Experimental Studies of the Resistance of Transport Ships at Moving in Composite Broken Ice

V A Zuev¹, N V Kalinina¹, Y A Moskvicheva¹

¹«Shipbuilding and aviation technology» department, Nizhny Novgorod State Technical University, named after R.E. Alekseyev, 603950, Minina str., 24, Nizhny Novgorod, Russia

E-mail: nvk5133@mail.ru

Abstract. Arctic ships move in broken ice most of the time. Therefore, forecasting the ice performance of ships when moving in a channel behind an icebreaker or in natural broken ice is relevant at the design stage. For this, theoretical and experimental studies of the movement of various models of ships in a small experimental basin were carried out. The process of modeling and testing of models of active ice navigation ships in a composite ice model is described. Test results and formulas for assessing ice resistance are given. They are derived from the analysis of model tests. Conclusions about the possibility of carrying out and obtaining reliable results of the experiment in small experimental pools are made. The resistance when moving ships in a wide ice channel does not differ from the resistance when moving ships in a field of broken ice. The jamming of ice floes between the edges of the channel and the side occurs when ships move in a narrow channel. Consequently, the "buffering effect" occurs and the resistance increases significantly.

1. Introduction
Ships move in different ice conditions during operation. Ships of the Arctic navigation have been operating in broken ice for a considerable time [1]. Therefore, predicting the resistance of ships when moving in broken ice is an important task.

The variety of ice conditions, the instability of the physical and mechanical properties of ice and the uncertainty of ice conditions make the analytical solution of the problem of predicting the resistance of broken ice very difficult.

The need to assess the ice qualities of a ships at the initial design stage forces one to resort to experimental research methods [2]. This approach provides reliable results, but is far from ideal. This is due to the fact that ice conditions, including the thickness, shape and length of ice fragments, their concentration and physical and mechanical characteristics, can change both in time and along the route. In this regard, resistance should be predicted using a probabilistic approach, but it has not received sufficient development.

A method for predicting the resistance of broken ice using experimental model studies of the interaction of ships with ice is considered in this article.

2. Theoretical research
Let's consider the process of interaction of ship with broken ice.
When the stem meets the ice floe, a collision occurs. The ice floe is partially sunk and tilts from a collision with the stem. The ice floe receives a push and slides to the right or left of the stem, following along the side in a partially submerged state. The ice floe gains some speed in the direction perpendicular to the center plane of the ship. Broken ice is compacted in the vicinity of the ship as a result of the moving apart of the ice floes by the sides. Neighboring ice floes that are not in direct contact with the hull of the ship are involved in movement. The dimensions of the indicated ice compaction zone depend on its concentration. The zone of compacted and moving ice is observed in the direction perpendicular to the ship’s course and in front of the stem. This happens if the submerged ice floe does not have the ability to slip along the side and is towed by the bow of the ship. The speed of the ship in broken ice is practically constant. The continuous movement of ships in broken ice fields has a steady character [1].

The problem of modeling the process of interaction of broken ice with the ship's hull is urgent [2, 3].

The peculiarity of the task is that during the tests, a small experimental pool was used without the use of artificial cold, but with the use of new materials to simulate broken ice. These materials must fully comply with the similarity conditions. Such tests in broken ice can be carried out at any time of the year. They do not require expensive refrigeration equipment, high labor intensity and cost of testing.

Model ice must correspond to real ice in terms of geometric, physical and mechanical characteristics. The possibilities of such tests are confirmed in works [1, 2, 3, 4, 5].

It is known that the similarity conditions can be obtained from the equations of the ship’s motion in ice, or using the π-theorem with a set of assumed dependences of the process on the characteristics of the ship and the environment.

Earlier it was noted [2, 4, 6, 7, 8, 9] that the force of ice resistance depends mainly on the geometric parameters of the ship and ice, on the speed of movement, and the forces of friction of ice floes against the hull. The strength of the ice practically does not affect the resistance of the ship [1].

Usually, the total resistance of the environment at ship movement is presented in the form [1, 4]:

\[ R = R_{ci} + R_w, \]  

where \( R \) - the total resistance, kN; \( R_{ci} \) - clean ice resistance, kN; \( R_w \) - water resistance, kN.

Modeling the interaction of a ship with ice and water obeys different laws. Therefore, the modeling conditions were considered separately. Simulation conditions for a ship moving in water are well known [1]. Let us consider only the conditions for modeling the interaction of the hull with ice. We will assume that broken ice can be modeled according to the conditions of gravitational similarity [1].

