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# NUMERICAL INVESTIGATION ON FREEZING IN BALLAST WATER TANK OF VESSELS OPERATING IN COLD CLIMATE CONDITIONS

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## ABSTRACT

For vessels operating in the cold climate regions, ballast water in side or hopper tanks above the waterline may freeze, starting at the top of the tank and at the side walls. So Hence countermeasures against freeze-up of the ballast tank such as air-bubbling system, hot steam injecting system, heating coil system and water circulating system are taken to prevent freezing phenomenon.
However, there are no rigorous investigation of anti-freezing to examine the effectiveness and validity of systems against freeze-up of the ballast tank, in which the temperature has about -25 ℃ (ambient air temperature) and 0 ℃ (sea water), respectively.
In this paper, to take in ensuring reasonable specifications for cold regions whether measures against freeze-up and to take measures such as above stated systems if there is confirmed to be an actual need to do so, the phenomenon of ballast tank freeze-up is simulated and discussed in low temperature conditions. With the results using the commercial CFD code, CFX, we discuss the most cost-effective solution to prevent freezing along the outer surface.

## INTRODUCTION

The low-temperature of the ice-bound sea through which the vessels are to sail require special measures for the hull structure, the outfittings and etc. Furthermore, in recent years, there has been substantial interest and demand for ships to navigate in cold region. Ships assumed to sail in atmospheric temperatures of about -10 to -20℃ in LMDAT(Lowest Mean Daily Average Temperature) and about -30 to -40℃ in Extreme Temperature fall under this category. So many features fitted to these ships to combat the low temperatures and icing are in addition to ice class requirements, and these are based on experience of operations.
When the rules or regulations are still being defined for the design of outfittings for ships in accordance with specifications for cold districts, various parties propose specific measures to fulfil the requirements. When designing the outfittings, it is crucial to secure safety, reliability,

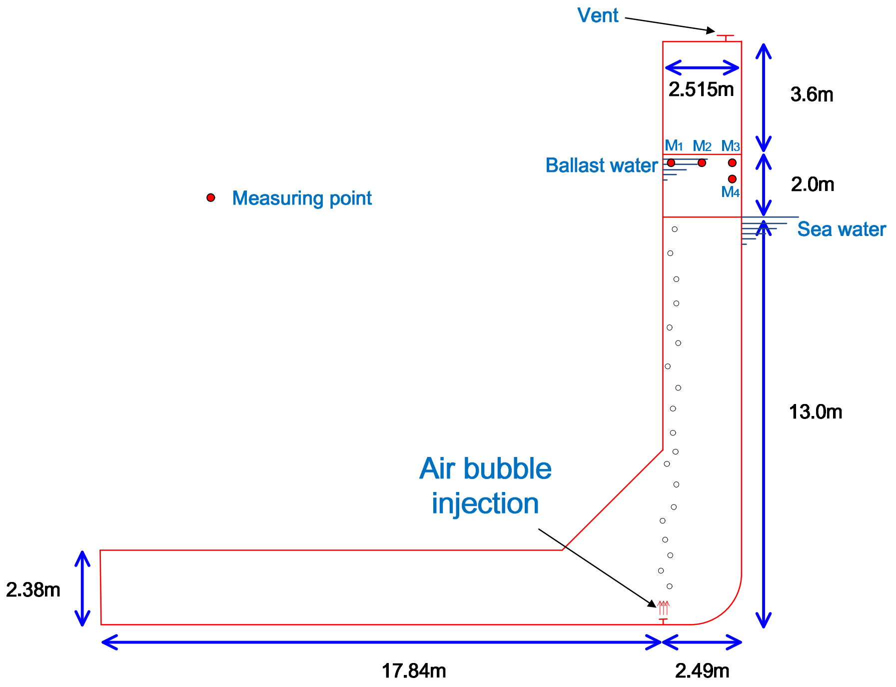
and a reasonable design all at once in a well and reasonably balanced manner according to the required low-temperature environment.
The very cold environment of the Arctic and the Antarctic could cause the ballast water, air and vent pipes, valves and section lines to freeze. It is unlikely that any sizeable tank will freeze solid since ice acts as an insulator; however, ice cannot be discharged when the vessel is loading and causes the deadweight capacity to be reduced.
Arrangements are to be provided to prevent water ballast freezing in tanks adjacent to the shell and located totally or partly above the ballast water line.
There are many systems to prevent ice formation in ballast tanks, and the followings are major to using;

- Heating systems
- Internal circulating / pumping systems
- Air-bubbling systems
- Steam injection systems

