ABSTRACT
The task to define the amount of ice channels in fast ice at approaches to the port of Sabetta to provide all-year-round navigation was set in 2012 in the framework of projects for gas field exploration and construction in the Ob Bay. This task was solved by both mathematical and physical stimulations. The paper describes methods and discusses preliminary results of physical modeling in the ice tank of AARI. A self-propelled model of LNGC which is going to be used in the Ob Bay has been created. The model provided geometrical and dynamic similarity and similarity of propellers thrust. Experiments implied successive passages in the channel once in 3–4 hours. The test goal was to study ice performance of a vessel in the channel in the conditions of ice accumulation. Two series of tests were conducted and showed that there are 2 parameters which have the major influence on ice performance of a LNGC: the volume of broken ice in the channel and ice consolidation on the channel edges. According to the preliminary data the second factor is more influential for large capacity vessels with a long parallel body part.

INTRODUCTION
Simulation of a LNGC movement along the ice channel in the ice tank is a part of a large project implemented by AARI under the commission of “Yamal LNG” regarding design of a transportation system for carrying liquid gas from Sabetta settlement to the coast of Yamal peninsula in the Ob Bay where a gas liquefaction plant is going to be built. Liquefied gas is assumed to be transported by large LNGCs which are designed especially for this project. The transportation system should function continuously all year round. In order to provide navigation of large tonnage ships in the Ob Bay it is necessary to dredge the seabed along the navigation route of about 50 km, thus, the question concerning the width of a dredge track rose. Waters in the Ob Bay are covered with ice the most part of the year; therefore transport ships should use an ice channel. The experience of shuttle use of ships in a certain part of the ice route shows that navigation of ship in the same channel in winter period becomes more hampered after a number of ship passages than navigation in a parallel new channel. The method of support of the route in operational condition by making a new parallel channel is easily applied in case of unlimited length of ice waterway. In case of limited waterway the number of new routes for the channel should be restricted. Therefore AARI faced the task to define the amount of ice channels in fast ice and their properties to provide all-year-round navigation of LNGCs. The required amount of ice channels defines the needed width of dredge.

AARI has solved the following tasks within the project:

- Mathematical modeling of the ice channel evolution*;
- Definition of morphometrical properties of the channel including its width, ice distribution under edges etc.;

* Evolution implies changes of the state broken ice in the channel under the influence of negative temperatures measuring from a ship passage in the channel
- Definition of the number of channels made during one season;
- Definition of the required width of dredge.

Physical modeling in the ice tank served an auxiliary tool to solve the set task; its goal was to verify the mathematical model and to add in situ data. Methods of the channel evolution simulation have been developed on the basis of AARI adopted methods of preparation of modeled ice with strength properties which are weakened at the scale of the experiment. Experiments have been carried out using a self-propelled model of LNGC made in accordance with the requirements of the similarity theory. As a result, factors influencing the speed of LNGC movement during the channel evolution were found out.

**OVERVIEW OF EXISTING EXPERIENCE**

One of the navigation regimes for transport ships in ice is ship movement in a channel cut in fast ice. Contrary to independent navigation in consolidated or drifting ice navigation in an ice channel has a number of particularities. On the one hand, the channel is clogged with broken ice that should decrease resistance of the ship navigation. However it refers only for a recently made channel. In time and depending on intensiveness of use the channel conditions considerably change. Consolidated rubble ice field form on the channel edges, they accumulate cold that leads to intensive ice formation on the edges and, consequently, to the channel narrowing. Volume of ice in the channel increases due to growth of young ice in open water between broken ice. Thus, broken ice thickness in the channel could exceed thickness of adjacent even ice. Very low temperatures and low intensiveness of navigation in the channel can lead to consolidation of ice cakes in the channel. All the abovementioned factors largely affect navigation, once there is a moment when transport ship navigation in the channel becomes impossible and there is a need to make a new channel. Evaluation of changes of the channel parameters during its use, evaluation of opportunities for ship navigation in the channel in the given area, definition of navigation speed, definition of the amount of channels necessary for support of continuous all-year-round navigation are important tasks and need to be taken into account when developing transportation systems and planning transport operations. These tasks have been solved by Russian and foreign experts during recent decades both by in situ observations and by simulation experiments.

