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Numerical Simulation of the Flowing of Ice Slurry in Seawater Pipe of Polar Ships

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Abstract—In recent years, as global warming, the sea-ice extent of North Arctic undergoes an evident decrease and Arctic channel has attracted the attention of shipping industry. Ice crystals existing in the seawater of Arctic channel which enter the seawater system of the ship with the seawater were found blocking the seawater pipe. The appearance of cooler paralysis, auxiliary machine error and even ship power system paralysis may be happened if seriously. In order to reduce the effect of high temperature in auxiliary equipment, seawater system will use external ice-water to participate in the cooling cycle and achieve the state of its flow. The distribution of ice crystals in seawater pipe can be achieved. As the ice slurry system is solid liquid two-phase system, the flow process of ice-water mixture is very complex and diverse. In this paper, the flow process in seawater pipe of ice slurry is simulated with fluid dynamics simulation software based on k-ε turbulence model. As the ice packing fraction is a key factor effecting the distribution of ice crystals, the influence of ice packing fraction on the flowing process of ice slurry is analyzed. In this work, the simulation results show that as the ice packing fraction is relatively large, the distribution of ice crystals is uneven in the flowing process of the seawater which has such disadvantage as increase the possibility of blocking, that will provide scientific forecasting methods for the forming of ice block in seawater piping system. It has important significance for the reliability of the operating of polar ships in the future.

Keywords—Ice slurry, seawater pipe, ice packing fraction, numerical simulation.

I. INTRODUCTION

IN 21st century, because of the global warming, the speed of the melting of Arctic sea ice is increasing. Satellite data show that less ice situation is appeared in the Northern Sea of Russian which continued for three months [1], and the Arctic waterway is easier to reach than before, with the development of the navigation and ice-breaking technology. In 1997, Finland Cruise UIKU arrived in Asia through the Arctic Northeast Passage firstly. Every summer, the number of the ships which pass through the Arctic waterway tends to increase. There are 46 ships in 2012 and 71 ships in 2013 [2]. Northeast Passage of Arctic waterway is the shortest channel connecting Eastern and Western Europe and Eastern Asia. Arctic waterway is shorter than traditional Malacca Strait and Suez Canal route. Energy consumption decrease by about 35%, and about 45% of economic benefits are enhanced. Arctic waterway is called golden waterway linking Asia and Europe by shipping industry. Contrast of Arctic route and traditional route is shown in Fig. 1. Red line represents the Arctic route, and blue line represents the traditional route. In recent years, the monitoring and investigation of arctic is increasing [3], laid a solid foundation for the opening of the Arctic waterway.

Compared to normal routes, the temperature of the seawater of Arctic is lower and sea ice is contained. It was found that ice crystals existing in the seawater. These crystals enter the seawater system of ship. The seawater pipe is blocking. Thus, cooling system will be influenced, and the temperature of cooling water will be too high. Dynamic system will be out of control in the case of serious. At present, studies of Arctic waterway are mostly concentrated in the changes of sea ice, feasibility analysis of navigation, legal issues and operational recommendations of polar ships, etc. Moreover, the ice packing fraction of seawater in different regions of Arctic waterway is different, and the flowing characteristics of ice slurry in seawater pipe are influenced by the difference of ice packing fraction. In this paper, the flow of ice slurry in seawater pipe is simulated, and the impact of ice packing fraction is researched. This work has important scientific significance and can provide a reference for the safe navigation of the polar ship.

II. ANALYSIS OF THE PHYSICAL PROPERTIES OF ICE SLURRY

A. Ice Slurry Density

Ice slurry is a mixture of sea water and ice crystals. The density of ice slurry is related to many factors, including the ice packing fraction. Moreover, in the flowing process of ice slurry the phase of ice crystals transforms. Then its size will change at the same time and the volume of ice slurry will be affected. In this paper ice packing fraction is considered merely, and apparent density of ice slurry is calculated as:

$$\rho_{iceslurry} = \frac{1}{\frac{X_S}{\rho_{ice}} + \frac{1-X_S}{\rho_{seawater}}} \tag{1}$$

$\rho_{iceslurry}$ - Apparent density of ice slurry; X_S - Ice packing fraction; ρ_ice- Density of ice; the density of sea ice is different from the density of freshwater ice. The density of fresh ice is approximately 914 ~ 915 kg/m³, and the density of sea ice is about 860 kg/m³ in summer. In this paper, ice density is 860 kg/m³, $\rho_{seawater}$ - density of seawater, $\rho_{seawater}$ = 1.025×10³ kg/m³.