Experience shows that the dependence of the clean ice resistance can be represented as:

\[ R_{ci} = f(L, B, T, \rho_w, \rho_l, h, r, S, v, f) , \]

where \( L, B, T \) – the main dimensions (length, width, draft) of the ship, m; \( \rho_w, \rho_l \) – density of water and ice, \( \text{t/m}^3 \); \( h \) - ice thickness, m; \( r \) – linear size of ice floes in plan, m; \( S \) – the concentration of broken ice, points; \( v \) – the speed of the ship, \( \text{m/s} \); \( f \) – the coefficient of friction of model or nature ice about the hull of the model or of the nature ship.

Assuming the geometric scale of the model \( \lambda = \frac{L_n}{L_m} \), the modeling conditions can be written as:

\[ \left( \frac{\rho_w}{\rho_l} \right)_n = \left( \frac{\rho_w}{\rho_l} \right)_m ; \quad \frac{r_n}{r_m} = \frac{h_n}{h_m} = \lambda ; \quad \frac{v_n}{v_m} = \sqrt{\lambda} ; \]

\[ Fr_n = Fr_m = \text{idem} ; \quad f_n = f_m ; \quad S_n = S_m . \]

where \( Fr = \frac{v}{\sqrt{gL}} \) – Froude number along the length of the ship; the index «n» means a full-scale (nature) characteristic, and the index, and the index «m» - for the model.

Conditions (3) make it possible to choose a material for simulating broken ice. We exclude the model of ice of natural composition, the paraffin and other unsuitable materials from use in small experimental pools. We give preference to tiles of high-pressure polyethylene. High-pressure polyethylene has long been used in the basin of the Nizhny Novgorod State Technical University, named after R.E. Alekseyev (NSTU). When it used, fairly reliable experimental results are obtained.
The density of high-pressure polyethylene (model ice) is \( \rho_{im} = 0.90 \ldots 0.92 \, \text{t/m}^3 \) [4]. The density of natural ice is \( \rho_{in} = 0.88 \ldots 0.92 \, \text{t/m}^3 \). The coefficient of friction of polyethylene on the freshly painted surface of the body model is \( f_m = 0.11 \ldots 0.15 \). For a full-scale ship, the coefficient of friction of ice on a steel hull is \( f_n = 0.10 \ldots 0.16 \) [10].

Numerous parameters characterizing full-scale ice conditions: thickness, shape and size of ice floes, concentration under a wide variety of ice conditions, instability of properties and characteristics of broken ice are difficult to accurately record. Therefore, the experiment approximately simulates the movement of a ship in a certain conditional environment with averaged characteristics. Similarity conditions are correspond only in relation to the most important characteristics of broken ice: thickness, concentration, channel width, density and coefficient of friction of ice fragments about the hull.

Therefore, broken ice can be modeled using polyethylene tiles of the same shape, square or triangular in plan, with dimensions at a constant ratio of their length \( r_m \) to thickness \( h_m \).

Our experiments have shown that triangular tiles are more preferable than square tiles, as ice floes do not get stuck between the channel edge and the hull when the model moves. The ratio \( r_m/h_m \) is taken equal to 5 \ldots 7, as the most frequently encountered at ice breaking during movement of icebreaker or waves.

Two types of tests are carried out in studies of the resistance of broken ice when the ship is moving. This is the movement of a model ship on calm water and in broken ice with the aim of isolating and recalculating clean ice resistance.

It is known [11], that when simulating the steady motion of a ship in calm water, it is necessary to provide geometric, kinematic and dynamic similarities. Kinematic and dynamic similarities are determined by the equality of the Froude and Reynolds numbers for the model and ship. So far it has not been possible to execute them simultaneously for normal conditions.

The solution was found in separate modeling, when the residual resistance is modeled and recalculated according to Froude's law of similarity, and the friction resistance is determined analytically using friction extrapolators [12].

As is known, such modeling produces a large-scale effect. The scale effect depends on the linear dimensions of the model and low Reynolds numbers. This is due to incomplete turbulent flow around the model. The scale effect is important when testing in small experimental pools, which include the NSTU pool with dimensions \( l \times b \times h = 15.60 \times 1.65 \times 0.85 \text{m} \). When choosing the scale of the model, it is necessary to check the fulfillment of conditions regarding the possible effect of the bottom and walls of the pool on the hydrodynamic resistance [13]. These conditions are detailed in [12]. When ice tests are carried out in the pool, the geometric characteristics of the ice are also modeled on the same geometric scale.

A reliable result is not always obtained, even when using flow turbulence methods at low Reynolds numbers.

