Control of ship tank heating systems to increase their energy efficiency

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Abstract. An important problem in the operation of icebreakers and Arctic ships is to prevent excessive icing of ballast tanks above the waterline. Uncontrolled ice formation can damage ballast systems and lead to malfunctions of ballast systems during cargo operations. This paper presents an analysis of the dynamics of water temperature in a ballast tank when the heating system is turned on and off. Recommendations on the control algorithm for the heating system that provides maximum energy efficiency are proposed.

1. Introduction
An important task in designing Arctic vessels is to choose the optimal way to control the internal icing of ballast tanks. Excessive ice formation in ballast tanks can be prevented by various methods, of which the most important are water heating and enhancing water circulation in the tank (air and steam bubbling, forced water circulation).

Previously [1], a comparative analysis of the energy efficiency (the energy efficiency criterion was the total heat flux on the ice surface providing a given ice thickness in relation to the power required for the operation of the system) of recuperative heat exchange, air bubbling, and forced circulation of water has been made, showing that the most energy efficient anti-icing systems are ballast water circulation and air bubbling systems. However, these systems have several disadvantages. A disadvantage of ballast water circulation systems is the complex design of the circulation circuit and the need to use a high-power pump. Air bubbling systems are easy to operate, but they have limitations when operating ships at very low outside air temperatures.

Ballast water heating is the least energy efficient compared to the other heating methods; however, it remains the most reliable way to prevent icing of ballast tanks under any extreme operating conditions. Based on the results of computational studies [2], the following recommendations have been developed to improve the energy efficiency of the heating system for ship's tanks:

- use of a layer of ice growing on the inner surface of the tank as a means of thermal insulation to ensure a decrease in heat loss from the tank to the environment;
- placing the coils as close to the structural waterline as allowed by their mounting options in order to reduce parasitic losses by reducing the overheating of seawater relative to the freezing point in ballast tanks below the waterline.

The normative point method [3] currently used in the design of heating systems for ship ballast tanks does not allow a correct calculation of the thermal regime of ballast tanks of complex geometric shapes. For the thermal design of such tanks, the use of CFD codes is required. However, modeling ice
accretion and melting by means of CFD codes is a very resource-intensive and time-consuming process which is impossible at the ship design stage.

In this regard, we analyzed the dynamics of water temperature in a ballast tank when the ballast tank heating system is turned on and off.

The objectives of this study were:
- to develop a mathematical model for the temperature dynamics of ballast tanks using different control algorithms (differing in the operating time of the system and heating power);
- to compare different heating options: regular (periodic heating with power determined by the method [3]), heating with constant power, parameter control (power regulation depending on icing);
- to formulate recommendations on the heating system control algorithm that provides maximum energy efficiency.

2. Mathematical model for the dynamics of the parameters of ballast tanks for various control parameters

The method for calculating the unsteady heating of ballast tanks is based on the following assumptions.
1. A three-point model is used (three volumes along the height of the tank, see Figure 1).
2. It is assumed that ice may be present on the entire inner surface of the wall adjacent to the outside cold air and on the upper free water surface (since the maximum filling of ballast tanks is 95% of the initial volume).

The dynamic temperature state and icing are given by the system of equations

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\begin{align*}
\frac{d\delta_{ice_{32}}(t)}{dt} &= \frac{1}{\rho_{ice}} \left( q_{out_{32}}(t) - q_{out_{ice_{32}}}(t) \right); \\
\frac{d\delta_{ice_{33}}(t)}{dt} &= \frac{1}{\rho_{ice}} \left( q_{out_{33}}(t) - q_{out_{ice_{33}}}(t) \right); \\
\frac{dT_1(t)}{dt} &= \frac{1}{M_1 c_p} \left( q_{coil}(t) - q_{ex}^{1-2} - q_{ex}^{2-3} - q_{ex}^{1-2}(\Delta T) - q_{out_{1}}(t)S_{11} \right); \\
\frac{dT_2(t)}{dt} &= \frac{1}{M_2 c_p} \left( q_{coil}(t) - q_{ex}^{1-2} - q_{ex}^{2-3} - q_{ex}^{1-2}(\Delta T) - q_{out_{2}}(t)S_{2} \right); \\
\frac{dT_3(t)}{dt} &= \frac{1}{M_3 c_p} \left( q_{ex}^{2-3} - q_{out_{31}}(t)S_{31} - q_{out_{32}}(t)S_{32} - q_{out_{33}}(t)S_{33} \right),
\end{align*}
\]
where $\delta_{icex}$, $\delta_{icex}$ are the ice thicknesses, $t$ is time, $\rho_{ice}$ is the ice density, $r_{ice}$ is the heat of melting of ice, $q_{out}$ is the heat flux from the wall to outside, $M_t$ is the mass of water in the volume, $c_p$ is the heat capacity of ice, and $Q_{coil}$ is the heat supply.