B. The Dynamic Viscosity of Ice Slurry

The components of Seawater-Ice Crystals Two-Phase Flow are complex. Apparent viscosity takes the place of viscosity

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commonly There are currently many computational models, and the famous model is Einstein suspension dynamic viscosity formula [4].

$$\eta_{\text{eff}} = \eta_L(1 + 2.5C) \tag{2}$$

η_{eff} - Suspension dynamic viscosity; η_L - Kinematic $viscosity\ of\ the$ liquid phase; C - Solid concentration. Moreover, Thomas formula is commonly used to solve the dynamic viscosity [5].

$$\eta_{\text{eff}} = \eta_L[1 + 2.5\text{C} + 10.05C^2 + 0.00273\exp(16.6\text{C})] \tag{3}$$

In this formula, liquid is treated as a uniform flow, and the concentration of particles and particle interactions are taken into account. It is more commonly used. In this paper this formula is used to calculate the apparent dynamic viscosity of ice slurry. The formula is calculated as:

$$\mu_{\text{iceslurry}} = \mu_{seawater(1+2.5X_V+10.05X_V^2+0.00273e^{16.6X_V})} \tag{4}$$

$\mu_{\text{iceslurry}}$- Dynamic viscosity of ice slurry; μ_{seawater}- Dynamic viscosity of seawater, 1.789*10^{-6} kg/m·s;

$$\text{X}_\text{V}=\frac{X_S}{X_S+(1-X_S)\times\frac{\rho_{\text{ice}}}{\rho_{seawater}}} \tag{5}$$

C. Specific Heat at Constant Pressure

Specific heat at constant pressure of ice slurry is obtained through the linear weighted two general properties of phase. The formula is shown as:

$$C_{p,iceslurry} = (1 - X_S)C_{p,seawater} + X_sC_{p,ice} \tag{6}$$

$C_{p,iceslurry}$- Specific heat at constant pressure of ice slurry; $C_{p,seawater}$ -Specific heat at constant pressure of seawater, 4218 J/kg·K; $C_{p,ice}$ - Specific heat at constant pressure of ice crystals, 2120 J/kg·K.

III. THE FLOWING MATHEMATICAL MODEL OF ICE SLURRY IN SEAWATER PIPE

A. Control Equation

Ice slurry can be viewed as a continuous fluid. Ice slurry flow steady in seawater pipe, and continuity equation and momentum conservation equations can be established.

Ice slurry is Seawater-Ice crystals Two-Phase Flow. Continuity equation of Seawater-Ice crystals Two-Phase Flow based on not phase transition process is shown as:

$$\frac{\partial}{\partial\ \text{t}}(\alpha_i\rho_i) + \triangledown\cdot(\alpha_i\rho_iu_i)=0 \tag{7}$$

i =L, S, represents the liquid and solid phases respectively, ▽ - Laplacian Operator; α - The volume fraction of the fluids; ρ - Density of fluids; u - Velocity of fluids. Momentum equation:

$$\frac{\partial}{\partial\ \text{t}}(\alpha_i\rho_i) + \triangledown\cdot(\alpha_i\rho_iu_i)=-\alpha_i\triangledown\text{P}+\triangledown\cdot\tau_\text{i} + \alpha_{\ i}\rho_i\text{g} + \text{M}_\text{i} \tag{8}$$

$$\tau_L = \alpha_L\mu_L(\triangledown u_L+\triangledown u_S^T)+ \alpha_L\left(\lambda_L - \frac{2}{3}\mu_L\right)(\triangledown\cdot u_L)\text{I} \tag{9}$$

$$\tau_S = -p_sI + \alpha_S\mu_S(\triangledown u_S + \triangledown u_S^T)+ \alpha_S\left(\lambda_S - \frac{2}{3}\mu_S\right)(\triangledown\cdot u_S)\text{I} \tag{10}$$

p - Static pressure, Pa; P_S - Positive stress between particles, Pa; τ - Shear stress, Pa; M - Momentum exchange between the phases, kg▪m^{-2}▪s^{-2}; μ - Shear viscosity, kg m^{-1} s^{-1}; λ- Bulk viscosity, kg▪m^{-1}▪s^{-1};I - Unit tensor.