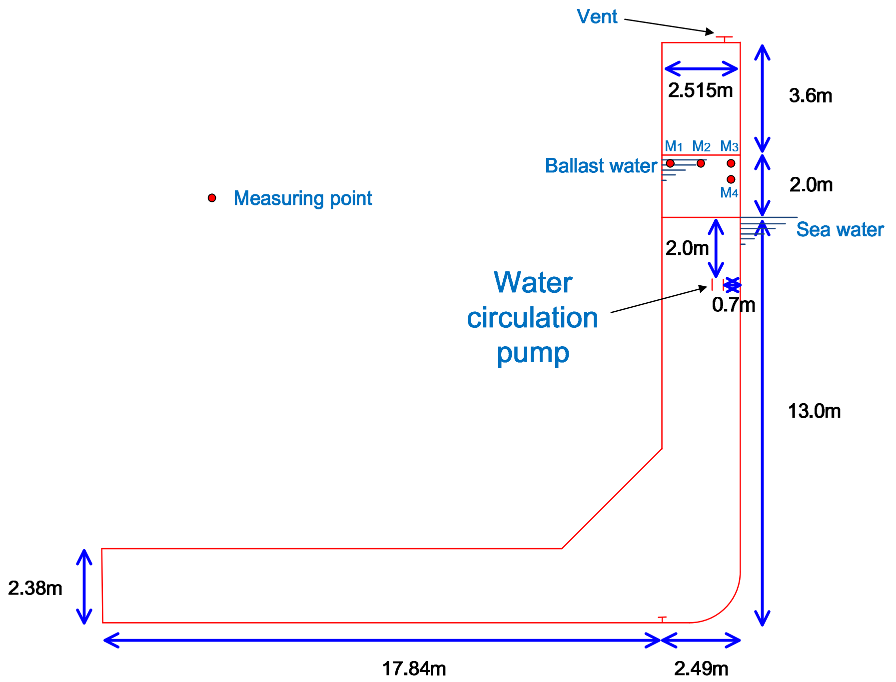
One conceivable method to prevent the ballast water from freezing is to heat it with steam or hot water. But this method would force the customer to invest in expensive measures to prevent water freezing in ballast tanks.
The most effective and commonly used is steam heating coils. The heating coils are usually fitted above the ballast waterline adjacent to the ships side shell. Makkonen(1984) indicates that heating is not practical for anti-icing or de-icing because of the large amount of energy necessary for latent heat. This approach would force the customer to invest in expensive measures to prevent the seawater from corroding the steam pipe, either by using a pipe material with high corrosion resistance from the beginning or by using general steel pipes based on the premise the maintenance during service (Hiramatsu et al.(2007)). Circulating the ballast water is considered an efficient alternative method because of the natural differences in temperatures in the tank. Moreover air bubbling system achieves the same effect as the circulation. Koo et al.(2007) performed numerical simulation to investigate the effectiveness of the air bubbling system used for winterization design concept for ballast tank. Through their results, it became clear that the air bubbling system equipped in each frame of water ballast tanks was effective to prevent freezing along the outer surface by promoting convective heat transfer. Furthermore, Jeong et al. (2011) carried out anti-icing performance tests for the ballast water using micro-bubble system and sea water circulation system at two temperature conditions(-10 ℃ and -25 ℃). Their applied anti-icing techniques such as micro-bubble system and water circulation system were showed good performance in the low temperature conditions.

**Figure 1**. Freezing of ballast water(Danish SNAME seminar, 2008)

In this paper, to take measures such as above stated systems, the air-bubbling system and the water circulating system, whether measures against freeze-up if there is confirmed to be an actual need to do so, the phenomenon of ballast tank freeze-up are simulated and discussed in low temperature environment.




(a) Air bubbling system




(b) Water circulating system

**Figure 2**. Schematic of a ballast tank typical of a container ship. The internal structure of the tank is not drawn

## NUMERICAL MODELLING

The transient numerical simulations of the fluid flow and heat transfer in the analyzed ballast geometries were performed with the CFX 14 commercial code. Figure 2 shows a schematic of a ballast water tank consisting of an air inlet at the bottom, a long base, turning section, vertical rise section and exit port. The shape and intricate internal geometry of the tanks is at present entirely driven by structural consideration of the vessel. The density of sea water depends on both salinity and temperature, but lies typically within a range of 1,024-1,030 kg/m$^3$.

The governing equation used in our numerical study consisted of the 3-dimensional, unsteady, time-dependent continuity, momentum and energy equations. The two-equation *k*-*ε* turbulence model was used to obtain the Reynolds stresses based on the eddy viscosity introduced in the Boussinesq approximation. In general, turbulence models seek to modify the original unsteady Navier-Stokes equations by introducing averaged and fluctuating quantities to produce the RANS equations. The values of *k* and *ε* derived directly from differential transport equations for the turbulence kinetic energy and turbulence dissipation rate are shown in Table 1. The temperature field was calculated using an eddy diffusivity approximation for the turbulent heat flux.

### Governing equations of two-equation turbulence models

The basic transport equations used in the CFX 14 are the continuity equation, the momentum equation and the energy equation presented here for the Newtonian fluid in the time-averaged form:

$$\partial_t \rho + \partial_j(\rho \bar{v}_j) = 0 \tag{1}$$

$$\partial_t(\rho \bar{v}_i) + \partial_j(\rho \bar{v}_j \bar{v}_i) = -\partial_i \bar{p} + \partial_j\left(\mu(\partial_j \bar{v}_i + \partial_i \bar{v}_j) - \frac{2}{3}\mu(\partial_l \bar{v}_l)\delta_{ji}\right) + g(\rho - \rho_{ref}) - \partial_j\left(\rho \overline{v_j' v_i'}\right)$$

$$\partial_t(\rho \bar{h}) + \partial_j(\rho \bar{v}_j \bar{h}) = \partial_j(\lambda \partial_j \bar{h}) - \partial_j\left(\rho \overline{v_j' h'}\right) \tag{2}$$

The set of transport equation is suitable for simulation of low speed flows with variable material properties.

