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Analytical Model of Navigable Channel Evolution in Ice Conditions

Evgeny B. Karulin, Marina M. Karulina and Oleg V. Tarovik
Krylov State Research Centre
St. Petersburg, Russia

Ship traffic via navigable freezing ice channels causes a gradual accumulation of small ice floes mixed with water, known as brash ice. The thickness of the brash ice layer may reach the values when ship navigation becomes difficult or even impossible. This paper introduces a computational model intended to predict ice channel evolution in winter. The model considers the thermodynamics of the ice-growing process and allows the estimation of the parameters of the cross-section of the ice channel depending on the number of freezing degree-days and the schedule of ship passages. Unlike existing models, the described scheme of channel evolution takes into account that some brash ice is pushed beneath ice channel edges by passing vessels, and therefore the obtained cross-section profile is similar to that observed in full-scale conditions.

INTRODUCTION

Ship navigation in freezing waters is conducted via ice channels made in the ice cover. A channel behind the icebreaker remains but is filled with broken ice fragments. Ships may use the same ice channel time and again. Between ship passages, a fresh ice cover grows in the channel under freezing temperatures. At each ship passage, the ice cover is broken again, and ice blocks are split into smaller pieces. Frequently used channels accumulate smaller ice floes (mean size 50 cm) mixed with water ("brash ice"). The water content is defined by the porosity of the brash ice, which influences the intensity of ice accumulation in the channel.

Ship navigation in ice channels filled with brash ice involves two main issues. First, it is necessary to know the current state of the ice channel. The second issue is related to ship performance in the ice channel, including the hull resistance and the effect of brash ice on propeller operation. This study examines only the first issue, the evolution of the ice channel during the winter season.

This study is focused on describing the channel cross-section shaping and transformation under the influence of repeated ship passages during a long winter season. In this context, the role of some thermodynamic factors in the ice growth process was left out of consideration.

Previously, a number of authors suggested some theoretical models to represent ice channel evolution (Ashton, 1974; Michel and Brenger, 1975; Vance, 1980; Sandkvist, 1981; Hamza, 1985; Riska et al., 2014; Klyachkin et al., 1999). Ettema and Huang (1990) identified the main factors influencing the evolution of channels: first are the number of freezing degree-days at the channel location and the frequency of ship passages through the channel.

Almost all of the above-mentioned models of ice accumulation and freezing in ice channels deal with the classical Stefan problem of the displacement of the liquid/solid (water/ice) boundary, which is solved using heat conductivity equations (Stefan, 1889). With respect to ice channels, the initial medium is assumed to be brash ice rather than water, and, accordingly, the case in hand deals with the interface between two phases: brash ice and solid ice at the upper part of the brash ice (the consolidated layer). This study considers the solution to the Stefan problem stated in such a way that it is possible to define how the thickness of the consolidated layer in the channel changes depending on the flow of the cold.

Note that the models that have been developed so far to describe the evolution of navigation ice channels are semi-empirical. Empirical coefficients applied in the proposed formulas are estimated based on full-scale measurements made in areas with mild or moderate ice conditions: most computational models refer to Baltic Sea ice conditions. Some results of full-scale measurements carried out for cross sections of navigation channels in the Baltic Sea are given in Nortala-Hoikkanen (1999), Riska et al. (1997), and Veitch et al. (1991). This kind of approach restricts the scope of application for the proposed computational models, since empirical coefficients determined based on field measurements allow us to evaluate the amount of brash ice only for the channels that are formed in similar conditions to the channel where these measurements were actually made (i.e., comparable thermodynamic conditions and schedule of ship journeys).

In connection with the latest efforts to master Arctic waters, these issues need to be considered in the context of the severe ice conditions typical of this region. For the Arctic, with its large number of freezing degree-days, channels can be expected to have more intensive accumulations of brash ice, which may be as thick as 10 m (Riska et al., 2014). The model of ice channel evolution given in Riska et al. (2014) was used to investigate ice thickness buildup processes in the Ob Bay ice channels. However, since there were no measurements regarding the cross-section profiles of navigable channels in Arctic waters, the data available from measurements in the Baltic Sea (Riska et al., 1997) were used to introduce a correction factor for calculating the brash ice thickness.

A common disadvantage of the channel evolution models under consideration is that these models neglect the horizontal movement of brash ice perpendicular to the channel axis in the process of ship motion, which pushes some brash ice under the channel edges, resulting in ice ridge features along channel boundaries. This process is observed in full-scale conditions, and it is probably caused not only by displacement of broken ice by the ship hull but also by the thrusters. Figure 1 shows (a) a real channel cross-section and (b) a rectangular cross-section of the Sandkvist (1981) calculation model using a so-called "equivalent" ice thickness that represents the ice thickness averaged across the width

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