B. Turbulent Model

Ice slurry is the mixture of sea water and ice crystals, vortex phenomenon may occur in the flowing process. In this paper RNG k-ε model is used. RNG k-ε model has higher precision and reliability in terms of the vortex. K, ε equations are shown in (11) and (12):

$$\frac{\partial}{\partial\ \text{t}}(\rho k) + \frac{\partial}{\partial\ x_i}(\rho ku_i) = \frac{\partial}{\partial\ x_j}\left(\alpha_k\mu_{eff}\frac{\partial\ \text{k}}{\partial\ x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M - S_k \tag{11}$$

$$\frac{\partial}{\partial\ \text{t}}(\rho\varepsilon) + \frac{\partial}{\partial\ x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial\ x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial\ \text{k}}{\partial\ x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \tag{12}$$

k -Turbulent Kinetic energy; ε - Turbulent energy dissipation rate; G_k- Turbulent kinetic energy caused by laminar speed gradient, $G_k = \mu_t\sqrt{2S_{ij}S_{ij}}$; G_b- Turbulent kinetic energy caused by buoyancy;

$$G_b = \beta g_i\frac{\mu_t}{Pr_t}\frac{\partial\ \text{T}}{\partial\ x_i};$$

Y_M - Compressibility impacts turbulence through the expansion and diffusion for high Mach number flow;

$$C_{1\varepsilon} = 1.42,\ C_{2\varepsilon} = 1.68,\ C_{3\varepsilon} = \tanh\left|\frac{v}{u}\right|$$

α_k and α_ε are the turbulent Prandtl number of the k and ε equations. The expressions of them are as:

$$\left|\frac{1.3929-\alpha}{0.3929}\right|^{0.6321}\left|\frac{2.3929+\alpha}{3.3929}\right|^{0.3679} = \frac{\mu_{\text{mol}}}{\mu_{eff}} \tag{13}$$

$$R_\varepsilon = \frac{C_\mu\rho\eta^3\left(1-\frac{\eta}{\eta_0}\right)}{1+\beta\eta^3}\frac{\varepsilon^2}{k} \tag{14}$$

$\eta = \text{sk}/\varepsilon, \eta_0 = 4.38, \beta = 0.012$. Turbulent viscosity is calculated as:

$$\text{d}\left(\frac{k\rho^2}{\sqrt{\varepsilon\,\mu}}\right)=1.72\frac{\bar{v}}{\sqrt{-1+C_v+\bar{v}^3}}\text{d}\bar{v} \tag{15}$$

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$\bar{v} = \frac{\mu_{\text{eff}}}{\mu}, C_v = 100$

Fig. 1 Arctic route and traditional route

IV. NUMERICAL SIMULATION OF THE FLOWING ICE SLURRY IN SEAWATER PIPE

First of all, ice slurry flows in seawater pipe of the polar ship. As the ice slurry is the seawater-ice crystals two-phase flow, the flowing characteristic is different from single-phase flow [6]. Straight pipe and elbow are common in Seawater Pipe, and the straight pipe is one of the most commonly used parts. We must think over the flowing characteristics of the Ice Slurry in straight pipe when its flowing characteristics are considered in the seawater system. In this paper, the numerical simulation of the flowing process of ice slurry is researched, and the speed of the Ice slurry in seawater pipe is 1 m/s.

A. Geometric Model

Fluent software is commonly used in engineering design and calculation software. In this paper, this software is used to analyze the flow of ice slurry in the straight pipe. Three-dimensional model is used by geometric model. Wall of the tube model is installed as solid wall boundary. Adiabatic condition is installed in this model. Straight tube geometry is shown in Fig. 2. Dimensions of this geometric model are shown in Table I.

B. Mesh Generation

Mesh generation is a very important part of the numerical simulation. If the mesh is not good, the speed of solving discretization equation is too slow. Sometimes the solution cannot be convergent. In severe cases, solution is impossible to get. In this paper, the flow of ice slurry in seawater pipe is simulated, and three-dimensional flow field is used. Structured mesh is used to generate mesh. The meshes are shown in Figs. 3 and 4.

