The influence of ice conditions when creating the hull for ice navigation

E M Gramuzov¹, N A Kuzmin, M Y Sandakov and N E Tikhonova

¹Nizhny Novgorod State Technical University n.a. R.E. Alekseev, Minin str., 24, 603950, Nizhny Novgorod, Russia

E-mail: ¹terkor@nttu.ru

Abstract. Mathematical model of the ice capable ship design and generalized optimization criteria that take into account the diversity of ice conditions in the area of operation are presented in the paper. The distribution of the duration of ice phenomena on inland waterways of the Russian Federation is shown. For the continuous ice cover, the dependencies of the expected ice thickness are presented. Classification of broken ice in the navigation areas of ships is shown.

The relevance of studies of ship’s operation in ice conditions remains quite acute for Russia due to the increase in hydrocarbon production on the Arctic shelf, operation of fishing fleet in the far North, transportation of rare earth metals from the Taimyr Peninsula, and protection of the Arctic territorial water boundaries. To solve these problems, it is necessary to study methods of constructing geometric shapes of ice capable ship hulls. This task is still relevant today.

The mathematical model of the ice capable ship design includes the analytical equations of design, constraints, development of a theoretical drawing, algorithms for calculating ice resistance to vessel’s movement, algorithms for verifying ship general calculations. The system of analytical design equations includes the equations of mass, buoyancy, ice resistance and stability. Ice resistance is calculated by the method [1], which is taking into account the hull geometry in full.

The main natural factor determining the duration of navigation on Russia's GDP is the ice regime of the waterway, characterized by the existence of the ice cover, as well as the ice thickness.

On the map of the Russian Federation (see Figure 1), it can be seen that the duration of ice phenomena in inland waterways of Russia increases from southwest to northeast within 130-245 days, which significantly affects the fleet operation duration during the year.

Ice conditions in different areas of inland waterways of the Russian Federation differ significantly [2]. The operation area and, consequently, the distribution of ice conditions influencing the choice of the main elements and geometry of the ice capable ship hull are studied in this paper.

A particular feature of the ice regime influence on navigation is considerable time variability for freezing-up and in sections of waterways. The time intervals between the early and late periods of freezing-up amount to 50 days, and the difference between the maximum and minimum duration of freezing-up reaches 40-50 days at the storage reservoirs, and 75-85 days in the rivers [2].

When the ice capable ship works in winter navigation, two important states of the ice cover can be distinguished. This is the ship movement in a continuous ice field and navigation in broken ice.
When the ice capable ship moves, one of the main factors affecting its operation in ice is thickness of the continuous ice cover.

For practical calculations of the expected thickness of continuous ice, empirical formulas are used [3]. They correlate the ice thickness $h$ (cm) to the sum of the average daily values of the negative air temperature $\Sigma(-T) \degree C$ for the period under consideration. The formula suggested by B.A. Apollov is often used, where the snow thickness $h_{cm}$ (cm) is taken into account

$$h = 1,8 \left( 1 + \frac{1}{h_{cm}\sqrt{\Sigma(-T)}} \right) \quad (1)$$

The ice thickness can be determined by the Stefan formula

$$h = 3\sqrt{\Sigma t} \quad (2)$$

for rivers and sand spits, and, where the current velocity is higher and the rate of ice formation is less, it can be determined according to the F. I. Bydin formula

$$h = 2\sqrt{\Sigma t} \quad (3)$$

where: $h$ is the ice thickness, cm; $\Sigma t$ – the number of degree-days of freezing or the successive sum of daily air negative temperatures.

The diversity of ice conditions can be represented as a certain matrix showing distribution of ice conditions in the district of navigation or just a matrix of ice conditions. It should be noted that if the ice capable ship works mainly to break the continuous ice cover, and if other ice conditions occur, if any, they will occupy a small fraction of the total operating time of the vessel in ice. Therefore, the ice conditions, which include a continuous ice cover of various thicknesses, are considered in this paper.

