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Brash ice growth model – development and validation

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ABSTRACT

Brash ice growth in frequently navigated areas like fairways or ports is quick due to the 'freezing – breaking' cycle induced by sub-zero temperatures and ship traffic. This problem is very acute in ports in Arctic areas where the temperatures are very low for long durations and the ship traffic is frequent. In order to take adequate action in managing the brash ice, the forecasts of the amount of brash ice expected should be reliable. The aim of this work is to develop and validate these prediction methods.

The growth model developed is based on extension of earlier growth models which modify the Stefan type growth modelling. The improvement on the earlier models is that the brash ice layer is divided into three layers (instead of two in earlier models): The consolidated layer just below the water level, the brash ice over the water level and the unfrozen brash ice below the consolidated layer. The thermodynamic model follows the Stefan formulation including only the heat flux from latent heat release upon freezing (Stefan, 1891 and e.g. Anderson, 1961). The modelling includes the cyclic breaking and refreezing.

The validation of the model is made using measurements carried out in winter 2013 in Luleå port and in winter 2015 in Sabetta in the Yamal peninsula. Luleå data suggests that the sideways motion of brash ice due to ship motion and wake should be taken into account when assessing the brash ice thickness. The analytical calculation over-estimates the brash ice thickness in the actual channel but under-estimates the total amount of broken ice. When applied to Sabetta data, the analytical calculation predicts well the observed brash ice thickness. It can be concluded that the analytical method that does not take into account any radiation heat fluxes can be applied in the high Arctic where solar radiation plays a minor role and ice surface is clearly below zero.

1. Introduction

Brash ice forms in frequently transited navigation channels if the ice cover stays immobile and ships are navigating along the same track the whole winter. In the beginning of winter when ice starts to form, broken ice forms slush (ice crystals mixed with water) when a ship passes in the channel and breaks the frozen layer. Gradually larger ice pieces start to form and the whole track will eventually be covered with ice pieces. As the ice pieces start from very small ice 'grains', it is clear that this kind of brash ice channel formation includes accumulation of ice into ice pieces during the breaking – freezing cycles. In the beginning of winter when ice pieces are small and there is not many of them, they do not cover the whole channel. When winter proceeds, more ice is formed and eventually the whole channel is covered. Then the thickness of the brash ice layer starts to grow. A photograph of a brash ice channel is shown in Fig. 1 where the small piece size is apparent and also the side channel edges. This kind of brash ice channel where the piece size grows due to frequent breaking – freezing cycles is referred here as Frequently Broken (FB) brash ice channel. Observations of ship channel properties are given for example in Tuovinen (1978) and Kannari (1983).

Another possible way of formation of a brash ice channel is when the ice cover is first let to freeze to a ice thickness h_i where this initial thickness is, say, more than 30 cm. In this case the first ship to pass along the channel breaks ice into relatively large ice floes – horizontal dimension may be of the order of 5 times the ice thickness and the ice coverage may be initially quite low (typically about 0.4–0.5). After breaking, the open water patches start to freeze and some thin ice forms on the open water patches between the ice floes which is again broken when the next ship comes and breaks the ice. This kind of process gradually abrades the larger pieces while the fragments from the new thin ice start to increase in size. The result is eventually similar to the FB brash ice channels with the exception that larger ice floes may

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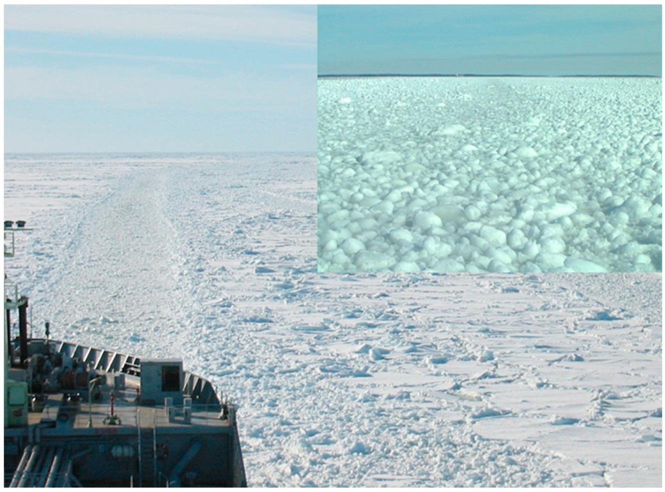

Fig. 1. A view of a typical brash ice channel showing also the side channel edges and a close up of the brash ice surface in the insert (photo K. Riska).

persist among the brash ice. Further research is required to fully understand the differences in the brash ice channel development, however here the focus is mostly on the FB type brash ice channels and neglecting in the modelling the initial growth phase when the ice coverage may be less than 100%.