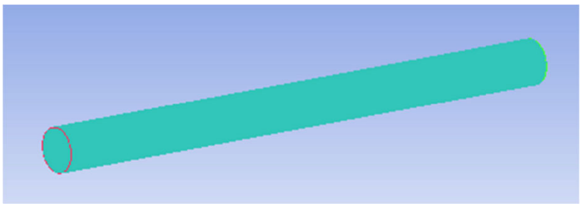

Fig. 2 Model of seawater pipe

TABLE I
MODELING PARAMETERS OF SEAWATER PIPES

Pipe Parameter	**Date**
outer diameter/m	0.32
wall thickness/m	0.01
length/m	4

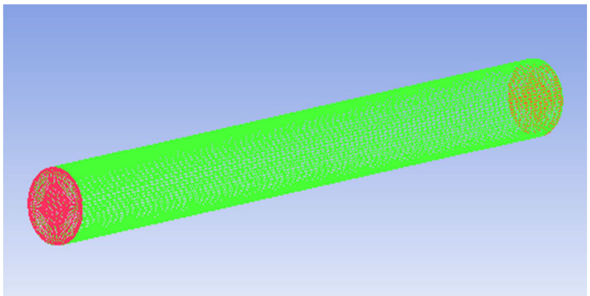

Fig. 3 Mesh of pipe

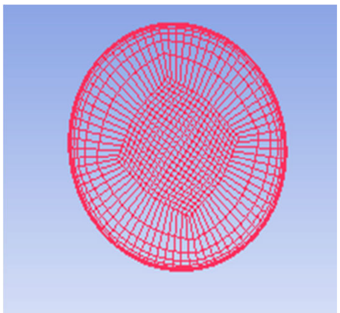

Fig. 4 Mesh of entrance of pipe

C. Solution of Numerical Simulation

In Fluent software, there are four methods which can solve the pressure - velocity coupling equation. They are IMPLE, SIMPLEC, PISO and Coupled. SIMPLE algorithm is mainly used when the flow field is incompressible. The staggered grid method is used to calculate the pressure field. Momentum equation is solved through Guess - Fixed, namely N-S equation. It is Semi-Implicit method which is the mainly used to solve pressure-linked equations. In this paper, this algorithm is used for the numerical simulation. The parameters are shown in Table II. Boundary condition is decided to be adiabatic boundary condition.

TABLEII
PARAMETER SETTING

parameter	**Date**
inlet temperature/K	271
outlet temperature/K	278
reference temperature of fluid in pipes/K	298
inlet velocity of water/ms^{-1}	1
inlet velocity of ice/ms^{-1}	1

The distribution of ice crystals is shown in Figs. 5-7 when the ice packing fraction is 5%, 10% and 15%. The case that the distribution of ice crystals is uneven appears when the ice packing fraction is different. The case is less obvious when the ice packing fraction is smaller.