Tests of ship models with Reynolds numbers \( \text{Re}<3 \cdot 10^6 \) are carried out in a small experimental pool of NSTU. The correction \( \Delta C_{F_{oa}} \) was offered for calculating the friction extrapolator at low Reynolds numbers in the Krylov State Scientific Center (KSSC) [11]. This correction is interesting. It is determined by the formula:

\[
\Delta C_{F_{oa}} = 0.65 \exp[1.5(0.5 - \text{Re} \cdot 10^{-6})] \cdot 10^{-3}
\]  

and is shown in Figure 1.

The friction coefficient of the model is determined at low Reynolds numbers \( \text{Re}<3 \cdot 10^6 \):

\[
C'_{F_{oa}} = C_{F_{oa}} + \Delta C_{F_{oa}},
\]  

where \( C'_{F_{oa}} = \frac{0.455}{(\log \text{Re})^{1.5}} \) - the coefficient of friction of an equivalent smooth plate.

The second term in equation (5) is small for Reynolds numbers \( \text{Re}>3 \cdot 10^6 \).
3. Experimental research
Experimental research of several models of ice navigation ships with ice categories from Ice3 to Arc7 at moving in clear water and broken ice of different thickness and different concentration from 4 to 9 points were carried out in the experimental pool of NSTU. Resistance to the movement of ships was determined during the test.

The correction $\Delta C_{FOM}$ for calculating the friction extrapolator (4) has been checked for plausibility.

For this, two geometrically similar models of one ship were tested with Renolds numbers from $0.6 \times 10^6$ to $3 \times 10^6$. ... These models were made in 1:18 and 1:35 scales.

As a result of dividing the hydrodynamic resistance of water to the movement of the model into two components: friction and residual resistance, an increase in the first component due to $\Delta C_{FOM}$ leads to a decrease in the second component ($C_{RM}$). Curves of the residual resistance coefficient $C_{RM}$ are shown in Figure 2.

Figure 1. The correction $\Delta C_{FOM}$ for the model to the friction coefficient from the Renolds number.

Figure 2. Curves of the residual resistance coefficients of the ship model from Fr:
° - model at 1:35 scale; • - model at 1:18 scale; × - recalculation with correction $\Delta C_{FOM}$. 
Tests in ice conditions were carried out both in a field of broken ice with the channel width $B_{ch}$ greater than the width of the model $B_m$ ($\frac{B_{ch}}{B_m} > 5$), and in a narrow channel of broken ice in order to simulate movement in the channel behind the icebreaker. The width of the narrow channel was set, and outside of it, plates of polyethylene of the same thickness are laid out. Fragments of tests are shown in Figures 3, 4, 5, 6, 7.

**Figure 3.** Fragment of tests of a supply ship model in a field of broken ice with a concentration of 9 points.

**Figure 4.** Fragment of tests of a ship model in a field of broken ice (ice thickness 10 mm with a concentration of 8 points).

**Figure 5.** The movement of the model in a field of broken ice 20 mm thickness with a concentration of 6 points.

Each experimental point was checked three times at least to increase the reliability of determining the resistance during the experiments.

The curve of residual resistance for Arctic transport ships (Fig. 8) was obtained during testing of models at moving in clear water. This curve can be used for forecasting the hydrodynamic resistance of Arctic transport ships $R_w$:

$$R_w = R_F + R_R,$$

where $R_F$ - frictional resistance, kN, determined by the usual methods [11, 12]; $R_R$ - residual resistance, kN, determined using the curve, shown in Fig. 8. Residual resistance $R_R$ depends on the Froude number $Fr$; displacement $D$, t; gravitational acceleration $g = 9.81$ m/s$^2$. 


4. Recalculation of the results of a model experiment on a full-scale ship

Clear ice resistance of model was recalculated on clear ice resistance of full-scale ship according to Froude number at constant concentration as follows:

\[ h_n = \lambda h_m ; \]
\[ v_n = \sqrt{\lambda} v_m ; \]
\[ R_{ci,n} = \lambda^3 R_{ci,m} . \]

Figure 6. Ice channel not filled with ice.

Figure 7. Model movement in a channel of broken ice 10 mm thickness.

Figure 8. Experimental values of residual resistance of Arctic transport ships.
As an example, the results of experimental studies of pure ice resistance $R_{ci,n}$ of a transport ship of the Arctic class Arc7 at moving in broken ice with a thickness of $h=1.8$ m and a concentration of 7 points are shown in Figure 9.

The main characteristics of the ship: displacement $V=17900$ m$^3$, length $L=123.1$ m; width $B=27.0$ m; coefficient of overall completeness $\delta=0.635$. In Figure 9 experimental points were converted to a full-scale ship.

The conversion to nature of the hydrostatic component of the resistance was carried out by known methods.