Two-equation turbulence models use the gradient diffusion hypothesis to relate the Reynolds stress tensor in the momentum equation (2) to mean velocity gradients:

$$\rho \overline{v_j' v_i'} - \frac{1}{3}\rho \overline{v_k' v_k'} \delta_{ji} = -\mu(\partial_j \bar{v}_i + \partial_i \bar{v}_j) + \frac{2}{3}\mu_t(\partial_l \bar{v}_l)\delta_{ji} \tag{3}$$

And the Reynolds flux vector to mean temperature gradient:

$$\rho \overline{v_j' h'} = -\frac{\mu_t}{Pr_t}\partial_j \bar{h} \tag{4}$$

In the *k*-*ε* model, the turbulent viscosity $\mu_t$ is modeled as

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{5}$$

Where *k* is the kinetic energy of turbulent fluctuations and *ε* is the turbulence dissipation rate:

$$k = \frac{1}{2}\overline{v_i' v_i'} \text{ and } \varepsilon = \frac{\mu}{\rho}\overline{\partial_j v_i' \partial_j v_i'} \tag{6}$$

Two additional transport equations are expressed for *k* and *ε:*

$$\partial_t(\rho k) + \partial_j(\rho \bar{v}_j k) = (P + G) + \partial_j\left(\left(\mu + \frac{\mu}{\sigma_k}\right)\partial_j k\right) - \rho\varepsilon \tag{7}$$

$$\partial_t(\rho \varepsilon) + \partial_j(\rho \bar{v}_j \varepsilon) = C_1 \frac{\varepsilon}{k} P + \partial_j\left(\left(\mu + \frac{\mu}{\sigma_\varepsilon}\right)\partial_j \varepsilon\right) - C_2 \rho \frac{\varepsilon^2}{k} \tag{8}$$

where *P* and *G* are turbulence kinetic energy production terms. Term *P* represents turbulence production due to shear stress and it is defined as

$$P = \mu_t(\partial_j \bar{v}_i + \partial_i \bar{v}_j)\partial_j \bar{v}_i - \frac{2}{3}\left(\rho k(\partial_l \bar{v}_l) + 3\mu_t(\partial_l \bar{v}_l)\partial_j \bar{v}_i\right)\delta_{ji} \tag{9}$$

The term $G$ describes generation of turbulence due to volumetric forces.

$$G = -\frac{\mu_t}{\rho Pr_t}\left(g_j \partial_j \rho\right) \tag{10}$$

In the standard $k$-$\varepsilon$ model, $C_\mu$, $C_1$, $C_2$, $\sigma_k$, $\sigma_\varepsilon$ and $Pr_t$ are empirically determined coefficients.

**Table 1.** The standard k-ε model coefficients

| $C_\mu$ | $C_1$ | $C_2$ | $\sigma_k$, | $\sigma_\varepsilon$ | $Pr_t$ |
|---|---|---|---|---|---|
| 0.09 | 1.44 | 1.92 | 1.0 | 1.3 | 0.9 |

**Table 2.** Initial conditions for numerical simulation

| | Ballast water conditions | Ambient temperature | Ballast temperature | Sea water temperature |
|---|---|---|---|---|
| Case I | | -25℃ | 0℃ | 0℃ |
| Case II | | -25℃ | 10℃ | 5℃ |
| Case III | Air bubble injection<br>- Mean diameter : 0.006 m<br>- Mass flow rate : 0.006962 kg/s | -25℃ | 0℃ | 0℃ |
| Case IV | Air bubble injection<br>- Mean diameter : 0.006 m<br>- Mass flow rate : 0.006962 kg/s | -25℃ | 10℃ | 5℃ |
| Case V | Water circulation<br>- Nozzle diameter : 0.3 m<br>- Water velocity : 2.0 m/s | -25℃ | 10℃ | 5℃ |

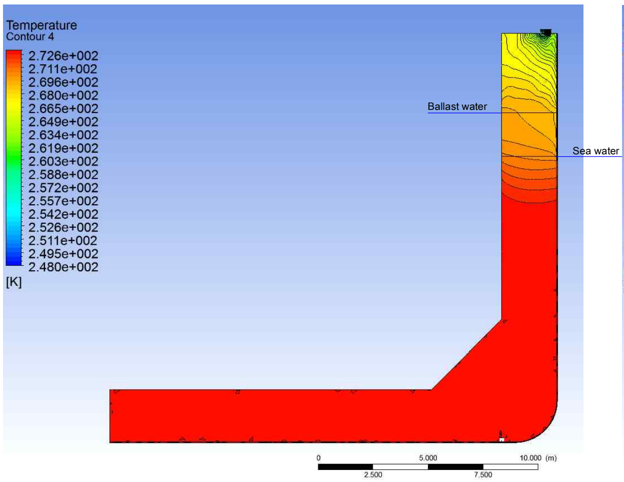
## RESULTS AND DISCUSSION

The freezing point of water depends on salinity i.e. the salt content the water. The greater the salinity, the lower the freezing point fresh water freezes at 0 ℃(32 ˚F). Sea water with salinity of 35 parts per thousand or corresponding gravity of 1.025 freezes at -3℃ or lower (28.6 ˚F).

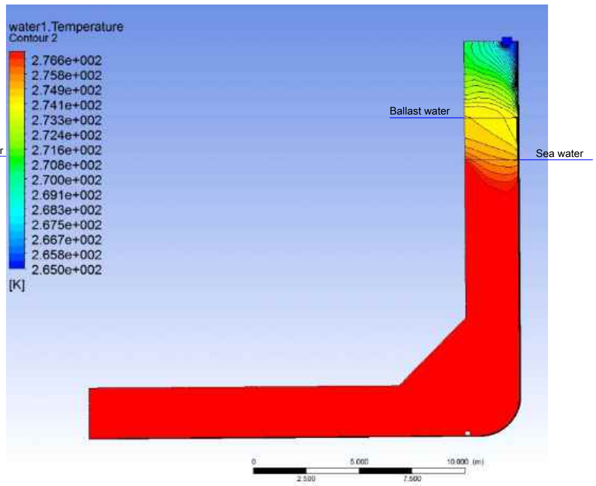
### Effects of air-bubbling system in the ballast tank

