COMPUTATIONAL STUDIES OF THE THERMAL STRESS STATE OF MULTILAYER GLAZING WITH ELECTRIC HEATING

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Ensuring the efficient and reliable safe operation of ground special equipment of various types, aircrafts is an important and urgent problem. Preservation of the strength, protective properties and transparency of the glazing of machinery cabins in a wide range of temperatures under various strength influences is one of the key components of this problem. Multilayer packages made of different types of glass are used for special equipment glazing. These packages are connected to each other with adhesive polymer materials. Electrically heated glazing, which allows to avoid the special equipment icing, as well as to protect the viewing area from fogging, is used for reliable and failure-free operation of special equipment at low temperatures. Based on this, an important problem that affects the efficiency of the use of special equipment is to ensure the reliable operation of electric glass heating. With the help of a software package developed on the basis of the finite element method for the analysis of the structures thermal stress in 3D formulation, which allows to consider a wide class of practical problems of varying complexity, the problems of non-stationary and stationary thermal conductivity and thermal elasticity for a trapezoidal frontal electrically heated multilayer glazing are solved. A study of the thermal stress state of glazing with an electric heating system, which allows to avoid freezing of glass operating at low temperatures, was carried out. The reasons for which the delamination of the multilayer glazing may occur (impermissible temperature modes, mechanical strength effects, violation of operating conditions) are determined. Multilayer glazing with an electric heating system is used for aircrafts, military equipment, land transport, which can be operated at different temperatures. In view of this, the study of their thermal stress state and determination of possible causes of delamination allows to ensure the operation reliability and increase the efficiency of the use of special equipment in different climatic conditions. It is planned to carry out further studies of the glass block thermal stress state taking into account the thermostat operation and determining the temperature sensors location points, as well as changes in the physical properties of materials and the power of the heating element with temperature changes.

***Keywords**: multilayer glass, electric heating, icing, temperature fields, thermal stress state.*

Introduction

The most important task in the development of ground special equipment and aircrafts is to ensure their effective and reliable operation. One of the most important components is the preservation of the strength, protective properties and transparency of the cabin glazing in a wide range of temperatures under various strength effects, which are specified in the technical specifications for the product [1–3].

Multilayer packages made of glass (silicate, organic) and connected to each other with adhesive polymer materials are used for glazing of special equipment [4]. Polyvinyl butyral (PVB), ethylene vinyl acetate, polyurethane or ionomers can be used as adhesive materials for glass [5]. Most often, PVB, which has high plasticity and adhesion to glass, is chosen for transport engineering [6].

If, as a rule, triplexes are used for ordinary motor vehicles glazing, then for armored vehicles, civil and military transport aircrafts those are packages with a significantly greater number of layers and, accordingly, package rigidity. To reduce the probability of damage to the carriage by shrapnel and to increase the bullet resistance of the glazing, anti-shrapnel films or an additional layer of polycarbonate can be glued to the outer surface of the inner layer of the package [7, 8].

For reliable and failure-free operation of special equipment at low temperatures, electrically heated glazing is used, which prevents its icing [9, 10]. Such glass protects the viewing area from fogging and getting covered with frost. Based on this, ensuring the reliable operation of electric glass heating is an important problem, the implementation of which affects the efficiency of the use of special equipment.

Electric heating is applied to the inner surface of the outer layer of glass [9, 10]. The heating element can be of single- or multi-section, film or mesh type. As a rule, the heated segment has a rectangular shape, the corners of the glass remain unheated, which can lead to icing if the electric heating power is insufficient. Fig. 1 shows icing forming on unheated areas of the glass.

Fig. 1. Icing on the glass

The glass must withstand the temperature difference, as there is a difference between it in the cabin and outside, overheating when the thermostat fails, as well as thermal shock when the electric heating is turned on during the cold season. In addition, the outer layer of glass is subjected to significant temperature loads, which is explained by a significant temperature difference along the thickness of the layer and on the surface of the glass near the electric heating zone border, which can lead to the cover glass cracking.

The described phenomenon is typical for the aircraft glazing, where the temperature difference inside and outside the cabin is even higher than in the glazing of ground special equipment. Fig. 2 shows the cover glass cracking that may occur in aircrafts. In addition, glass overheating can lead to boiling of the adhesive layer or a change in its adhesive properties, which can cause a decrease in transparency and even delamination in the case of errors in the glass design and the wrong method of its fastening. At the same time, it is known that the strength of the entire glass block depends significantly on the quality of the adhesive layers.