The heat fluxes between the volumes ($Q_{ex}^{i-f}$) and into the outboard ($Q_{out}$) depend on the temperature difference between the volumes and are shown in Figure 2.

The ice thickness is determined from the condition

$$q_{ice} = q_{out}.$$ 

The heat flux from the water to the ice surface is

$$q_{ice} = \alpha(T - T_{ice}),$$

where $\alpha$ is the heat transfer coefficient, $T$ is the water temperature in the tank.

The heat flux from the ice surface to the outside is

$$q_{out} = \frac{T_{ice} - T_{out}}{R},$$

where $R = $ \frac{1}{a_{out}} + \frac{\delta_{ice}}{\lambda_{ice}} + \frac{\delta_{wall}}{\lambda_{steel}}$ is the thermal resistance, $\delta_{wall}$ is the wall thickness, $\lambda_{ice}$ is the thermal conductivity of sea ice, and $\lambda_{steel}$ is the thermal conductivity of steel.

The values of the heat transfer coefficients for the inner surfaces are taken in accordance with recommendations [4]. The thermal resistance of partitions is $R = \frac{1}{a_{vertical}} + \frac{1}{a_{horizontal}} + \frac{\delta_{wall}}{\lambda_{steel}}$.

3. Simulation of the heating of a typical feed ballast tank

In this section, we consider the icing dynamics for the heating ballast tank of an ice-class vessel (the geometry of the computational domain is shown in Figure 1). The calculations are performed for a typical ballast tank size ($b=0.2$ m, $L=7$ m, $H=0.7$m).

The power of heating system is chosen according to the standard [3]. The initial water temperature in the ballast tank is equal to the seawater temperature (-2°C). The atmosphere temperature is -30°C.

The boundary conditions are
- the adiabatic wall on the plane surface inside the vessel;
- the ship side surface is divided into two parts: above the water line (WL) and on the deck, boundary conditions of the first kind are applied – the temperature is equal to the sea water freezing temperature $T_{ice}$; below the WL (underwater part), boundary conditions of the third kind are applied with outboard water heat transfer coefficient $a_{out}$ and temperature $T_{out}$;
- on the surface of the heating element (coil), a boundary condition of the second kind is applied – heat flux $Q_{coil}$.

4. Analysis of various control algorithms for ballast tank heating systems

Three different operating modes of the heating system are considered.

1. Regular mode: heating is switched on and off every 4 hours, and the system is designed to heat water from -2°C to 4°C [3].
2. Continuous heating with a power that is only 2% of the value required by [3].
3. Heating with power depending on the icing of the inner surface.

The main results are presented in Table 1 and Figure 3.

**Table 1.** Comparison of the three operating modes of the heating system

| Operating mode | Maximum ice thickness, $\delta_{icemax}$, m | Maximum temperature, $T_2$, °C | Amount of heat supplied in 7 days, J |
|----------------|------------------------------------------|-------------------------------|-------------------------------------|
| 1              | 0.005                                    | 72.0                          | $2.2 \cdot 10^{10}$                |
| 2              | 0.1                                      | 0.1                           | $1.3 \cdot 10^9$                   |
| 3              | 0.11                                     | 0.1                           | $1.2 \cdot 10^9$                   |
When using the recommended [3] periodic heating mode of ballast tanks (period of 4 hours), there is significant overheating of ballast water, which leads to an increase in heat loss and a decrease in the energy efficiency of the heating system.

![Graph showing temperature changes](image)

**Figure 3.** Dependence of temperature in the volumes on time for three operating modes of the heating system

5. **Conclusions**

The results of the study show that the regular operation mode of heating ballast tanks [3] is not optimal in terms of energy efficiency.

To improve energy efficiency, it is possible to recommend the operating mode of the ballast tank heating system for Arctic ships with a constant thermal power at the level of 2% of the heating system rated power calculated in accordance with the recommendations [3]. This allows maintaining a constant thickness (maximum allowable) ice on the inner surface of the tanks.

5. **References**

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