The air-bubbling ice-prevention systems keep the water in motion and carry warm water upward from the motion. In this method, the formation of ice on the surface is prevented naturally. To examine the effect of the air-bubbling ice-prevention system, and the water-circulating ice-prevention system, 5 cases were considered, as presented in Table 2. Figures 3(a) to (d) show the numerical observations of temperature field and time variations in the ballast tank, where the time corresponds to 51, 177, 101 and 446 minutes, respectively, after the simulations start. In the figure, Case III and IV in Figs. 3(c) and (d) are the case of anti-freezing equipment such as an air-injected system, and Case I and II in Figs. 2(a) and (b) are not equipped the air bubbling system. Even though the ambient air temperature and sea water are -25 ℃ and around 0 ℃ respectively, the air-bubbling system effectively prevents ballast water from freezing by the circulation of ballast water due to the air bubble trajectories without any heating system, as shown in the Figs. 4(a) and (b).

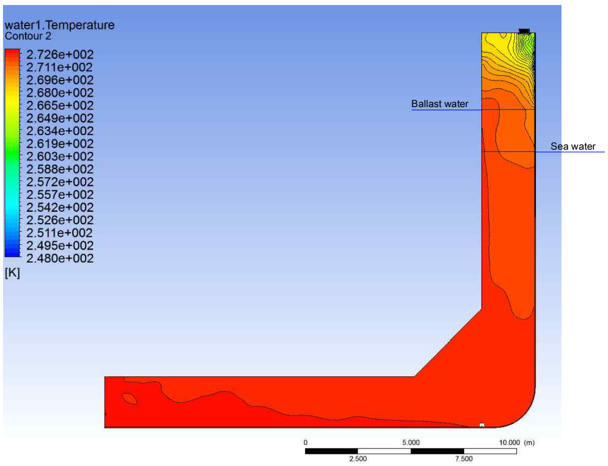
Figures 5(a) and (b) show the flow pattern with velocity vectors for Case I and Case III, respectively. In the Fig. 5(b), to prevent ballast water in a ship navigating in the intense cold area from freezing, by introducing the compressed air through an air nozzle and then discharging it from the bottom of each ballast tank so that cold water in an upper layer is substituted with hot water in a lower layer with the use of convention due to ascending of bubbles produced by discharged compressed air. With this arrangement such as air-bubbling ice-prevention system, it is possible to effectively prevent ballast water in a ship navigating in the cold regions from freezing.



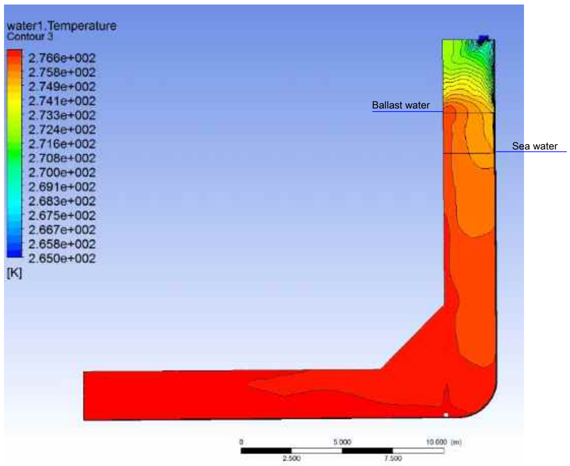

(a) 51 minutes (Case I)




(b) 177 minutes (Case II)



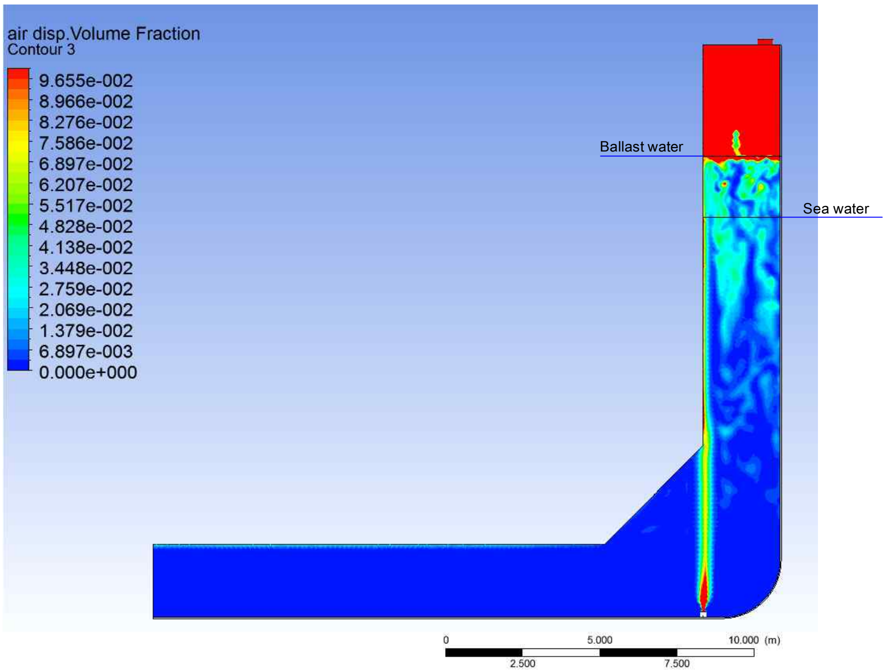

(c) 101 minutes (Case III)