Fig. 2. Cracks in the cover glass

As shown in papers [6, 11, 12], the mechanical properties and adhesion of PVB depend on the adhesive layer thickness and significantly decrease with temperature increase. Thus, when the temperature increases from 20 ºC to 40 ºC, the tensile strength decreases by almost 4 times for glue with a thickness of 2.28 mm and by about 2 times with a glue thickness of 0.76 mm [11]. Therefore, the glass heating system, as a rule, includes a temperature relay, which prevents overheating of the glass block and strengthening of the contact between the layers. Fig. 3 shows a characteristic defect in the form of delamination, which was formed during the glass operation.

Fig. 3. Glass delamination

In the general case, the multilayer glazing delamination can occur for various reasons: violation of the package manufacturing technology; unacceptable operating temperature modes, which lead to the loss of adhesive properties of the glue; incorrect fastening of the glass block along the contour, etc.

Since electrically heated glass is used for modern aviation equipment and land transport and operates in different climatic conditions, the study of temperature fields and stresses in glazing when the temperature of the surroundings changes is a relevant problem.

In this paper, with the help of original software developed for the analysis of the thermal stress in 3D formulation of structures [13], which allows to consider a wide class of practical problems of varying complexity [14, 15], the problems of non-stationary and stationary thermal conductivity and thermal elasticity are solved for the trapezoidal frontal electrically heated multilayer glazing.
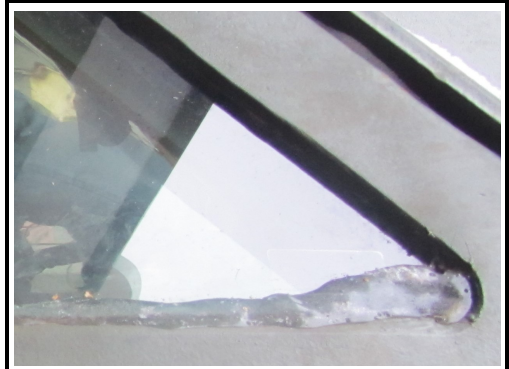
Problem statement

A multilayer package of heated glass is considered, its dimensions (in mm) are shown in Fig. 4. It is needed to add that there are 11 layers of glass in the package, 9 of which have a thickness of 6.44 mm, and the others have a thickness of 2 – 5.8 mm. The glass is glued with a film of polyvinyl butyral with a thickness of 0.36 mm.

The heating element with a power of 90 W and a size of 438×426 mm is located between the first and second layers of glass. The case when the thermostat is missing (or does not work) is considered.
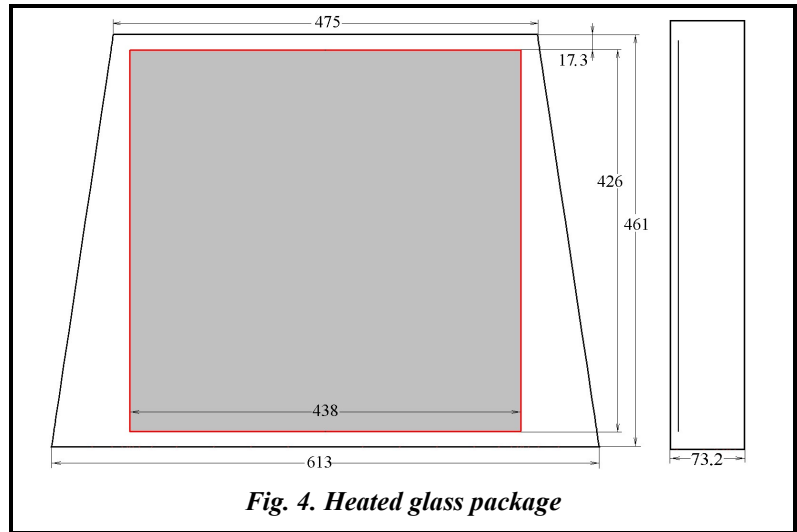

Fig. 4. Heated glass package

The thermophysical characteristics of silicate glass were taken as follows [13]: coefficient of thermal conductivity K_{glass}=0.0161 W/(cm·ºC); volumetric heat capacity ρc_{glass}=1.875 J/(cm³·ºC); for polyvinyl butyral – K_{glue}=0.0017 W/(cm·ºC); ρc_{glue}=1.6 J/(cm³·ºC).