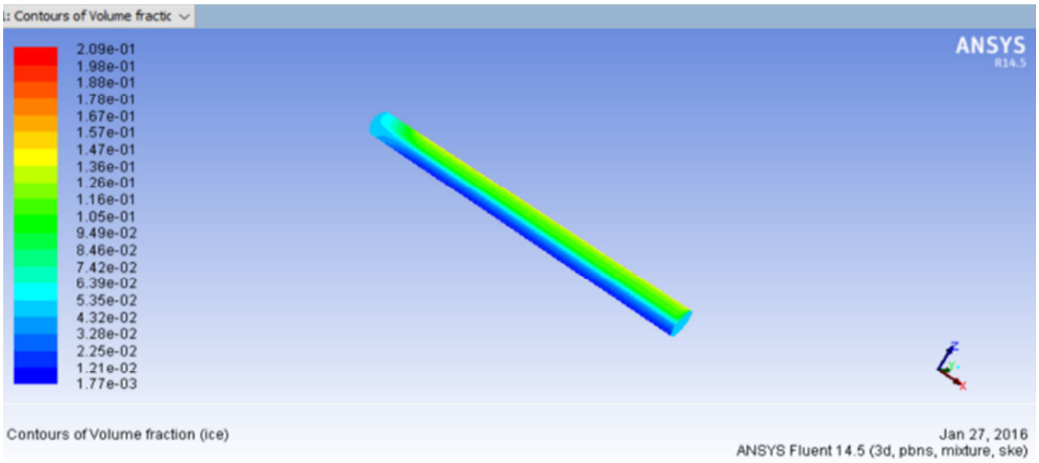

Fig. 5 Distribution of ice crystals when ice packing fraction is 5%

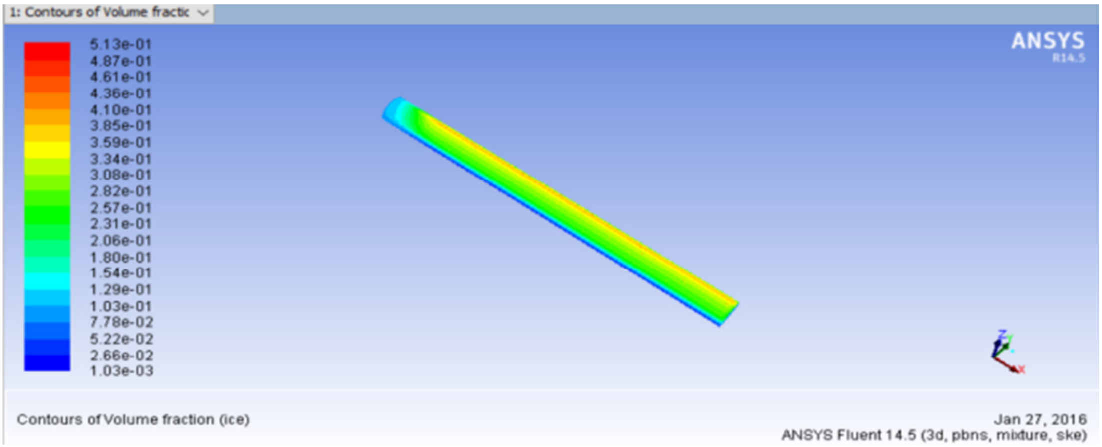

Fig. 6 Distribution of ice crystals when ice packing fraction is 10%

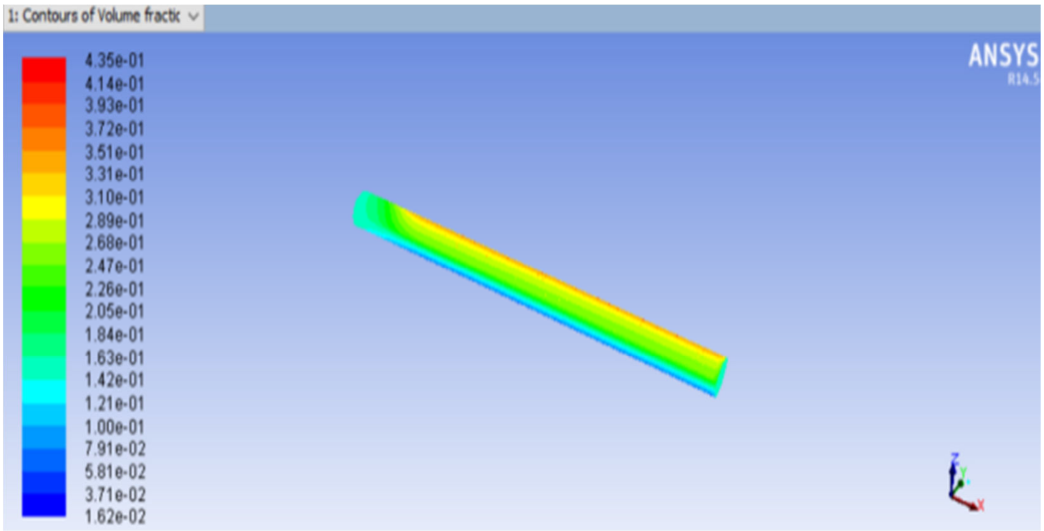

Fig. 7 Distribution of ice crystals when ice packing fraction is 15%

V. CONCLUSION

In this paper, Fluent software is used to simulate the flow of ice slurry in the seawater pipe of polar ship, and ice packing fraction that influences the distribution of ice crystals in the seawater pipe is investigated. The results show that with the increase of the ice packing fraction the distribution of ice crystals is more uneven. Generally, the more uneven distribution of ice crystals is, the greater possibility of ice block that appears will increase. When polar ships navigate in the sea area that seawater contains more ice crystals, stability of the seawater system should be paid more attention.

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REFERENCES

[1] Cui Juan Sui, Zhanhai Zhang, Dinghui Wu, “Interannual and decadal variation analysis of Arctic sea ice extent between 1979 and 2012,” *J. Chinese Journal of Polar Research*. vol.2, 2015, pp. 174-182.

[2] Dan Wang, Jie Zhang, Hao Zhang, W.-K. Chen, “Study of arctic water transit policy and its development on circumpolar nation and regions”, *J. Chinese Journal of Polar Research.* no.1, 2015.

[3] Peterson B J, McClelland J, Curry R, et al. “Trajectory shifts in the Arctic and Subarctic freshwater cycle”. *J. Science,* vol. 313. no. 5790, pp.061-1066.

[4] B. S. Kim, H. T. Shin, Y. P. Lee, “Study on ice slurry production by water spray”. *J, International Journal of Refrigeration*, 2001, pp.176~184.

[5] Andrej Kitanovski, Didier Vuarnoz, Derrick Ata-Caesar, et al. “The fluid dynamics of ice slurry”. *J, International Journal of Refrigeration,* vol. 28, 2005, pp. 37~50.

[6] Shengchun Liu, Ling Hao, Jinghong Ning, “Review on the flow and thermal characteristics of ice slurry in resistance components” *J. Refrigeration.* Vol.11, 2015. pp.59-65+77.