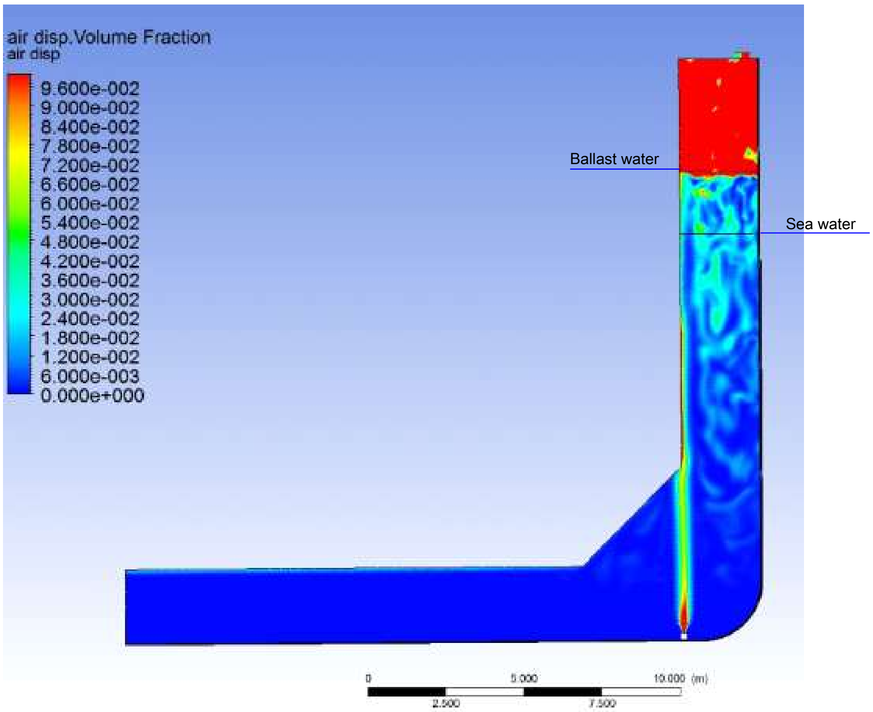

(d) 446 minutes (Case IV)

**Figure 3**. Temperature distributions in ballast tank about 51(Case I), 177(Case II), 101(Case III) and 446(Case IV) minutes after the simulation starts, respectively.

Figure 6 shows the time variations of temperature change at 4 monitoring points, as shown in Fig. 2, after simulations start. In the Case I of Fig. 6(a), the freezing temperature was reached after 46 minutes, but the case with air bubbling system (Case III or Case IV) didn’t drop below freezing sea water temperature in the ballast tank. The reason is that a continuous spouting of air bubbles up from the bottom of the ballast tank effectively prevents blockage of the tank. The force of the air bubbles can be expected to break up ice as it forms. The bubbles also help to melt the ice by bringing up the warmer seawater from the bottom of the tank, as shown in Fig. 4 and Fig. 5(b).

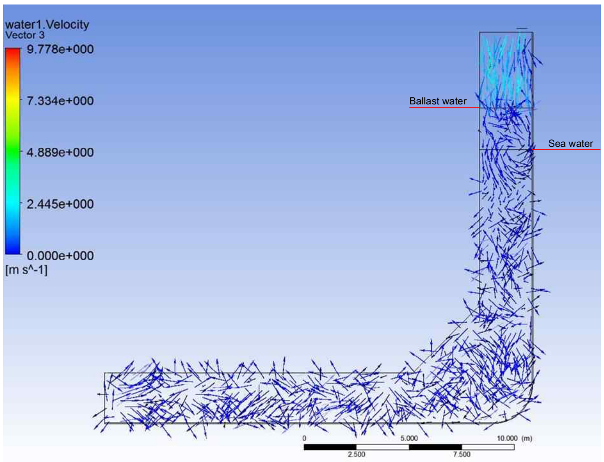



(a) 101 minutes (Case III)

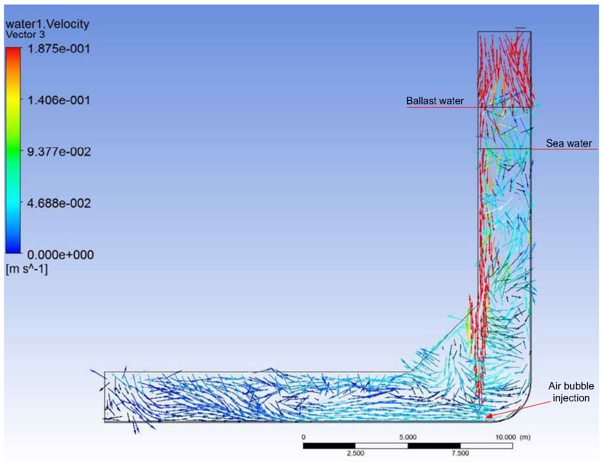



(b) 446 minutes (Case IV)

**Figure 4**. Flow patterns with air volume fraction due to a continuous spouting of air bubbles up from the bottom of the ballast tank. The force of the air bubbles can be expected to break up ice as it forms.




