Modeling of thermal processes in anti-icing gratings for arctic purposes

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Abstract. The problem of modeling thermal processes in anti-icing gratings, which are used in arctic conditions, is considered. The task is of practical importance, including for the design of air intake grilles for ship systems operating in arctic conditions. A mathematical model of thermal processes is presented, which takes into account the processes of heat transfer in the lattice due to the thermal conductivity of its internal elements, due to convective heat exchange with the external air, due to heat release during electric heating, and also due to phase transformations during icing and melting of ice. The problem is solved in a three-dimensional formulation, using a software package developed at Bauman Moscow State Technical University. Some results of numerical simulation are presented.
Key words: supercomputer, composite structures, finite element.

1 Introduction

At present, the problem of the development of the Arctic territories and the development of the ocean shelf for the extraction of minerals, as well as oil and gas products, has acquired great importance [1-6]. In this regard, an important task for shipbuilding is the creation of special vessels for navigation in high latitudes, including a promising icebreaking fleet. One of the serious problems that designers of Arctic ships have to overcome is the fight against icing of critical parts of ship structures, including air intakes of ventilation and air conditioning systems for residential and industrial premises. When the grilles of ventilation systems are iced up, the cross section of the air intake ducts narrows, the amount of air entering the ship's systems decreases, which can disable them. At present, shipbuilders do not have much experience in designing anti-icing systems for ventilation grilles. The experience of designing systems for heating pipes and tanks for general industrial use, which is available to world leaders in the development of industrial heating systems, is insufficient to fulfill the tasks.

2 The concept of heat exchange in the anti-icing heating system

The concept of creating an anti-icing system for heating air intake grilles based on the electric heating method was chosen, the heat exchange in which is determined by the following main

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heat flows:

- heat exchange inside heat-generating electric heating elements (HGEHE);
- heat exchange between the heat-generating electric heating elements and the housing of the louvre of the air intake grille;
- heat exchange between the louvre housing of the air intake grille, ice formations on the housing and the external environment (air containing water vapor, raindrops, snow formations).

During the operation of the heating system, water formations from melting ice are formed between the ice formations and the louver housing, which, depending on the design features of the heating system and specific operating conditions (placement of the heating system and the air intake grille relative to the vessel, sea rolling, wind load, operation of the propulsion system, etc. .) can be partially removed from the heating zone due to spreading, i.e. under the action of hydrodynamic forces and gravity. Depending on the specific conditions of ice formation on the surface of the louver body, when ice melts and part of the water is removed (spreading), an air gap may form between the water layer and the remaining ice, in which the heat exchange mode changes.

A comprehensive calculation of heat transfer for an anti-icing system is based on a joint solution of mathematical problems of heat transfer for all 3 listed elements.

3 Mathematical model of heat transfer in the anti-icing system for heating air intake grilles

The energy equation for calculating heat transfer in the structural elements of the HGEHE and air intake grille (AIG) has the following form [7]:

$$\rho c_v(\theta)\frac{\partial \theta}{\partial t} = -\vec{\nabla}\cdot\vec{q} + \rho q_m, \tag{1}$$

where θ - is the temperature; ρ - density; $c_v(\theta)$ - heat capacity at constant volume; q_m - density of power of heat release in the heating element (in AIG q_m=0); $\vec{q}$ - is the heat flux density vector for which the Fourier law holds:

$$\vec{q} = -\lambda\cdot\vec{\nabla}\theta, \tag{2}$$

where λ - thermal conductivity tensor, $\vec{\nabla}$ - nabla-operator [8].

As the temperature rises, the thermal conductivity coefficients of λ materials generally increase. The dependence of thermal conductivity coefficients on temperature is generally quite complex, but for most solids, liquids, and gases at moderate temperatures it turns out to be almost linear, i.e.

$$\lambda = \lambda_0\left[1 \pm b\left(\theta - \theta_0\right)\right], \tag{3}$$

where λ_0 — thermal conductivity at temperature θ_0, b — a constant determined experimentally.

The initial condition for the heat equation (1) is to set the temperature at all points of the structure occupying the area G at the moment t = 0, from which the time is counted:

$$\theta(\mathrm{M,t})|_{t=0} = \theta_0(\mathrm{M}), \quad \mathrm{M} \in \mathrm{G}, \tag{4}$$

where θ_0(M)- given function.