Mechanical characteristics of glass [9] – material density ρ_{glass}=2.5·10⁻⁶ kg·s²/cm⁴; elasticity modulus E_{glass}=64000 MPa; Poisson's ratio ν_{glass}=0.22; coefficient of linear thermal expansion α_{glass}=9·10⁻⁶ 1/ºC; for glue – ρ_{glue}=1.2·10⁻⁶ kg·s²/cm⁴ E_{glue}=280 MPa; ν_{glue}=0.39; α_{glue}=8.3·10⁻⁵ 1/ºC, respectively. It is assumed that at the temperature of 10 ºC there are no residual stresses in the package.

The first layer of glue on the outside contains a thermal element, which is considered as a volumetric heat source [13] with a power of

$$Q = \frac{90}{43.8 \cdot 42.64 \cdot 0.036} = 1.34 \ \text{W/cm}^3.$$

Boundary conditions of heat exchange at the ends of the package were set equal to T_∞=10 ºC, α_T=0.00001 W/(cm²·ºC). From the inside, the heat exchange of the multilayer glazing with air at a temperature of 10 ºC was carried out by natural convection, and from the outside the unit was blown with cold air.

Physical properties of air at a pressure of 760 mm Hg are given in the Table 1 [16], K_{air} – thermal conductivity coefficient, ρ_{air} – density, C_{air} – heat capacity, ν_{air} – kinematic viscosity, $P_{r\,air}$ – Prandtl number.

The heat exchange of a package blown with air at a velocity ω_{air}, m/s, was determined using criteria dependencies [16]:

$$\alpha_{air} = \frac{Nu \cdot K_{air}}{l} \ \text{W/(m}^2\text{·ºC),}$$

Table 1. Physical properties of air depending on temperature

T, ºC	$K_{air} \cdot 10^2$, W/(m·ºC)	ρ_{air}, kg/m³	$C_{p\,air}$, kJ/(kg·ºC)	$\nu_{air} \cdot 10^6$, m²/s	$P_{r\,air}$
-40	2.12	1.515	1.013	10.04	0.728
-30	2.20	1.453	1.013	10.80	0.723
-20	2.28	1.395	1.009	11.79	0.716
-10	2.36	1.342	1.009	12.43	0.712
0	2.44	1.298	1.005	13.28	0.707
10	2.51	1.247	1.005	14.16	0.705
20	2.59	1.205	1.005	15.06	0.703

Table 2. Value of heat exchange coefficients α_{air}, W/(m²·ºC)

ω_{air}, m/s	Air temperature T_{air}, ºC				
	-40	-30	-20	-10	0
1	7.79	7.6	7.3	7.1	7.00
4	23.60	22.9	21.6	21.0	21.00
8	41.10	40.0	38.3	37.4	36.86
16	71.60	69.8	67.0	65.1	64.20

where $Nu = 0.032 \cdot Re^{0.8}$, $Re = \dfrac{\omega_{air} \cdot l}{\nu_{air}}$, Nu – Nusselt number, Re – Reynolds number, l – the length of the wall that is equal to 0,5 m.

The obtained values of the heat exchange coefficients depending on the temperature and air velocity are given in the Table 2.

With natural air convection, the Nusselt number:

$$Nu = 0.15 \cdot \left(G_r \cdot P_r \right)^{0.33},$$

Grashof number G_r

$$G_r = \frac{\beta l^3 g \Delta T}{\nu_{air}^2},$$

where β – temperature coefficient of volume expansion of air, l =0.5 m, g=9.81 m/s^2, ΔT – characteristic temperature drop.

Then $G_r = \dfrac{0.5^3 \cdot 9.81 \cdot 10}{303 \cdot 14^2} = 0.21 \cdot 10^6$,

$Nu = 0.15 \cdot \left(0.21 \cdot 0.705 \cdot 10^5 \right)^{0.33} = 73.2$,

$\alpha_{air} = \dfrac{73.2 \cdot 2.51 \cdot 10^5}{0.5} = 3$ W/(m^2·ºC).
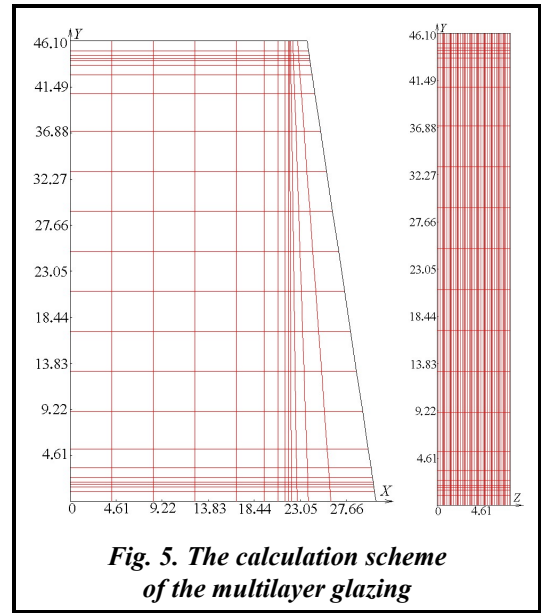