**Table 1. The ice conditions matrix**

| Ice thickness | $h_1$ | $h_2$ | … | $h_n$ | $\Sigma d_i = 1$ |
|---------------|-------|-------|---|-------|-----------------|
| A share of the given ice thickness | $d_1$ | $d_2$ | … | $d_n$ |... |
The fraction of the ice thickness \( d_i \), depending on the way of establishing the ice conditions, can be represented in two ways [4]. In the first case, it is the relative time relative to the vessel movement \( \bar{t}_i \) 
\[
\left( \sum \bar{t}_i = 1 \right)
\]
in specific ice conditions. In the second case, it is the relative length \( \bar{d}_i \) 
\[
\left( \sum \bar{d}_i = 1 \right)
\]
of a part of the route with constant ice conditions. Depending on the representation of \( d \), we will talk about the first and second ways of specifying ice conditions.

Optimization is carried out according to the generalized criteria [5]. For the first method of specifying ice conditions, the generalized criteria are as follows:
\[
K_1 = \sum C_i \bar{t}_i / \sum V_i \bar{t}_i \quad K_2 = q_T \sum N_i \bar{t}_i / \sum V_i \bar{t}_i
\]
(4)

When specifying ice conditions in the second way, the generalized criteria will look like:
\[
K_1 = q_T \sum \left( N_i / v_i \right) \bar{V}_i, \quad K_2 = \sum \left( C_i / v_i \right) \bar{V}_i
\]
(5)

where:
- \( K_1 \) - the relative fuel consumption of the main engines for icebreaking work, kg / km;
- \( K_2 \) - the specific resulted expenses for icebreaking work, thousand rubles / km;
- \( C \) - the resulted expenses, rub / h;
- \( v \) - ship’s speed, km / h;
- \( N \) - total power on propeller shafts, kW;
- \( q_T \) - the specific fuel consumption of the main engines, kg / kW·h.

Optimization criteria are called generalized criteria because they take into account the diversity of ice conditions in the area of operation, and for the same vessel the criteria will be of different values depending on the ice conditions distribution.

For the timely start of transportation depending on Russia’s GDP, an artificial breaking of ice is performed with the help of icebreakers with canals laying along the main navigable routes. The ice cover movement starting, ice channels cease to exist, and transport vessels are conducted in broken ice. It is at this time, when the most difficult period of the fleet piloting through ice starts. The main obstacles for ice capable transport ships during this period are the following: drifting large ice fields, ice jams and a cohesive multilayered broken ice. A large number of shallow ice is formed by the interaction of ships with ice cover. The matter is that intensive fleet piloting through ice, is carried out as a rule on the same relatively small sections of the waterway (100-300 km) and within the boundaries of large offshore moorings.

Ice conditions when navigating in broken ice are specified by a large number of factors affecting the vessel’s operation in ice.

According to the classification of broken ice proposed in [6], the broken ice is divided into the sizes of individual ice floes: large-sized, fine ice, and ice porridge. The size of large-sized ice is considered to be from 5 to 20 m, fine ice from 0.5 to 5 m, the size of ice porridge particles is to be less than 0.5 m.

The main features, the surface of broken ice is to be assessed, are cohesion and destruction. In addition, broken ice has parameters determining its size. These are thickness of the ice floe and its range (the average size of the diameter of the ice floe).