The total heat balance on the heated and cooled surfaces of the HGEHE and AIG can be represented as the sum of the flows:

$$q_\Sigma(M) = q_e^0(M) + q_R(M) - q_S(M) \tag{5}$$

where

$$q_e^0 = \alpha(\theta_e - \theta_w)$$

- heat flow describing the convective heat exchange between a solid surface with a cold temperature and the surrounding air, where α – convective heat transfer coefficient, θ_e - temperature of the external air flow;

$$q_R(M) = \sigma_{SB} \int_\Sigma \chi(M,M')\varepsilon(M')\varepsilon(M)\ (\theta^4(M') - \theta^4(M)) \frac{\cos\psi_1(M,M')\cos\psi_2(M,M')}{r(M,M')^2} d\Sigma \tag{6}$$

- the total radiant (radiative) heat flux incident on the surface under consideration from a more heated part of the surface and given off from this area of the surface with temperature θ_W , $\varepsilon(M')$ - coefficient of thermal radiation of the area at point M of the surface, σ_{SB} - Stefan-Boltzmann constant, $\psi_i(M,M')$ - angles of inclination of the thermal radiation beam connecting the points M and M' of the surface $r(M,M')$ - distance from point M to point M', $\chi(M,M')$ - an indicator function that determines the areas of the structure that are in the shadow area with respect to point M;

$$q_S = \dot{m} Q_S \tag{7}$$

- heat flux absorbed due to the effects of ice melting and evaporation of water droplets on the surface, where $\dot{m} = \varphi_A \rho_A \vec{v} \cdot \vec{n}$ - mass rate of occurrence of ice formations on the surface of the structure due to convective motion, Q_S - the total thermal effect of melting and evaporation of ice formations; ρ_A - ice density, φ_A - concentration of ice formations in the oncoming flow, $\vec{v}$ - airflow speed,

$$q_\Sigma = -\vec{n} \cdot \lambda \cdot \vec{\nabla}\theta \tag{8}$$

- heat flow going to heat the material due to thermal conductivity.

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$$q_m = \gamma W_e / V_e, \tag{9}$$

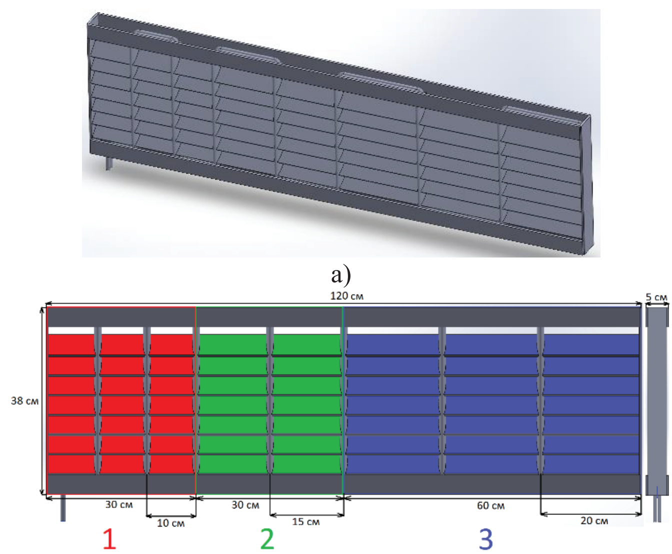
- the heat dissipation power density in the heating element, where W_e - electric power of the heating source, V_e - heating source volume, γ - the thermal equivalent of the transfer of electrical energy into thermal energy.

4 Parameters of the simulated anti-icing grating for arctic purposes

The anti-icing grill consists of 3 elements: a steel body, a heating wire and a quartz sand filler. The filler is located in the space between the wire and the body.

Structure length 120 cm, width 38 cm and height 5 cm. Wire diameter 1 cm.

The design is divided into 3 sections: small, medium and large. Distance between posts: 10 cm, 15 cm and 20 cm, respectively.



a)

b)

Fig. 1. Model of anti-icing grid. a) general view, b) dimensions of the grille and its section (1 - small, 2 - medium, 3 - large).

