Improving the energy efficiency of ship tank heating systems

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Abstract. One of the challenges for creating objects of marine equipment operating in arctic conditions is to prevent freezing of fluids in tanks at extremely low temperatures as it may cause damage to the ship and its systems. This problem can be solved with efficient heating systems for ship tanks. In the paper the ballast tank heating simulation and optimization of heating coil position is discussed. The considered heating coil is typical for icebreakers and ice-class vessels (Arc 5 and above). On the basis of the performed computations the recommendations for improving the energy efficiency of ship heating systems are formulated.

1. Introduction
Due to the active development of the continental shelf of the Russian Federation and increasing importance of the Northern Sea Route, a large number of marine equipment (atomic icebreakers, arctic ships, equipment for offshore mineral resources development) intended for work in arctic conditions is designed and built in Russia.

In the design of marine equipment for operating in arctic conditions the problem of freezing water in ballast tanks above the waterline (WL) has to be considered. Freezing starts from the top and from the side walls (see figure 1) and can lead to ventilation pipes and valves icing [1]. The formation of ice can disrupt the ship’s ballast system operation (cause a problem with the reception and discharge of ballast) and lead to ship destabilization and failure.

Figure 1. Example of ballast tanks freezing [1].

In accordance with the rules of the Russian Maritime Register of Shipping [2], the tanks with ballast and drinking water, which are in contact with the ship hull or rooms with possible temperature below 0°C, must be equipped with the heating systems. A widely used deicing method is to heat
liquids in ship tanks with heating coils, where the heat transfer agent may be steam, water or organic agents.

The heating system calculation is usually carried out in accordance with the Russian guidance document “System for heating liquids in ship tanks. Design rules” [3] proposing the point method of thermal calculation and determining heat transfer coefficients on the internal surfaces of the tank by the classical Mikheev formulas [4]. For heat transfer calculation in guidance document [3] the inversion of water temperature expansion coefficient at temperatures about 0°C is not considered. The same applies to the influence of the tank design features, including the ship framing inside the tank.

On arctic ships, the ballast system includes aft and side tanks. Aft ballast tanks have a rather complex shape (see figure 2) and are equipped with internal permeable walls to reduce fluctuations in the water level in the tank when the ship is rolling. For accurate thermal analysis of such tanks it is necessary to perform the full-scale CFD (computation fluid dynamics) modeling of free-convective flow near cold walls, taking into account tank design features.

The objectives of presented research are:
− to perform the simulation of the ballast tank heating system for arctic ships according to the standard [3] and with full-scale CFD modeling, and to compare and analyze the results;
− to analyze the influence of the heating system design (the coil position) on its energy efficiency.

2. CFD heating simulation for complex shaped ballast tanks
In this section, we consider the heating simulation for an ice-class vessel aft ballast tank of complex shape (the geometry of the computational domain is shown in figure 2). The heating system is designed according to the standard [3]: the water in the ballast tank is heated from -2°C to +2°C with the heating system operating for 4 hours. The initial water temperature in the ballast tanks is -2°C and is equal to the seawater temperature. The outdoor air temperature is -30°C.

Figure 2. Aft ballast tank (computational domain).

Figure 3. Computational mesh (coil).

2.1. Initial data
Numerical simulation of the free-convective flow features near the cold walls is performed taking into account the elements of ship framing (the computational mesh with hexahedral cells is constructed with mesh generator (trimmer) and is shown in figure 3). It is assumed that the tank is completely filled with water.

The calculations are carried out using supercomputer technologies in the Star-CCM+ software. The k-ω SST Menter turbulence model is used. The boundary conditions are
− the adiabatic wall on the deck and on the corresponding diametral plane surface;
− the ship side surface is divided into 2 parts: above the WL the first kind boundary conditions are applied: the temperature is equal to the sea water freezing temperature $T_{ice}$; below the WL
(the underwater part) the third kind boundary conditions are applied with outboard water heat transfer coefficient \( \alpha_{\text{out}} \) and temperature \( T_{\text{out}} \):

- on the surface of the heating element (coil) a boundary condition of the first kind is applied: temperature \( T_{\text{coil}} \).

2.2. Numerical simulation results

The velocity distribution and flow direction in an arbitrary section along the tank are depicted in figure 4. The figure shows the fluid flow through the thin holes in the bulkheads between the spars (the coil is depicted in red color). The average temperature of the tank water rose from -2.14°C to 0.4°C during 4 hours of heating system operation, while the temperature of the fluid at the aft end of the tank remained almost unchanged (about -2°C) (figure 5). According to the standard [3], the average temperature was supposed to rise to +2°C. Thus, it can be concluded that the application of the standard procedure [3] do not allow to correctly calculate the thermal regime of ballast tanks of complex geometric shape.