The cohesion of the broken ice is the ratio of the total area of the ice floes in the given area to the water area. The cohesion of ice is determined according to a ten-point scale (Table 2)

The ice cover of the large water reservoirs of the European part of Russia, in contrast to the Arctic, is a very uniform field in terms of thickness and strength. When such a homogeneous field is destroyed by vessels, a small size ice should be formed in the pilot area. [6]. This is facilitated by the interaction of vessels with the ice cover when the latter is monotonous, and the dimensions of river transport vessels are commensurate with each other. Thus, the thickness and extent of individual ice floes in the pilot area should fluctuate around some average values. Based on the results of full-scale observations, the average value was obtained the curve showing the distribution of ice floes of various lengths in the navigational zone of the fleet (see Figure 2).
Table 2. The scale of cohesion of broken ice

| Points | Characteristics of the surface of the water area | The ratio of the area of floating ice to the area of the water area (%) |
|--------|-----------------------------------------------|-----------------------------------------------------------------|
| 0      | No Ice                                        | 0                                                               |
| 1      | Separate ice floes                           | 10                                                              |
| 2      | Very rare ice                                | 20                                                              |
| 3      | Rare Ice                                     | 30                                                              |
| 4      | Rarefied ice                                 | 40                                                              |
| 5      | Ice of average cohesion                      | 50                                                              |
| 6      | Low rarefied ice                             | 60                                                              |
| 7      | Cohesive ice                                 | 70                                                              |
| 8      | Very solid ice                               | 80                                                              |
| 9      | Almost continuous ice                        | 90                                                              |
| 10     | Solid ice                                    | 100                                                             |

Destruction of broken ice is determined by external signs (color, water saturation) of ice and is estimated in points on a five-point scale (Table 3).

The thickness and length of broken ice are determined in various ways, including direct measurements.

Table 3. Scale of the ice cover destruction

| Points | Characteristics of ice | Approximate strength of ice in comparison with winter ice (%) |
|--------|------------------------|--------------------------------------------------------------|
| 0      | Absence of external signs of destruction   | 100                                                          |
| 1      | Individual spots of water from melted snow on the ice | 90                                                          |
| 2      | The ice cover is poured with melt water     | 80                                                          |
| 3      | Intense destruction of the upper snow layers| 60                                                          |
| 4      | The ice is blue, the intercrystalline interlayer is destroyed | 40                                                          |
| 5      | Ice is strongly impregnated with water, crumbles into individual crystals | 10                                                          |

The obtained distribution of the ice length (see Figure 2) shows that small ice [6] is 87% of the total amount of broken ice in the pilot area. It should be noted that ice floes with diameters less than 0.5 m are neglected. Of the total number of ice floes in the observed area, 45% -30% are from 2 to 4 meters. The results of full-scale observations confirm the assumption that the dimensions of the ice floes in the navigational zone fluctuate within a narrow range. Based on the results of field studies, a relationship was established for the river ice thickness and the length of ice floes (see Figure 3)

Explicitly defined parameters of broken ice make it possible to use them in the future to build a matrix of ice conditions, with reference to operation of ice-breaking vessels in broken ice. This, in turn, makes it possible to take advantage of the proposed mathematical model of the ice capable ship design [1], implemented as packages of applied programs for a personal computer.

The approach to assess the ice situation when creating geometry of an ice capable ship hull allows us to solve optimization problems for any content of the ice conditions matrix.
Figure 2. Distribution of ice floes of various lengths in the navigational zone of the fleet.

Figure 3. Dependence of ice length on ice thickness

References
[1] Ionov B P and Gramuzov E M 2001 Ice navigation of vessels. Monograph *SPb: Shipbuilding* 512
[2] Sandakov M Yu 2004 An overview of the ice regime on Russian inland waterways Pros. Conf. The future of technical science, NSTU 206-207
[3] Bogorodsky V V and Gavrilov V P 1980 Ice L.: Gidrometeoizdat 383
[4] Zuev V A and Tikhonova N E 1999 Justification of the choice of design characteristics of river icebreakers 3rd International Conference on Marine Intellectual Technologies: Proceedings of the conference, collection of reports, S. Petersburg 1 42-45
[5] Ionov B P, Gramuzov E M and Zuev V A 2013 Designing of icebreakers SPb: Shipbuilding 512
[6] Tronin V A 1966 To assess the ice situation on rivers and reservoirs. Proceedings of GIIVT, Moscow: Transport 85 76-75