5 Simulation results

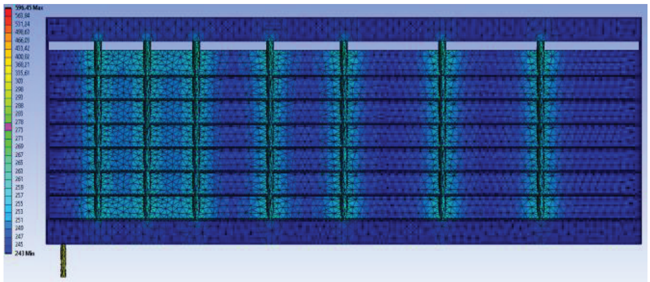
The simulations were carried out using the software systems Ansys and SMCM , developed at the Scientific and Educational Center "Supercomputer Engineering Modeling and Development of Software Systems" of the Bauman Moscow State Technical University. Values of constants taken in calculations

- heat gain q_m = 450 W / kg;

- ambient temperature θ_e =243 °K;

- heat transfer coefficient $\alpha = 5W/(m^2 K)$;

- simulation time $t_{\max} = 14400$ c.



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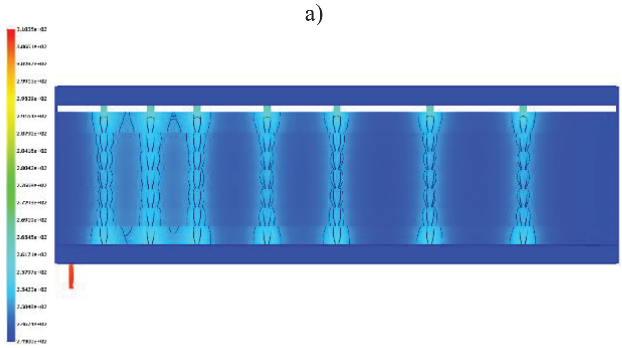

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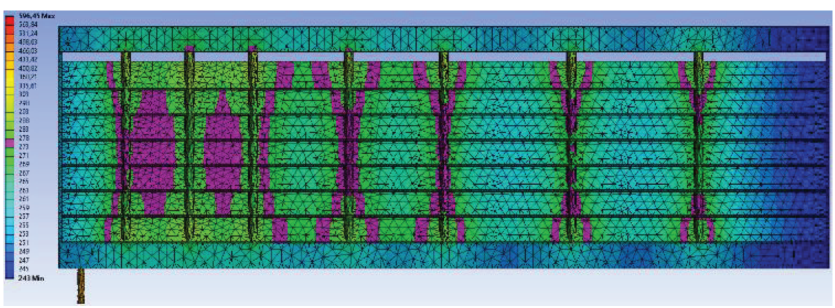
Fig. 2. Simulation results for 720s. a) Ansys b) SMCM.



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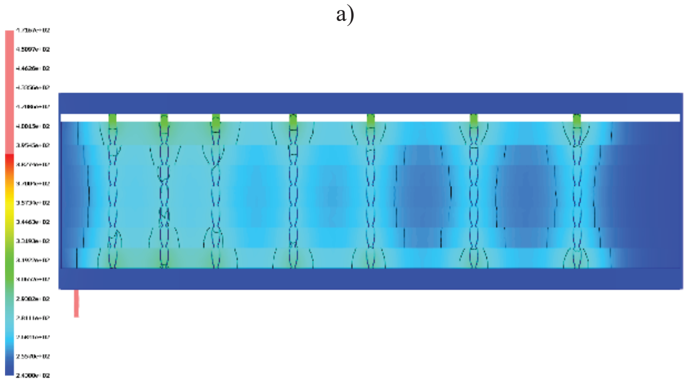

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Fig. 3. Simulation results for 3600s. a) Ansys b) SMCM.

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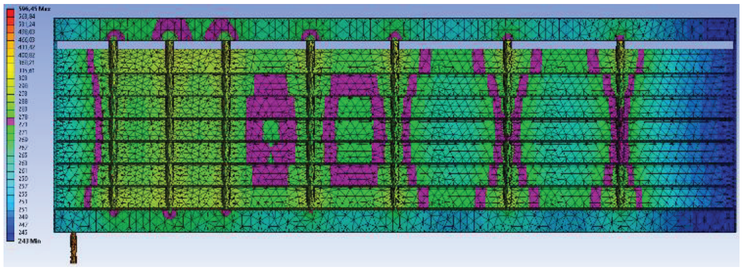

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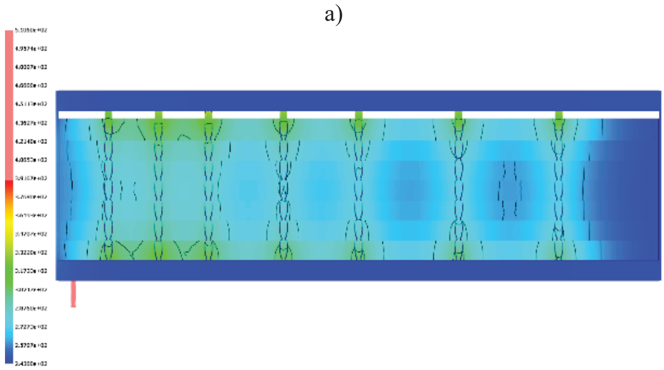