One of the first attempts to solve the given tasks were made by Soviet scientists in the early 1970s in order to extend navigation in the port of Dudinka in the Enisey River (Report, 1971; Report on research and development, 1972; Report, 1973). During 1971/72 and 1972/73 navigations AARI experts conducted in situ investigations in the Gulf of Enisey where the channel was supported and transport ships were piloted by the icebreakers “Captain Belousov”, “Captain Voronin”, “Captain Melekhov” and “Murmansk”. The channel passability depending on frequency of its use was researched, ice thickness profiles were measured, power unit and propeller complex operation parameters were fixed, and weather conditions were described. It was found out that the channel age significantly influenced the speed of an icebreaker movement: if it was 6–7-day-old channel the icebreaker speed reduced 1.5–2 times.

Foreign scholars have also been studying the problem of ship navigation in old channels during recent decades. This issues are especially relevant for regions with all-year-round ferry service or regular navigation of transport vessels, in particular, the Gulf of Finland, the Gulf of Bothnia, the system of Saima lakes, near the coast of the Canadian archipelago (Kostilainen, 1981; Sandkvist, 1981; Kannari, 1983; Nortala-Hoikkanen, 1999; Leiviska, 2004; Ice management…, 2011 et al.). The given papers studied the issue of ice thickness
growth in the channel compared to surrounding even ice thickness at regular passages of ships in the channel. For example, according to observations in the Baltic Sea (Nortala-Hoikkanen, 1999) it was defined that the ratio of broken ice thickness in the channel to surrounding even ice thickness reached 3 by the end of winter period, meanwhile the ratio of ice rubble in the channel edges to the same surrounding even ice thickness could be considerably higher. Evaluating ship navigation in the ice-clogged channel it was attempted to link ice resistance to a ship movement or its speed at given capacity with effective ice thickness or bulk of ice in the channel. In particular, Kannari (1983) showed a dependency of thickness of ice clogging in the channel on frost degree-days and amount of ship passages in the channel. The main goal of the most of given investigations was to develop methods of assessment of broken ice thickness in the channel at different stages of its use. Basic components of the well-known formulae include thickness of even ice where the channel has been cut, total amount of frost degree-days and a coefficient which depends on water area – deep sea, river, lake etc. Based on the research results the conclusion that more intensive navigation leads to considerable increase of ice thickness in the channel was drawn.

There were some model tests in different ice tanks in order to define parameters of an ice channel at various schemes of their use. A large investigation which included in situ data, calculations under mathematical models and experiment in an ice tank was conducted in 1990 CRREL – Cold Regions Research and Engineering Laboratory, USA, it was aimed at studying ice accumulation in frequently used ice channels (Ettema, Huang, 1990). The research resulted in the following conclusion: if a ship passed the channel twice a day the volume of ice in the channel increased 2–3-fold compared to the situation if ice in the channel was growing during a whole ice season without ship navigation. This result was obtained for freshwater ice in rivers and lakes of North America.

A special program for simulation of broken ice in the channel in the ice tank conditions was carried out at NRC Institute for Ocean Technology and described in the paper (Wang et al, 2009). It was connected with the fact that in Finish-Swedish regulations ship ice passability was defined according to a ship capacity to move in the channel clogged with broken ice of the given properties with the permanent speed of 5 knots, but there was not an established method of broken ice preparation in the ice tank so far. The paper analyzed influence of broken ice structure on its resistance to ship movement. However no data on changes of broken ice conditions, its consolidation or growth of ice thickness due to ice formation were provided.

Summarizing all data from available literature one can state that there was not analogue to the conducted experiment. Its main features included provision of navigation without an icebreaker, use of a large tonnage ship, operation of a transportation system in sea ice. Therefore, approaches, methods and means of experiment implementation for model test have been developed for the first time.

DESCRIPTION OF EXPERIMENTS

Methods of modeling

As it has been mentioned in literature physical modeling of the channel evolution is not a wide-spread type of experiments carried out in ice tanks. Hence implementation of works required special unique methods of modeling. There are the following basic provisions of the methods worked out in theory:

- A model of a ship to be used in situ is developed;
• At channel freezing after the model passage modeled ice is formed in the channel;
• The experiment implies multiple repetition of the model passages along the channel in certain time periods.

A number of parameters should be fixed at each passage since they characterize the conducted experiment:
• The model response to ice interaction is measured;
• Morphometric channel properties (concentration of ice, dimensions of broken ice in the channel, channel width etc.) are defined;
• Physical-mechanical ice properties are determined.