***Fig. 5. The calculation scheme
of the multilayer glazing***

Since the glass structure is symmetrical and the boundary conditions are the same, calculations were performed for half of the package. The calculation scheme of the multilayer glazing with discretization into finite elements is shown in Fig. 5. In the plane X=0, there are boundary conditions of symmetry u_x=0; $\tau_{yz}=\tau_{zx}=0$ – for the mechanics problem, $q=$ – thermal insulation for the thermal conductivity problem.

Primary research results

The non-stationary thermal conductivity problem was solved for the following time values: t=60 s, 120 s, 240 s, 480 s, 900 s, 1800 s, 3600 s, 7200 s. The solution of the stationary thermal conductivity problem was also considered.

It should be noted that the thermal conductivity of the multilayer glazing materials is so low that even after two hours the temperature field is far from stationary. This is also explained by the low power of the heating element. A significant part of the heat from the heating element leaves through the plane, which is blown by air from the outside. In this regard, for each value of the outside air temperature, it is possible to estimate the velocity at which the flow around multilayer glazing will begin to freeze, i.e. the temperature of the external surface in the stationary mode will be equal to 0 ºC. The heating power per 1 m^2 of the surface is:

$$q = \frac{90}{0.438 \cdot 0.4264} = 482 \text{ W/m}^2.$$

The flow of heat through the outer surface in the middle part of the multilayer glazing is equal to [17]:

$$q = \alpha_{air}(t_{glass} - t_{air}) = -\alpha_{air} \cdot t_{air} = 0.0482 \text{ W/cm}^2.$$

Using this ratio, a table of heat exchange coefficients at which icing begins is made (Table 3).

Using the Table 2, it is possible to find the air velocity at which icing will occur by interpolation.

The Nusselt number at which icing of the outer surface of the multilayer glazing will occur is

$$Nu = \frac{\alpha_{air} \cdot l}{K_{air}},$$

the Reynolds number is equal to

Table 3. Values of heat exchange coefficients at which icing begins

T_{air}, ºC	-40	-30	-20	-10	-5	0
α_{air}, W/(m^2·ºC)	12.00	16.08	34.10	48.20	96.00	∞

Table 4. The value of the air velocity at which icing will occur, depending on the temperature

T_{air}, ºC	-40	-30	-20	-10
ω_{air}, m/s	1.72	2.55	4.42	10.61

Table 5. Values of air velocity at which icing will occur, with a power of the heating source of 270 W

T_{air}, ºC	-40	-30	-20	-10
ω_{air}, m/s	6.80	10.06	17.45	42.00

$$Re = \left(\frac{Nu}{0.032} \right)^{1.25} = \left(\frac{\alpha_{air} \cdot l}{K_{air} \cdot 0.032} \right)^{1.25} .$$

Knowing the Reynolds number *Re*, the velocity of the air flow is calculated according to the following relation:

$$\omega_{air} = \frac{Re \cdot \nu_{air}}{l} .$$

The value of the air velocity at which frosting of the outer surface of the multilayer glazing will occur at the power of the heating source of 90 W is given in the Table 4.

The case when during heating the current strength was 10.4 A at a voltage of 26 V was considered as well. In this case, the power of the heating source will be 270 W, which is 3 times more than indicated above. At the same time, the velocity of the air flow at which icing of the outer surface of the multilayer glazing will occur will increase by 3.95 times (Table 5).

The temperature distribution at a wind velocity of 4 m/s and an air temperature of -10 ºC and -20 ºC on the outer surface of the multilayer glazing is shown in Fig. 6 and Fig. 7. And in the layer of the heating element placement, with a power of 90 W, it is shown in Fig. 8 and Fig. 9.