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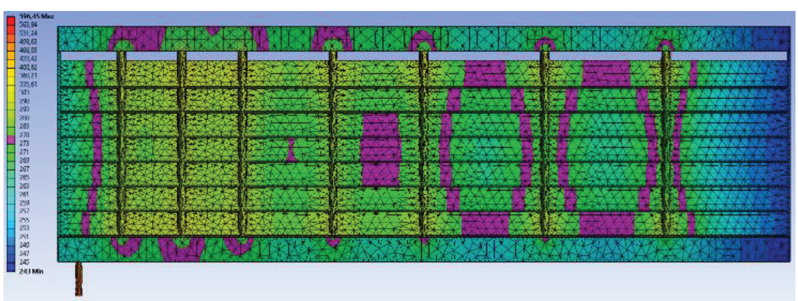
Fig. 4. Simulation results for 5040s. a) Ansys b) SMCM.



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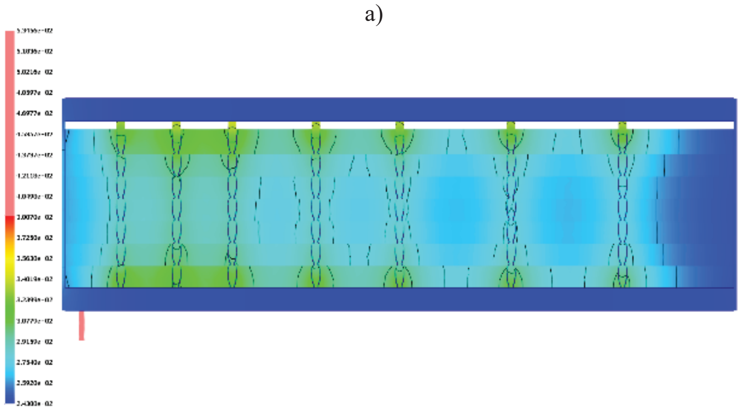

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Fig. 5. Simulation results for 6480s. a) Ansys b) SMCM.

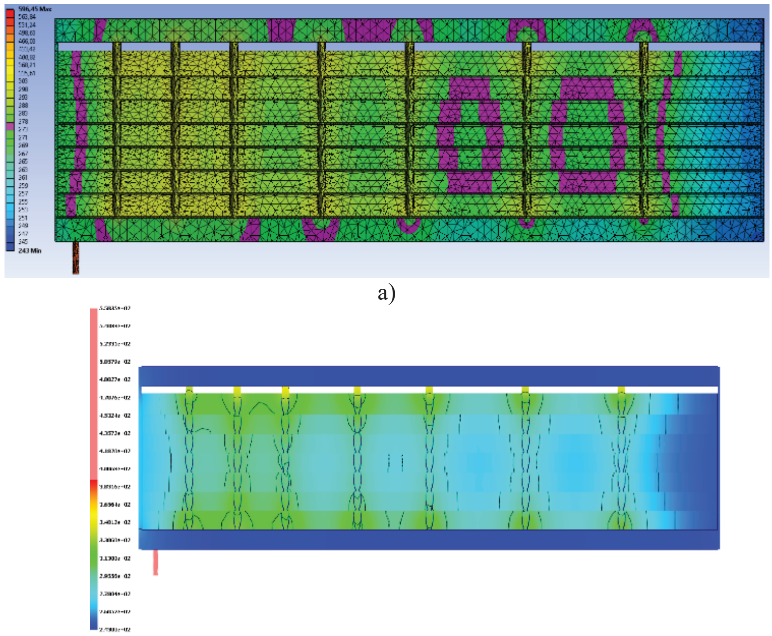

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Fig. 6. Simulation results for 9360s. a) Ansys b) SMCM.