Moreover, technical photographing and filming are carried out.

The criteria of the channel passability is that ice resistance to a ship movement does not exceed propulsion power. These methods exclude modeling of temperature regime and time scale.

To provide strength similarity of original even ice as well as newly ice formed in the channel it is necessary that open water areas in the channel between broken ice to be clogged with modeled ice. Thus, “filling” with modeled ice was performed simultaneously with the ship passage. Minimum thickness of modeled ice which meets similarity criteria comprises 3–4 mm that depending on scale corresponds to 15–20 cm in situ. It is impossible to get smaller thickness. The thing is that during “filling” the channel firstly elastic film of overcooled drops emerges in open water areas which later become crystallization cores for growth of modeled ice. Time and a certain temperature regime are required for this film to transform into a thin layer of modeled ice with the given properties. In terms of AARI ice tank this thickness requires inter-passage time period to be about 4 hours, which was used in the experiments.

**LNGC model**

A self-propelled model in the scale of 1:60 equipped with 3 Azipod propellers analogous to the real ship has been made. There are mass and size characteristics of the model:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (design water line), mm</td>
<td>4822.4</td>
</tr>
<tr>
<td>Width (design water line), mm</td>
<td>840.5</td>
</tr>
<tr>
<td>Draught (design water line), mm</td>
<td>196.7</td>
</tr>
<tr>
<td>Side height, mm</td>
<td>393.3</td>
</tr>
<tr>
<td>Hull weight, kg</td>
<td>94</td>
</tr>
<tr>
<td>Ballast weight, kg</td>
<td>450</td>
</tr>
</tbody>
</table>

To provide similarity of simulation of ship movement in the ice channel and to ensure ice distribution in the channel area and under its edges self-movement of the ship generated by its own propellers is the requirement. Design scheme of Azipod propeller and an assembled propeller model prepared for installation in the LNGC model are shown in fig. 2.
RESULTS OF EXPERIMENTS

Due to the matters of secrecy only descriptive results of experiments are discussed in this section, there are no quantitative assessments of ice passability of a large tonnage LNGC in the old channel.

Firstly, one should mention that the growth of ice concentration in the channel has been observed while the number of the model passages along the channel have increased. Consequently, the share of open water surface has decreased. Fig. 3 shows changes of the channel appearance in the course of successive passes. According to expert estimates, ice concentration has been the following:

3 points after the first pass;
4 points after the second pass;
5 points after the third pass;
6 points after the forth pass.

At the same time ice crumbling has been observed. After the first passage there almost has not been small ice cakes (less than 2 mm in diameter if converted into in situ sizes) (see Fig. 3a). When the number of passages has grown the share of this fraction has constantly increased (Fig. 3b, c, d).

The given processes lead to increase in ice resistance to ship movement in the channel.
Later the following process has been identified during the experiments. It is known that broken ice formed due to the ship movement has the form of segments. Therefore, the channel edges formed after the first model passage in even ice has the form of a number of arches.
prominent outwards the channel axis (Figs. 4 and 5). While the number of passages increases, the process of clogging of edge irregularities with ice particles occurs due to the abovementioned increase of the amount of small ice fractions. Consolidation of these particles and their consolidation with the original edge lead to leveling the edges (Fig. 4). Meanwhile, the channel width decreases and becomes comparable to the ship width.

![Fig. 4. The form of the channel edges after the model passage in even ice (on the left) and leveling the channel edges after several passages (on the right)](image)

Therefore, in the course of multiple passages of the model the channel edges form changes from arch-shaped to straight linear profile. Since after some passages the ship starts interacting with the channel edges along the length of cylindrical parallel body part that leads to considerable growth of ice resistance to the ship hull. The scheme of the process is shown in Fig. 5.

![Fig. 5. Leveling of the channel edges due to small ice cakes accumulation: 1 – the channel edge after the first model run; 2 – small ice cakes accumulating near the channel edges; 3 – the actual channel edges after 3–4 passes; 4 – unbroken even ice; 5 – LNGC](image)

Besides natural and expected ice formation on the surface of emerging open water the fact of ice consolidation on submerged sides of the channel and broken ice has been found out during the experiments (Fig. 6).
Consequently, vertical section in the area of old-newly formed ice border is characterized by the arch-shaped form. The scheme of the process is shown in Fig. 7.