(a) Case I (51 min)



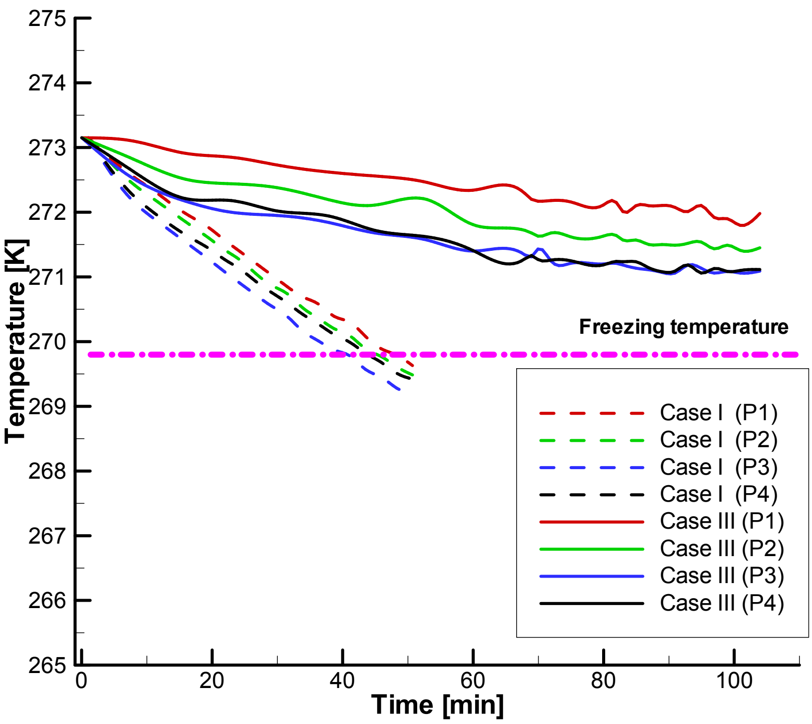

(b) Case III (101 min)

**Figure 5**. Velocity vectors for Case I and Case II, respectively.

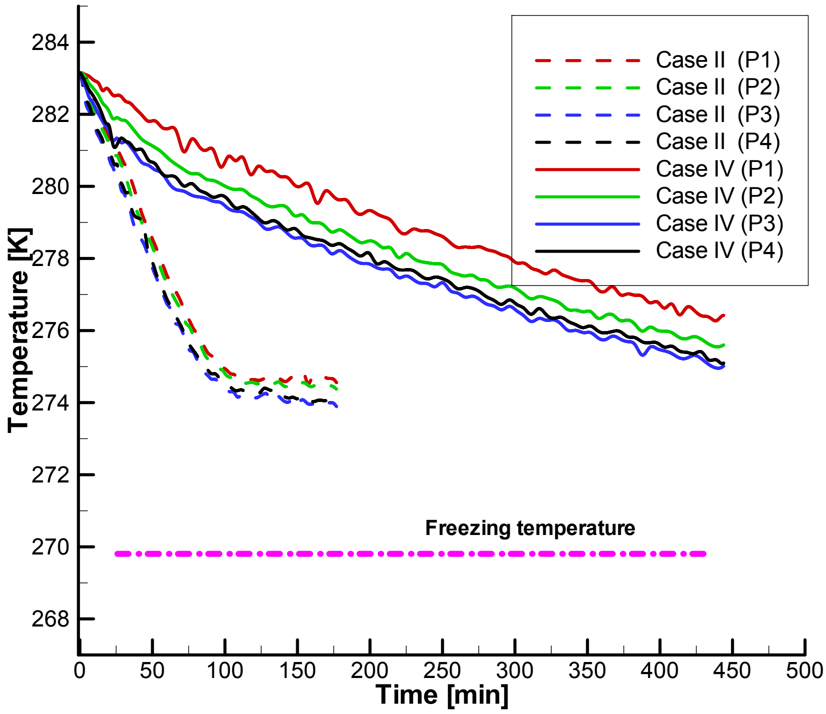
**<u>Effects of the applied ice-prevention systems in ballast tank</u>**

The air-bubbling ice-prevention system and the water-circulating ice-prevention system keep the water in motion and substituted with warm water upward from the motion. Consequently, the surface of water is agitated continuously to prevent the tank from freezing.

Figure 7 shows the time variations for temperature change at 4 monitoring points for the air-bubbling system and the water-circulating system to compare the both system. Moreover, Figs. 8(a) and (b) represent the flow patterns for both cases. In Figs. 8(a) and 9(a), continuous air bubbles up from the bottom of the ballast tank bring up overall the warmer seawater with the force of air bubble, but the water circulating system just circulates at the upper side of ballast tank as shown in Fig. 9(a). Hence the authors believe that the bubble ice-prevention system is more effective than that of the waters circulating.




(a) Case I and Case III (continued)




