Simulation of thermal conditions of anti-icing systems

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Abstract The paper presents the results of modeling the conjugate processes of flow around the cold air flow, heat exchange between the flow and the air intake grating body (AIG) and heating of the structure by the anti-icing system (AIS). Modeling is carried out using a software package developed at the Computational Mathematics and Mathematical Physics Department of Bauman Moscow State technical University. A parametric numerical study of the thermal modes of the AIS at different flow rates and temperatures was carried out, as a result of which the power of the heating system was determined to maintain the temperature of the AIG body in a given mode. The developed method and the results of numerical simulation are used to create the AIS for marine vessels operating in the Arctic, in particular to protect against icing AIG marine ventilation systems for nuclear icebreakers series "Moscow".

Introduction
At present, the problem of the development of the Arctic territories of Russia and the development of the ocean shelf for the extraction of minerals and oil and gas products is of great importance. One of the major problems that designers of Arctic vessels have to overcome is the fight against icing of various critical parts of ship structures, including air intakes of ventilation and air conditioning systems of residential and industrial premises. The icing of the grates narrows the cross-section of the air intake ducts, reduces the amount of air entering the various ship systems and, in some cases, can disable them. For de-icing air-intake grids (AIG) develop special anti-icing system (AIS) heating [1-3]. The problems of modeling the ice accretion processes were considered in [1], but the problem of joint modeling of the processes of flow around the AIG with the AIS cold air flow and heat transfer processes in these systems were not considered. This work is devoted to the modeling of conjugate processes of gas dynamics and heat transfer in the structures of AIG and AIS.

General view and the device of the AIS heating of ship's AIG
Anti-icing heating system of ship's AIG was developed in the scientific and educational center "SIMPLEX" BMSTU together with Bi Pitron (St. Petersburg) "[4-6]. AIS AIG is designed to protect the air intake grilles of marine ventilation systems from icing when exposed to negative temperatures up to 60°C. A fragment of the design of the AIG with the developed AIS is shown in figure 1. AIG is a system of louvers interconnected by the supporting hollow struts, which feature an electric heating cable.
To calculate the heat exchange in the design of blinds with internal heating from electric heaters, it is necessary to calculate the convective heat flow withdrawn from the surface of the blinds when exposed to cold air flow, as well as the calculation of the coefficient of convective heat exchange between the surface of the housing and the cold air flow.

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To model the processes of heat transfer to AIG, we consider the formulation of the conjugate problem of gas dynamics of the air flow around the structure and the thermal conductivity of the wall of the structure with the conditions of internal electric heating. This conjugate problem in the General formulation consists of a system of equations of dynamics of a linearly viscous heat-conducting gas (formed from the continuity equation, equations of motion, equations of energy and determining relations) describing the movement of cold air masses on the surface of the blinds AIG [7-9]:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + p \mathbf{E} - \mathbf{T}_v &= 0, \\
\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + p \mathbf{v} - \mathbf{T}_v \cdot \mathbf{v}) + \mathbf{q} &= 0, \quad \mathbf{x} \in V_1
\end{align*}
\]

(1)

\[
p = R \rho \theta, \quad e = c_v \theta, \quad E = e + \frac{1}{2} |\mathbf{v}|^2, \\
\mathbf{T}_v = \mu_i (\nabla \cdot \mathbf{v}) \mathbf{E} + \mu_v (\nabla \otimes \mathbf{v} + \nabla \otimes \mathbf{v}^T), \\
\mathbf{q} = -\lambda \nabla \theta, \quad \mathbf{x} \in V_1
\]

(2)

Also the equations of thermal conductivity of the body AIG

\[
\rho_s c_s \frac{\partial \theta}{\partial t} = \nabla \cdot (\lambda \nabla \theta), \quad \mathbf{x} \in V_2
\]

(3)

here marked with: \( \rho \) – gas density, \( t \) - is time, \( E \) is the density of full energy of the gas: \( E = c_v \theta + |\mathbf{v}|^2 / 2 \), \( c_v \) — heat capacity of gas at constant volume, \( \theta \) is the gas temperature, \(|\mathbf{v}|^2 = v^i v_i\) - is the square of the modulus of velocity, \( p \) – pressure, \( R \) – gas constant (\( R = R / \mu \) , \( \mu \) – the molecular mass of gas \( R \) - universal gas constant), \( \mathbf{E} \) - is the metric tensor, \( \mathbf{T}_v \) - the tensor of viscous stresses in the gas, \( \mathbf{q} \) - vector of heat flux,
Consider 4 cases of boundary conditions for the system of equations (1)...(3):

a) At the interface $\Sigma_1$ between the areas $V_1$ и $V_2$, which is a solid impermeable wall (surface of the body of the AIG), the conditions of adhesion, the balance of heat flow and the equality of temperatures of the air flow and the solid wall are set:

$$
\mathbf{v} = 0, \quad \lambda \nabla \theta \Big|_{\Sigma_{1-2}} \cdot \mathbf{n} = \lambda \nabla \theta \Big|_{\Sigma_{1+2}} \cdot \mathbf{n} + \varepsilon \sigma \theta_w^4, \quad \theta \Big|_{\Sigma_{1-2}} = \theta \Big|_{\Sigma_{1+2}} \quad (4)
$$

b) At the subsonic boundary $\Sigma_2$, if the air flow inlet to the region $V_1$, 5 conditions are specified:

$$
\rho = \rho_e, \quad \mathbf{v} = \mathbf{v}_e, \quad \theta = \theta_e \quad (5)
$$

c) At the subsonic boundary $\Sigma_3$, air flow out of the area $V_1$, the following 5 conditions are specified:

$$
\rho = \rho_e, \quad \frac{\partial \mathbf{v}}{\partial n} = 0, \quad \frac{\partial \theta}{\partial n} = 0 \quad (6)
$$

where: $\frac{\partial \mathbf{v}}{\partial n} = \mathbf{n} \cdot \nabla \otimes \mathbf{v}$ - the normal derivative of the velocity vector.

d) On the internal (heated) boundary $\Sigma_4$ the solid wall is given the conditions of the heat inflow:

$$
-\lambda_s \nabla \theta \Big|_{\Sigma_4} \cdot \mathbf{n} = q_w \quad (7)
$$

where $q_w$ - the specified heat flux supplied to the electric heating, $\varepsilon_s$ - integral coefficient of thermal radiation of a solid surface, $\sigma$ - Stefan-Boltzmann coefficient.