Due to the model movement ice coming under the channel edge has been identified. The width of ice under the channel edge comprised 1/3–1/4 of the channel width. Its depth distribution comprised 2–3 thicknesses of original even ice (Fig. 8). In the given figure photos have been taken from even ice towards the channel axis.

One should mention that ice coming under the channel edge has got the given parameters after the first passage. The subsequent model passages have not resulted in considerable changes of these parameters, i.e. ice accumulation under the channel edge has stopped. It has been observed that consolidation has mainly occurred between ice cakes and even unbroken ice. Mutual consolidation of ice flows has been quite rarely observed.

It is noteworthy that ice cakes consolidation leads to hardening of even ice adjacent to the channel edge. As a result of two abovementioned processes – leveling of the channel edges
and ice rubbing on side surfaces – the facts of large ice fragments breaking out of the edge have been witnessed at final stages of the experiments.

Here is the mechanism of this phenomenon. As it has been described ice comes under the channel edges after the first passage then it consolidates with even ice thus making it harder. At the same time small ice cakes clog in the channel edge irregularities. Due to consolidation with the edge and formation of new ice clogged areas also acquire big strength. Until the channel width becomes equal to the model width along the hull the model can successfully pass this channel leveling some protrusions. When the edge levels completely it faces the process of ice formation equal to that shown in Fig. 7. As a result once the actual channel width becomes smaller than the model width. However ice breaking is performed not by the bow part but by the cylindrical parallel body part area. Since the model movement is provided by cart towing vertical force is applied to the channel edges along the whole cylindrical parallel body part of the model. This loading leads to breaking of large fragments out of the channel edges. A crack goes beyond the ice coming under the edges area. The length of these fragments is comparable to the length of cylindrical parallel body part of the model; maximum width reaches up to 1/2 of the channel width.

CONCLUSIONS

Physical modeling of the ice channel evolution has been carried out in the test ice tank of AARI. The first and one of the most important results is the developed method of model study of ice performance of a large LNGC in the old channel.

In the course of experiments studying the channel evolution growth of ice concentration in the channel along with increase in the number of the model passages along the channel has been observed. The process of ice crumbling has been mentioned with the share of small ice cakes constantly increasing. Both factors lead to increase in resistance to the model movement in the channel. The same situation is usually observed in nature conditions. So, it could be said that the model tests are similar to full-scale observations in a qualitative sense.

While the amount of passages increases clogging of the channel edges with ice cakes occurs. Consolidation of these particles and their freezing to the original channel edges leads to the edges leveling. Thus, the channel width decreases and actually equates to the ship width. Hence the ship interacts with the channel edges along the whole length of the hull cylindrical parallel body part.

The fact of ice growth on submerged side surfaces of the channel edges and broken ice has been observed, so vertical section in the area of old-newly formed ice border is characterized by the arch-shaped form.

Ice comes under the channel edges, its width amounts to 1/3–1/4 of the channel width, its depth distribution comprised 2–3 thicknesses of original even ice. Ice coming under the channel edge has got the given parameters after the first passage, ice accumulation under the channel edges stops. Consolidation of broken ice and unbroken even ice has been observed. Mutual consolidation of ice cakes almost does not exist. Ice cakes consolidation leads to hardening of even ice in the area adjacent to the channel edges.

Leveling of the channel edges, formation of ice on submerged side surfaces of ice, hardening of the edges in the area of ice accumulation under the channel edges leads to formation of the channel which width is smaller than the model width. Taking into account the long cylindrical parallel body part the factor exerts the main influence of the growth of resistance to the model movement in the channel.
Therefore, it has been found out that ice resistance to the ship movement in the channel includes 2 components:

- Resistance of broken ice in the channel;
- Resistance of friction on the channel edges.

To specify significance of each of these factors additional experiments are going to be carried out. During March–April 2013 the full scale observations of ice channel in the Ob Bay were performed. The obtained data will be used for verification of model tests.

REFERENCES
Report on research and development. Development of proposals to increase the period of navigation along the Northern Sea Way to Dudinka in order to transport cargo of Norilsk mining field. Assessment of technical opportunities and economic efficiency of navigation in the extended periods based on data of 1971 experiment. State Design and Assembly Research-Scientific Institute of Sea Transport SoyuzMorNIIPROEKT. M., 1972.
Report on expeditionary works A66/*70 on board of the icebreaker “Captain Melekhov” in 1972–73 autumn-winter navigation period. AARI archives. L., 1973