However, it should be emphasized that in the case of natural air convection (at a flow velocity of 0 m/s and a heat exchange coefficient of 5 W/(m²·ºC), for the case when the power of the heating element is 90 W, the temperature of the outer surface of the multilayer glazing at an air temperature of -40 ºC and indefinitely long heating (stationary mode of thermal conductivity) can reach +32 ºC, and in the layer where the heating element is placed it can reach +34 ºC. At an air temperature of +30 ºC, these temperatures can reach +86 ºC and +88 ºC, respectively.

For the case of the heating element with a power of 270 W, these temperatures are much higher and reach 127 ºC, 130 ºC and 197 ºC, 200 ºC, respectively. For PVB, such temperatures are unacceptable, the limit temperatures for PVB are 45–75 ºC. Given this, in order to avoid overheating of the multilayer glazing in the room or at a positive temperature of the outside air, it is advisable to install thermocouples to measure the temperature of the multilayer
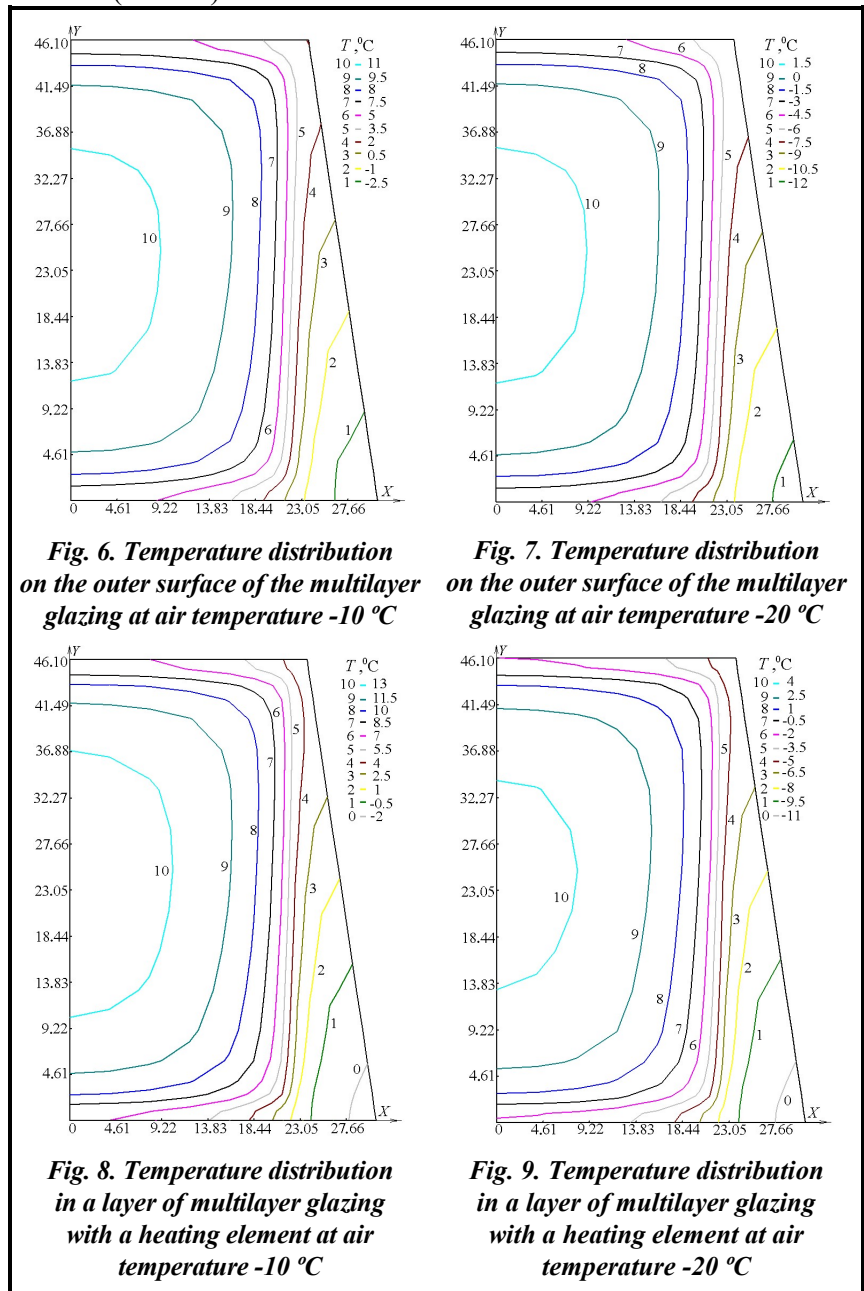

Fig. 6. Temperature distribution on the outer surface of the multilayer glazing at air temperature -10 ºC

Fig. 7. Temperature distribution on the outer surface of the multilayer glazing at air temperature -20 ºC

Fig. 8. Temperature distribution in a layer of multilayer glazing with a heating element at air temperature -10 ºC

Fig. 9. Temperature distribution in a layer of multilayer glazing with a heating element at air temperature -20 ºC

glazing and a relay that would turn off the heating element when the temperature reaches a certain unacceptable value.