(b) Case II and Case IV

**Figure 6**. Time variation of temperature change in the ballast tank at 4 monitoring points

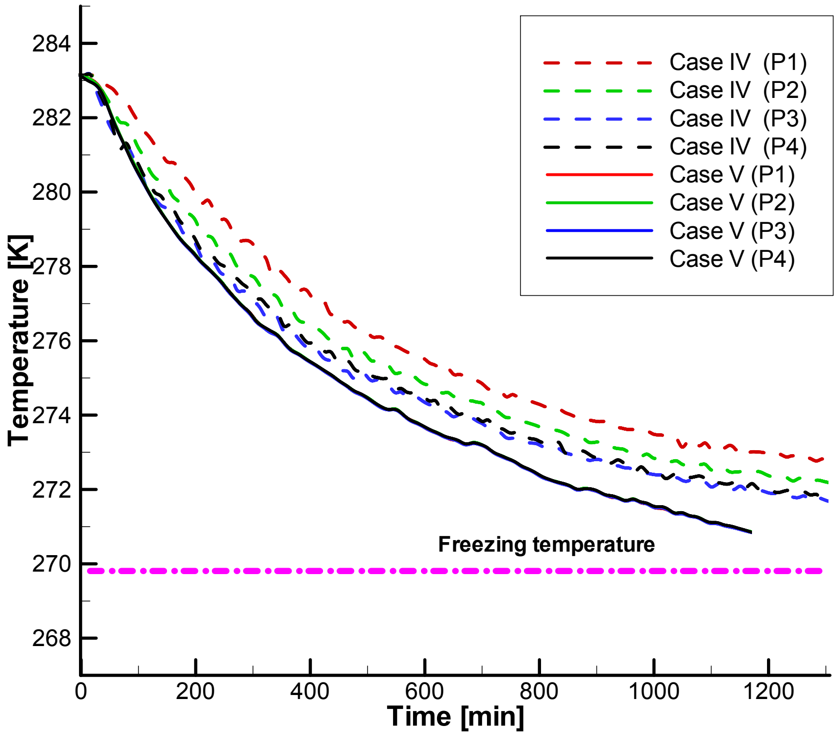
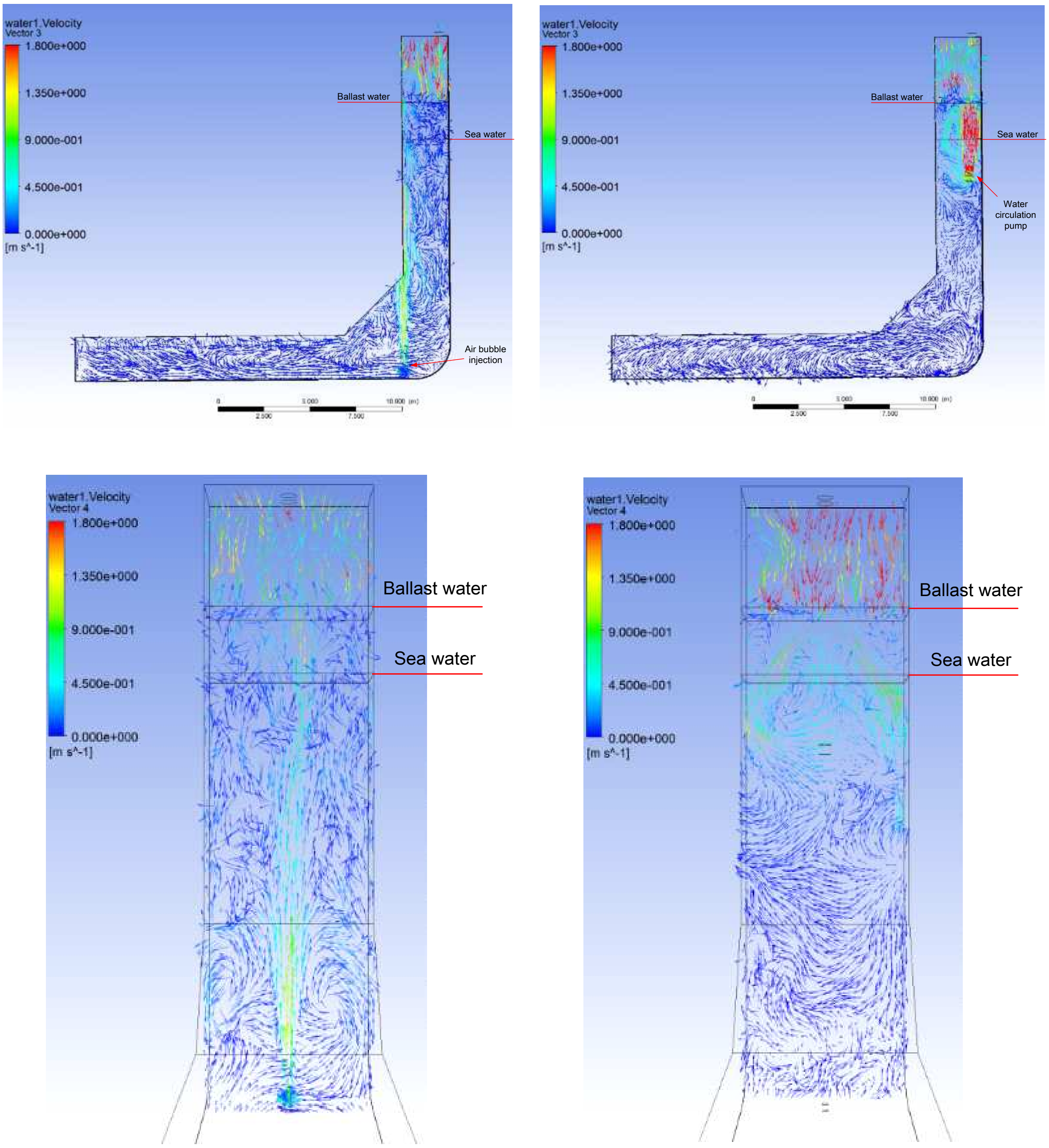