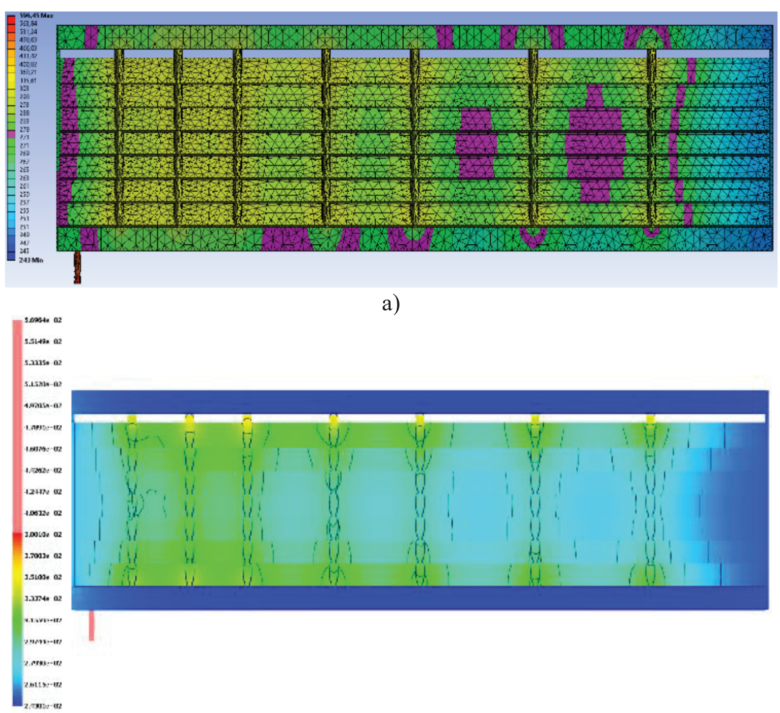

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Fig. 7. Simulation results at 14400s. a) Ansys b) SMCM.

Also, for a more detailed comparison, temperature values were taken from 3 points

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located in each section (Fig. 8).

Fig. 8. Points for taking temperature values (1 - small section, 2 - middle section, 3 - large section).

From the obtained data were built graphs (Fig. 9-11). Time is dimensionless and 1,2,3,…20 is equivalent to 720,1440,2160,…,14400 s.

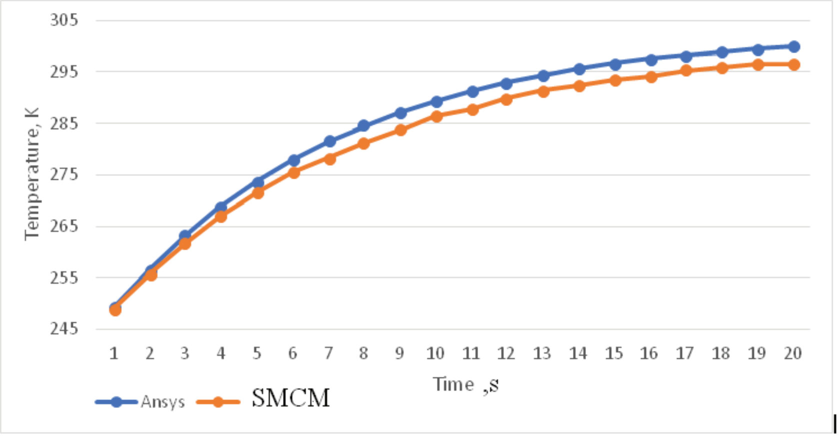

Fig. 9. Graph of comparison of temperature values over time in a small section (Fig. 8).

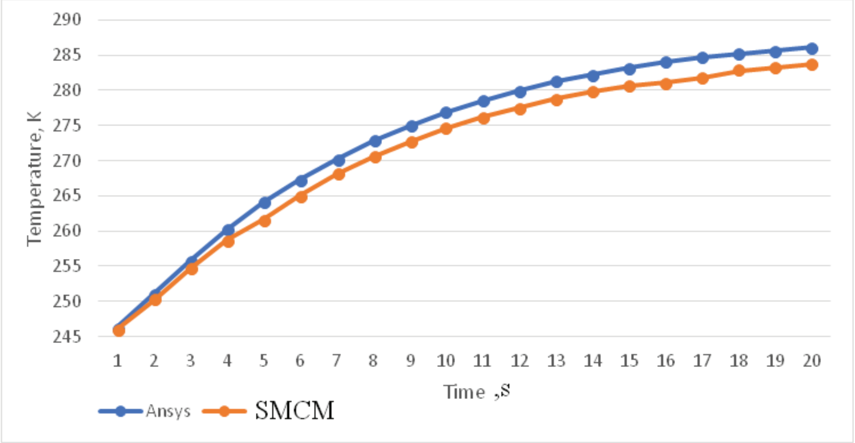

Fig. 10. Graph of comparison of temperature values over time in the middle section (Fig. 8).