![Figure 4. Velocity field in arbitrary cross section along the tank.](image)

![Figure 5. Temperature fields in tank volume.](image)

3. Energy efficiency of heating systems

In work [5] it is shown that the presence of an ice layer with a thickness of 0.1 m allows to significantly reduce the heat removal to the environment and, thereby, reduce the heat loss. Thus, we need to maintain the temperature regime of the tank water, which ensures the given ice thickness on the inner surface of the tank contacting with the outdoor air above the WL (below the WL water in tank is always in a liquid state). The thickness of the ice is chosen to ensure ship stability and uninterrupted operations of the ballast system. A constant value of ice thickness is ensured with equal heat flux on the ice surface (see figure 6):

\[ q_{\text{ice}} = q_{\text{in}} = q_{\text{out}}. \]

The heat flux from the water to the surface of the ice is

\[ q_{\text{in}} = T_{\text{in}} \cdot \alpha_{\text{in}}. \]

The heat flux removed from the surface of the ice is

\[ q_{\text{out}} = \frac{T_{\text{ice}} - T_{\text{out}}}{R}, \]

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

Heat loss through the side of ballast tanks below WL \( q_{\text{shipboard}} \) is undesirable. Therefore, the thermal efficiency of the heating system can be defined as
4. Optimization of heating system coil position in side ballast tanks

4.1. Side tanks of arctic ships

The side ballast tanks of arctic vessels have a similar design presented in figure 7. The main geometric features are the presence of a small area in contact with outdoor air (III), and areas below WL (I and II) through which the main heat loss to the environment occurs. The tank is divided by transverse decks into several sections in height, in order to prevent water from oscillation during rolling. The water exchange between sections is carried out through small holes.

The effect of the heating coil positions on the thermal efficiency of the heating system is examined. The heating system coil is fixed near the section flooring (top or bottom). Four positions for installing heating coil in the side ballast tank of a universal atomic icebreaker (UAI) are considered (see figure 7). The calculations are performed in a two-dimensional formulation using the Star-CCM+ software.

![Figure 7. The side tank of the universal atomic icebreaker, coil positions.](image)

![Figure 8. Calculated temperature distribution in the side ballast tank of the UAI for three positions (positions 2, 3, 4 in figure 7) of the heating coils.](image)
4.2. Numerical results

Figure 8 shows the calculated temperature distribution in the ballast tank for three heating system coil positions (2, 3 and 4) after 4 hours of heating system operation. For the coil installation on the bottom of the tank (position 1) in 4 hours of work the heat fluxes in the tank section above the WL providing a predetermined thickness of ice have not been obtained.

Table 1 shows the thermal efficiency \( \eta \) for different coil positions. The table also includes the estimate of the thermal efficiency of the heating system obtained with the point method [3], which does not take into account the division of the tank into sections. From presented results it can be noted that the position of coil on the upper flooring (positions 3 and 4) provides an increase in the thermal efficiency of the heating system by a factor of 2-3 compared with position 2 (which is now implemented in the UAI).

| Coil position | Thermal efficiency of the heating system \( \eta \) | Coil surface temperature, \(^\circ\)C | Average volume temperature in the tank, \(^\circ\)C |
|---------------|-----------------------------------------------|---------------------------------|----------------------------------|
| 2             | 0.310                                         | 56.0                            | +5.70                            |
| 3             | 0.740                                         | 17.0                            | -0.16                            |
| 4             | 0.995                                         | 10.2                            | -1.00                            |
| according to [3] | 0.540            | 37.0                            | +2.00                            |

5. Conclusions

The standard point method [3] fails to correctly calculate the thermal regime of ballast tanks of complex geometric shape. For thermal calculation of such tanks it is necessary to use CFD simulation. On the basis of the performed computations results, it is possible to formulate recommendations for improving the energy efficiency of the heating system of ship tanks:

- the ice layer growing on the inner surface of the tank can be used as thermal insulation, it ensures the reduction of heat loss from the tank to the environment;
- position of heating coil as close as possible to WL (taking into account the coil installation technological limitations) allows reducing “parasitic” heat loss by decreasing overheating of seawater relative to the freezing temperature in ballast tanks below the waterline.

6. References

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