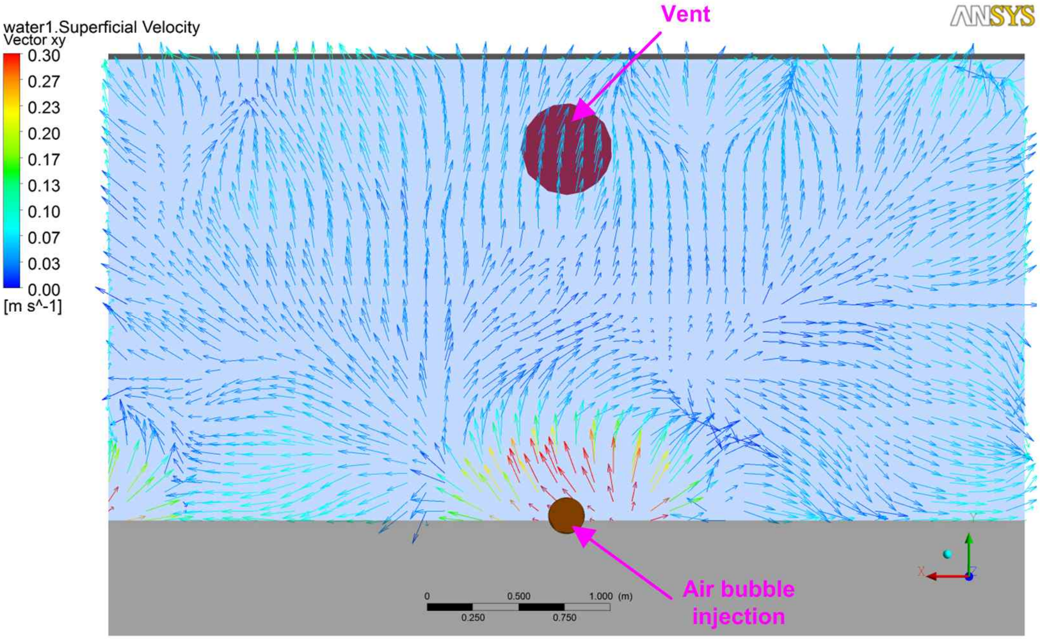

**Figure 7.** Comparison of the anti-freezing effectiveness between air-bubbling system and water-circulating system in ballast tank.



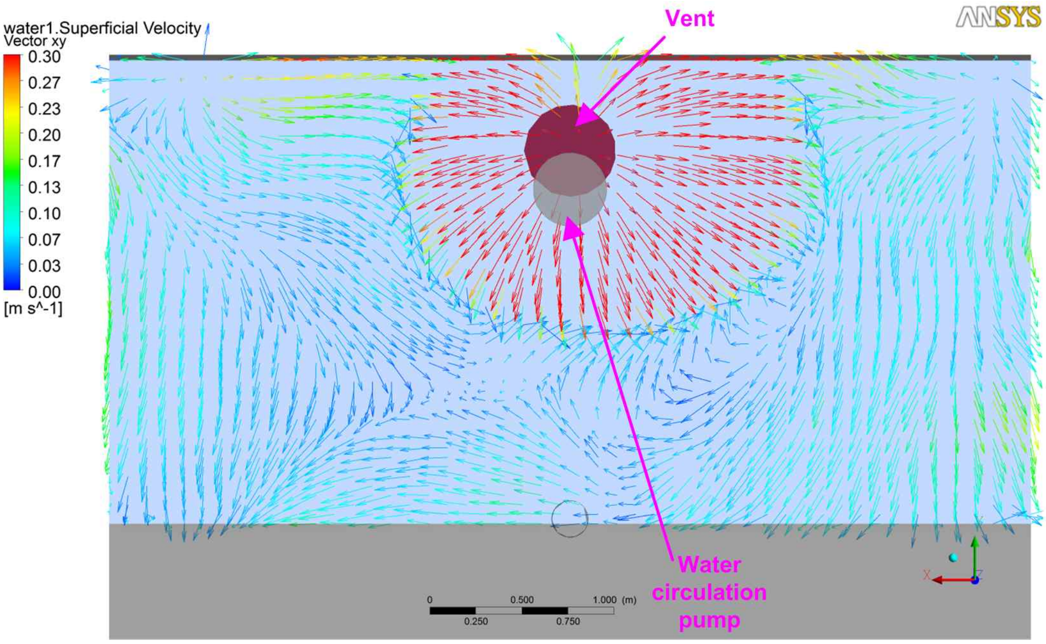

(a) 1307 minutes (Case IV) (b) 353 minutes (Case V)

**Figure 8**. Velocity vectors at vertical plan of ballast tank for Case IV(Air-bubbling system) and Case V(Water-circulating system), respectively.

Concluding, the numerical simulation demonstrated that water in tanks may freeze making it impossible to empty bilge and ballast tanks, which may also result in structural damage. Fore peak and after peak ballast tanks are particularly vulnerable to freezing as they are often exposed to the ambient air temperature, being mostly above the waterline. Wing ballast tanks extending above the waterline are also vulnerable to freezing, and any ballast tank filled with fresh water will freeze more quickly than if containing sea water. If ballast tanks are pressed-up, with any standing water in the air vent pipes and sounding pipes, these pipes may freeze, preventing the ballast from being pumped. The ship design should ensure that freezing is minimized or eliminated by judicious arrangement of the tanks and piping, and selection of valves and heating systems.




(a) 1307 minutes (Case IV)




(b) 353 minutes (Case V)

**Figure 9**. Velocity vectors at horizontal plan of ballast tank for Case IV(Air-bubbling system) and Case V(Water-circulating system), respectively.

## CONCLUSIONS

Vessels sailing in cold districts must be designed not only with sufficient strength against ice, but also adequate winterization countermeasures at low temperature about -10 to -20 ℃ in

LMDAT and -20 to -30 ℃ in extreme temperature. Then the anti-freezing systems, such as ballast water circulating system and air bubbling system, have been used to the ballast tank navigating in cold region.

In this paper, numerical investigations were conducted to examine effectiveness of the air-bubbling ice-prevention system and the water-circulating ice-prevention system applied to winterization of ballast tank for ships operating in polar waters. Through the results, it became clear that ballast water circulating countermeasures such as the air-bubbling ice-prevention system help to prevent or slow its freezing, and effectively protects ballast water from freezing by the circulation of ballast water due to the air bubbles trajectories without any heating system.

## ACKNOWLEDGEMENT

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