The total resistance of nature was determined as

$$R_n = R_{ci,n} + R_{ww,n} .$$

Figure 9. Clean ice resistance of the ship in broken ice with a thickness of $h=1.8$ m, concentration 7 points ($\bar{S} = 0.7$):
- experimental data, converted to a full-scale ship; — — calculated resistance curve.

5. Semi-empirical calculation of resistance during the movement of transport ships in broken ice

As a result of the analysis of model tests of Arctic transport ships in conditions of extended navigation, a semi-empirical dependence to determine the clean ice resistance of broken ice was proposed:

$$R_{ci} = \rho_0 g a B h \left(0.145 \frac{B}{h} + 1.3 \text{Fr}_h + \text{Fr}_h^2 \right) f(\bar{S}) ,$$

where $\alpha$ – the coefficient of completeness of the waterline; $\text{Fr}_h = \frac{v}{\sqrt{gh}}$ - Froude number by ice thickness; $f(\bar{S})$ – is a function that takes into account the effect of ice concentration on resistance:

$$f(\bar{S}) = \sin^2 \left( \frac{\pi}{2} \bar{S} \right) .$$

This dependence (8) includes static, dissipative and inertial components and corresponds to the data of model tests with a relative error not exceeding $\pm 10\%$. This fact is confirmed by the obtained calculated curve, which shown in Figure 9. The results of calculating the clean ice resistance by the semiempirical dependence for comparison with experimental data are shown in Figure 9.

The calculation of the clean ice resistance, according to the semiempirical dependence (8), is shown in Figure 9 and showed good agreement with the results of the model experiment.

6. Conclusion

Conclusions are made from the analysis of the results obtained.
Model experimental studies can also be carried in small experimental basins. But it is necessary to introduce a correction for the values of frictional resistance.

Tests of models of ships in the channel and in the field of broken ice showed that when moving in a wide channel \( \frac{B_{ch}}{B} > 3 \), the resistance value does not differ from the resistance at moving in the field of broken ice.

If the width of the channel exceeds the width of the ship by 2...3 thickness of ice, then ice wedging between the edges of the ice channel and the ship’s side occurs and the «buffer effect» appears.

In this case, the resistance to the movement of the ship can increase by 1.4 times. The resistance decreases with increasing channel width. It was not possible to obtain an empirical dependence of the resistance on the \( \frac{B_{ch}}{B} \) value.

The obtained semi-empirical model (8) of the broken clean ice resistance depends on the characteristics of the ship, the thickness and ice concentration, and the speed of movement. It can be used to predict the ice performance of ships.

7. References

[1] Ionov B P, Gramuzov E M 2013 Ice propulsion of ships: Monograph (SPb.: Shipbuilding) 502 p
[2] Ryvlin A Ya, Kheisin D Ye 1980 Tests of ships in ice (L.: Shipbuilding) 207 p
[3] Sazonov K E, Dobrodeev A A 2017 Ice propulsion of large ships (SPb.: Krylovsky state. scientific. Center) 119 p
[4] Zuev V A 1986 Means for extending navigation on inland waterways (L.: Shipbuilding) 207 p
[5] Zuev V A, Gramuzov E M 2016 New approaches to modeling the ice environment during model tests of ships Polar mechanics 3 pp 31-42
[6] Ionov B P, Gramuzov E M, Zuev V A 2013 Design of icebreakers: Monograph (SPb.: Sudostroenie) 506 p
[7] Sazonov K E 2010 Calculation of the ice resistance of the ships along the channel laid by the icebreaker Proceedings of the Krylov State Scientific Center 335 T 1 pp 101-112
[8] Zavyalova K N, Shishmarev K A, Khabakhpasheva T I 2018 The movement of external load on broken ice in the channel Izvestia of the Altai State University. Mathematics and Mechanics 4(102) pp 73-78
[9] Moskvicheva Yu A 2017 Influence of broken ice on water resistance during the movement of ice navigation ships Transport systems 2(5) (Nizhny Novgorod) pp 10 - 15
[10] Doronin Yu P, Kheisin D Ye 1975 Sea ice (L: Gidrometeoizdat) 320 p
[11] Pavlenko V G 1991 The propulsion and controllability of ships (M.: Transport) 397 p
[12] Handbook on the theory of the ship 1985 In 3 volumes Ed. Ya I Voytkunsky (L.: Shipbuilding)
[13] Moskvicheva Yu A 2015 Influence of the concentration of broken ice and the width of the ice channel on the ice resistance of ships Proceedings of NSTU im. R.E. Alekseeva 4(111) pp 228-233

Acknowledgments

The research was carried out with the financial support of the RFBR in the framework of scientific project № 19-08-00820.