Temperature differences in the multilayer glazing are very small, so the level of temperature stress is also low. The maximum tensile thermal stresses in the adhesive layers in the direction of the multilayer glazing thickness are about 0.2 MPa, which does not exceed the permissible value of 40 MPa.

The calculations expected that the physical properties of glass and PVB do not depend on temperature. The change in the resistance of the heating element when the temperature increases or decreases, which affects the power of the heating element, was also not taken into account. In addition, the residual stresses that occur during the manufacture of the multilayer glazing and are summed up with the operational stresses are unknown.

Conclusion

Electrically heated glass is widely used on land transport and aircrafts to avoid icing and fogging of translucent structures. Studying the operation of the electric heating system and the thermal stress state of the glass allows to reduce the risk of the glass damage during operation and choose rational parameters of the electric heating even at the design stage. This is important to ensure reliable and efficient operation of vehicles in various weather conditions.

Calculated studies of the thermal stress state of multilayer glazing with an electric heating system when used in winter and summer conditions were carried out. Calculations were performed for a 21-layer package consisting of 11 layers of silicate glass connected by PVB layers.

It has been established that the glass heats up significantly during long-term electric heating, and this, in turn, leads to overheating of the PVB layer, which is unacceptable, because it can lead to the package delamination, since the adhesive properties of PVB are significantly dependent on temperature, or even to the boiling of PVB, which is manifested in the formation of bubbles in the adhesive layer. Based on this, the glass should be equipped with a thermoregulation system to prevent such overheating.

In the future, it is planned to study the thermal stress state of the glass block, taking into account the thermostat operation and determining the temperature sensors location points, as well as changes in the physical properties of materials and the power of the heating element with temperature changes.

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Розрахункові дослідження термонапруженого стану багатошарового скління з електрообігрівом

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Забезпечення ефективної роботи й надійної безпечної експлуатації наземної спецтехніки різних видів, літальних апаратів є важливою й актуальною задачею. Збереження міцності, захисних властивостей і прозорості скління кабін техніки в широкому діапазоні температур при різних силових впливах – одна із ключових складових цієї проблеми. Для скління спецтехніки застосовуються багатошарові пакети, що виготовляються з різних видів скла, які з'єднуються між собою клейовими полімерними матеріалами. Для надійної й безвідмовної роботи спецтехніки в умовах низьких температур використовується скління з електрообігріванням, що дозволяє уникнути його обледеніння, а також захистити оглядову зону від запотівання. Виходячи з цього, важливим завданням, що впливає на ефективність використання спецтехніки, є забезпечення надійної роботи електрообігріву скла. За допомогою програмного комплексу, розробленого на основі методу скінченних елементів для аналізу тривимірного термонапруженого стану конструкцій, що дозволяє розглядати широкий клас практичних задач різної складності, розв'язані задачі нестаціонарної й стаціонарної теплопровідності й термопружності для трапецієвидного лобового електрообігрівного склопакета. Проведено дослідження термонапруженого стану скління із системою електрообігріву, яка дозволяє уникнути замерзання скла, що працює в умовах низьких температур. Визначені причини, з яких може відбуватися розшарування склопакета (неприпустимі температурні режими, механічні силові впливи, порушення умов експлуатації). Багатошарове скління із системою електрообігріву використовується для літальних апаратів, військової техніки, наземного транспорту, які можуть експлуатуватися при різних температурах. З огляду на це дослідження їх термонапруженого стану й визначення можливих причин розшарування дозволяє забезпечити надійність роботи й підвищити ефективність застосування спецтехніки в різних кліматичних умовах. Планується проведення подальших досліджень термонапруженого стану склоблока з урахуванням роботи терморегулятора і визначенням точок розташування термодатчиків, а також змін фізичних властивостей матеріалів і потужності нагрівального елемента зі зміною температури.

Ключові слова: *багатошарове скло, електрообігрів, заледеніння, температурні поля, термонапруже-ний стан.*

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