україна, м. Київ, проспект Повітряних сил, 31, Київський національний університет будівництва і архітектури
Роб. тел.+38(044) 241-54-40
E-mail: biruk.iai@knuba.edu.ua
ORCID ID: https://orcid.org/0000-0002-3669-9744

Автор (науковий ступінь, вчене звання, посада): аспірант кафедри технологій захисту навколишнього середовища і охорони праці, ДОВГАНОВСЬКИЙ Максим Олександрович
Адреса робоча:03037 Україна, м. Київ, проспект Повітряних сил, 31, Київський національний університет будівництва і архітектури
Мобільний тел.:+380982434680
E-mail: dovhanovskyi_mo-2022@knuba.edu.ua
ORCIDID: https://orcid.org/0009-0006-2064-805X