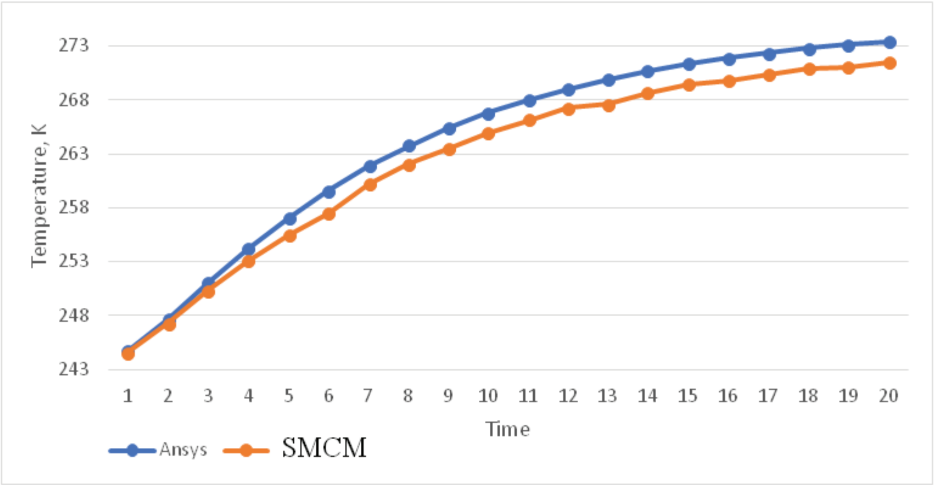

Fig. 11. Graph of comparison of temperature values in time for a large section (Fig. 8).

6 Conclusion

In a result of the work done, the process of heating the anti-icing grid for the Arctic was simulated. Under given conditions, the grille is completely warmed up, which means that icing will not occur on it and, therefore, the amount of incoming air will remain unchanged. The simulation also showed that the large section does not heat up efficiently, unlike the small and medium ones.

With decreasing temperature of cold air from minus 20 to minus 60 ° C, the required power of the electric heater for heating the blinds increases from 315 W/m^3 to 4,500 W/m^3. Changing the heat transfer coefficient from 5 to 10 greatly affects the required electric heating power.

Carried out modeling of heat transfer processes of the heating system at different capacities of HGEHE, made it possible to predict the received temperature, required for the task.

References

1. M. Bhamidipat, Smart Anti-Ice Coating. URL: http://www.virtualacquistitionshowcase.com/document/440/briefing
2. Yu.V. Zakharov, *Ship installations of air conditioning and refrigerating machines* (Shipbuilding, Leningrad, 1972)
3. Yu.I. Dimitrienko, M.N. Koryakov Engineering journal: science and innovation **9** (2013) URL: http://engjournal.ru/catalog/mathmodel/technic/1116.html
4. Z. Tokhtarov, V. Perov, V. Borisov et al, FDMP-fluid dynamics & materials processing DOI: 10.32604/fdmp.2022.019534
5. Yu.I. Dimitrienko, V.Yu. Chibisov, A.G. Kirchanov, Engineering journal: science and innovation **12(48)** (2015) DOI: 10.18698/2308-6033-2015-12-1453
6. A.G. Kirchanov Y.I. Dimitrienko V.Yu. Chibisov, I.K. Krasnov, *Method of Monitoring Icing Louver Air Intake Grille, patent for the invention RUS 2563710* (2014)

7. A.G. Kirsanov, V.V. Korotkov, A.V. Ryzhkov, A.Yu. Gavrilov, *Method of heating ventilation grids with blinds and device for its implementation. Russian patent No. 2474766* (2013)
8. Yu.I. Dimitrienko, *Thermomechanics of Composites Structures under High Temperatures* (Springer, 2015)
9. Yu.I. Dimitrienko, *Tensor analysis and Nonlinear Tensor Functions* (Kluwer Academic Publishers, Dordrecht/Boston/London, 2002)
10. E.Y. Loktionov, E.S. Sharaborova, T.V. Shepitko, Sustainable energy technologies and assessments, DOI: 10.1016/j.seta.2022.102003
11. L. Miao, Y.C. Wang, R. Kavtaradze et al, International journal of heat and mass transfer, DOI: 10.1016/j.ijheatmasstransfer. 2022.122866