The initial conditions for the system (1)–(3) have the form:

$$
t = 0 : \quad \rho 0, x^i = \rho_0^0, \quad \mathbf{v} 0, x^i = 0, \quad E 0, x^i = c_s \theta_0^0 \quad (8)
$$

where $\rho_0, \theta_0$ - set value.

**A method for numerical solution of the conjugate problem of gas dynamics, heat exchange and heating of AIG**

The numerical solution of the conjugate problem (1) - (8) was carried out in a model two-dimensional formulation—the normal cross-section of one support pillar of the AIG ASO was considered (Fig.2), in which the solution domains are both bounded by two concentric ellipses.

For the numerical solution of the conjugate problem, the following method was applied: an iterative cycle by "slow" time was introduced $\bar{T} = t / t_0$, corresponding to the process of heat propagation in the wall of the structure of the AIG, where $t_0$ - characteristic heating time of the structure. Within this cycle, a "fast" time was introduced $\bar{\tau} = t / t_f$, where $t_f$ - characteristic setting time of the gas flow. At each n-th step of the slow-time iteration $\bar{T}(n)$ the calculation was carried out in 5 stages: 1) select the temperature $\theta_w^{(n)}$ the surface of the structure at the n-m step, with this temperature by establishing the solution of the system of equations of gas dynamics (1), (2) with boundary conditions (5), (6), and instead of (4) set the conditions
\[ \mathbf{v} = 0, \quad \theta_{\mid_{\Gamma_{1}}(n)} = \theta_{w(n)} \]  

(9)

1) as a result, the gas, including temperature \( \theta_e \) on the external conventional boundary of the wall, as well as the heat flow from the air to the solid surface of the structure \( q_- = -\lambda \nabla \theta_{\mid_{\Gamma_{1}}(n)} \cdot \mathbf{n} \).

2) heat transfer coefficient \( \alpha = \frac{q_-}{\theta_e - \theta_{w(n)}} \), 3) the heat balance equation on the solid surface of the AIG structure (the second equation of the system (4)) was compiled, which was considered as a nonlinear algebraic equation for calculating the temperature \( \theta_{w(n+1)} \) surfaces in the next iteration step:

\[ \alpha (\theta_e - \theta_{w(n+1)}) = \alpha_s (\theta_{w(n+1)} - \theta_0) + \varepsilon \sigma \theta^4, \]  

(10)

where we have used Newton's equation for heat flow \( q_- = \alpha (\theta_e - \theta_{w(n+1)}) \) and \( q_+ = \alpha_s (\theta_{w(n+1)} - \theta_0) \), where \( \alpha_s \) - the heat transfer coefficient in a solid wall, the calculation method of which is described below; 4) the heat equation (3) with the boundary condition of the given temperature was solved \( \theta_{\mid_{\Gamma_{1}}(n+1)} = \theta_{w(n+1)} \). Then the transition to the next (n+1) step of the iterative cycle was carried out.

**Optimization of the AIS design based on the results of numerical modeling**

Were carried out several series of numerical simulations of the variant of warm-up designs shutters blinds AIG with AIS. The following parameters were varied: cold air temperature in the range \( \theta_e = -10\ldots -50^\circ \)C; flow rate of cold air in the range of 5 to 20 m/s; the power of the electric heater W, falling on 1 element of the AIS lattice, in the range from 100 to 1000 watts.

**Figure 2**-the Calculated temperature field of the air flow flowing around the design of the blinds AIG at a temperature of cold air a) \( \theta_e = -30^\circ \)C, air flow rate 20 m/s and heat flow density of the electric heating system \( q_w = 210 \text{ W/m}^2 \), b) \( \theta_e = -50^\circ \)C, air flow rate 20 m/s and \( q_w = 670 \text{ W/m}^2 \).
The heat flux density values were varied in the calculations \( q_w = \gamma W/S \), where \( \gamma \) - thermal equivalent of electric energy transfer to thermal, \( S \) - the area of the heated surface of the shutters. Some results of numerical simulation are shown in Fig.2. Mathematical modeling of thermal processes in the design of AIG allowed to find the optimal distance between the ribs. When increasing the distance greater than the optimum, the electric heating system does not provide the task - to maintain a positive temperature (+2 °C) on the surface of the AIS.

Some test results are shown in figure 3. It was found that this design of the air intake grating provides its protection from icing at ambient temperatures up to minus 40 °C with the inclusion of one heating cable and up to minus 59.3 °C with the inclusion of two heating cables. The results of bench tests of the prototype of the AIG marine ventilation system confirm the effectiveness of the heating system when it operates at low ambient temperatures up to -59.3°C.

Conclusions
The work on the mathematical modeling of thermal modes of operation of air intake grids with electric heating system allowed to choose the optimal values of the design parameters of the AIS and to establish the most effective modes of electric heating of typical AIG ship ventilation systems at operating temperatures up to -60°C.

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