The basic references of brash ice growth modelling are Sandkvist (Sandkvist, 1980; Sandkvist, 1981; Sandkvist, 1986), Ettema and Huang (1990) and Riska et al. (1997). In these studies a growth model for broken ice of porosity *p* was developed assuming a uniform layer of broken i.e. brash ice. The porosity dealt with here is called macro-porosity to distinguish from the micro-porosity which is related to liquid and air within the ice pieces. Macro-porosity refers to water (or air above the water level) between ice pieces. Porosity is defined as the ratio between water volume between ice pieces and total volume (below waterline).

After a breaking event caused by a ship passage, the water at and under the water level started to freeze – this is usually called consolidation. The freezing proceeds until the next ship passage occurs which breaks the ice. It is usually assumed that the piece size does not influence the freezing – breaking process and that the porosity stays constant. The freezing of the mixture of brash ice pieces and water is modelled by a basic heat flux problem following the work of Stefan (1891) and for example Anderson 1961. The heat flux released when ice freezes is transported by conduction to atmosphere where the temperature is assumed to be below freezing. The freezing process is thus a balance between the heat flux out of ice and heat flux created by freezing. The rate of growth of the thickness of the brash ice layer is shown to be about 1.8 times the growth rate of level ice in similar conditions (see for example Veitch et al., 1991; Lepparanta and Hakala, 1992; Lepparanta et al., 1995), depending on mainly the porosity as the growth rate is roughly proportional to $1/\sqrt{p}$ (exactly, if snow cover is ignored).

In this paper we consider additional parameters, such as the freeboard, to these models, and present the model development, example calculations of parameter sensitivity and validation. The development of the model was done partly by trainees who made their dissertations based on this work, see Tobie (2014) and Chomatas (2015).

Several analytical and numerical models have been developed to model level ice growth, see for example Semtner (1976), Maykut (1978), Ebert and Curry (1993), Bitz and Lipscomb (1999), Ukita and Martinson (2001) and Huwald et al. (2005) to mention a few. These models do investigate the effect of radiation on ice growth but not the freezing of broken ice.

2. Brash ice growth model

The aim of this study is to develop a model to calculate the freezing

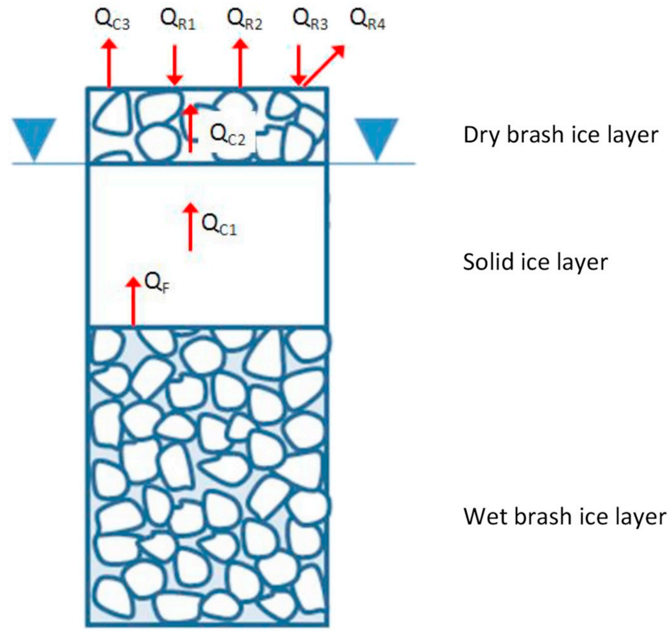

Fig. 2. Three layers included in the growth model and the heat fluxes present.

of brash ice below the waterline of the broken brash ice. The brash ice is divided into three layers: Brash ice above the water level, here the pores are filled with air (called here 'dry brash ice'); solid ice frozen from brash ice below the water level and brash ice below the solid ice where the pores are water filled (called here 'wet brash ice'). The solid ice layer growth is influenced by the following heat fluxes which are presented in Fig. 2 The fluxes and equations for them are (the radiation heat flux components are presented only for the sake of completeness, the radiation is not taken into account in the following derivation; to take radiation into account forms actually one of the main future enhancements of these derivations):

In-coming long wave radiation	Q_{R1}	Numerical values given in e.g. Maykut & Untersteiner (1971).
Out-going long wave radiation	$Q_{R2} = \epsilon_L \sigma T_0^4$	
In-coming short wave solar radiation	Q_{R3}	Value depends on local conditions, see e.g. Maykut and Untersteiner (1971)
Reflected solar radiation	$Q_{R4} = \alpha Q_{R3}$	
Heat conduction in bottom layer	$Q_{C1} = \lambda_i \frac{T_f - T_{sf}}{h}$	
Heat conduction in top layer	$Q_{C2} = \lambda_D \frac{T_{sf} - T_0}{H_D}$	
Heat conduction into atmosphere	$Q_{C3} = h_a(T_0 - T_a)$	
Heat flux due to freezing of ice	$Q_F = \rho_i p L \frac{dh}{dt}$.	

The temperatures T_{sf} and T_0 are explained in Fig. 3. The heat