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Analytical investigation of propeller operation in brash ice

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ABSTRACT

The ship performance in ice is affected not only by increased hull resistance due to ice component but also by reduced efficiency of propellers due to ice interaction. This paper considers a specific case of ice influence on propellers of ice-going ships, namely the propeller operating in brash ice. The brash ice is a mixture of water and small pieces of ice (mean size 50 cm), and this medium has a different density and viscosity compared to water. The presented analytical investigation consisted of two parts: 1) studying the influence of environment density and viscosity variations on hydrodynamics of propeller blade section using the numerical simulation of viscose flow around the blade sections by COMSOL Multiphysics® software; 2) evaluations of propeller performance (thrust and torque coefficients) based on propeller check calculation using the data on blade section parameters (lifting force and drag coefficients) obtained in the first phase of investigations. The object of research studies is a propeller of known geometrical and hydrodynamic characteristics. It allows us to assess how changes in environment (ice coming into play) affects the propeller efficiency. Calculations are done for different immersions of propeller disk in brash ice, which let us follow the variations of propeller thrust and torque versus brash ice thickness. In view of the lack of confident field data about propeller operation in brash ice, the results of analytical studies are assessed indirectly for adequacy. For this purpose, the results are qualitatively appraised against the published model experiment data on propeller operation in brash ice. The research results revealed that if propeller is immersed into brash ice to a depth equal to 20% of its diameter thrust coefficient reduces by ~10-15%, while torque coefficient increases by ~15-30%. These theoretical evaluations are well correlated with results of model tests for icebreaker performance carried out in ice basin.

KEY WORDS: Brash ice, Ship performance, Ship Propeller, Thrust, Torque.

INTRODUCTION

Movement of ice-going vessels in brash ice typical for old ice channels, port and ship intensive ice maneuvering water areas is one of operation modes thereof. The brash ice is a mixture of water and small pieces of ice (mean size 50 cm) and its thickness may be quite significant equitable to ship draught resulting in inevitable direct interaction of propellers therewith.

In this case ship performance shall be assessed with due account for not only increased hull resistance when moving in brash ice but also variations in ship propulsive performance, in particular, propeller performance curves and hull efficiency factors (wake fraction and thrust deduction fraction).

As against to a number of studies covering brash ice effect on ship resistance, a few publications target propeller operation in brash ice so far. Kostilainen (1981) offers results of cavitation tunnel model tests for propeller 0.24 m in diameter being operated in open water and in a layer of plastic particles simulating brash ice. Layer thickness was 0.075 m and 0.150 m (0.31 and 0.62 of propeller diameter). The results demonstrated that propeller operation in a 0.15-m-thick layer of plastics was accompanied by the significant torque increase as against to open water operation. At that propeller thrust remained almost the same. Propeller thrust and torque slightly increased in 0.075-m-thick layer. It's worth noting that such important parameters like plastic density and internal friction coefficients and propeller-plastic friction have not been analyzed. However, these characteristics define thrust and torque coefficients.

Other data on propeller operation in brash ice are obtained through model tests of Terry Fox icebreaker performance in ice basin of the Institute of Ocean Technologies (IOT), Saint Johns, Canada (Wang et al., 2009). The experiments, among others, included propulsion tests of ship model moving in open water and in channel filled with brash ice that enabled plotting propeller performance curves. Twin-screw ship model was tested, measurements were done for port side propeller. Modeling scale was 1:20.8, propeller model diameter was 0.22 m. The test results revealed reduced thrust coefficient for propeller being operated in brash ice and increased torque coefficient as compared to corresponding values for open water operation.

The above listed investigations are experimental. The goal of this study was the development of theoretical approach for quantitative assessment of interrelation between the depth of propeller immersion into brash ice and its hydrodynamic performance – thrust and torque coefficients. Open propeller was studied: variations in hull-efficiency factors – wake and thrust deduction fractions – were not addressed for brash ice operation.

Brash ice is considered to be an operating medium where propeller rotation takes place. Its characteristics – density and viscosity affecting propeller thrust and torque coefficients are different from respective parameters for open water. The investigation is carried out in two stages. The first stage includes numerical computations of hydrodynamic coefficients of propeller sections' blades (lift force and drag force coefficients) at different viscosity of liquid. Liquid viscosity corresponded to open water and brash ice. Thrust and torque coefficients of the examined propeller for various disk immersions into brash ice are defined under the second stage based on propeller check calculation.

As per the results of theoretical investigations brash ice brings reduced thrust coefficient and increased torque coefficient of propeller as against to open water operation. Comparison with experimental data obtained by Wang et al. (2009) demonstrated high results' correlation in terms of both quality and value.

DESCRIPTION OF COMPUTATION PATTERN

Propeller and its hydrodynamic characteristics

When propeller operates in liquid the generated thrust T and torque Q needed for rotation are found with formulae (Ship Theory Handbook, 1985):

$$T = K_T \rho n^2 D^4 \ \ [\mathrm{N}] \tag{1}$$

$$Q = K_Q \rho n^2 D^5 \ \ [\mathrm{N \cdot m}] \tag{2}$$

where ρ – liquid density, kg/m^3; n – propeller speed, 1/s; D – propeller diameter, m; K_T and K_Q – propeller thrust and torque coefficients, respectively, to be defined with the below formulae:

$$K_T = \int_{r_H/R}^{1} \frac{z}{4} C_Y \left(\frac{b}{D}\right) \left(\frac{v_R}{Dn}\right)^2 \cos\beta_I (1 - \varepsilon \tan\beta_I)\, d\left(\frac{r}{R}\right) \tag{3}$$

$$K_Q = \int_{r_H/R}^{1} \frac{z}{8} C_Y \left(\frac{b}{D}\right) \left(\frac{r}{R}\right) \left(\frac{v_R}{Dn}\right)^2 \cos\beta_I \,(1 - \varepsilon \tan\beta_I)\, d\left(\frac{r}{R}\right) \tag{4}$$

where r_H – propeller hub radius, m; $R = D/2$ – propeller radius, m; z – number of propeller blades; C_Y – lift force coefficient of propeller section blade at current radius; b – section length at current radius of propeller, m; r – current radius of propeller, m; v_R – resultant flow speed (considering induced velocities) incident to blade section at current radius, m/s; β_I – induced advance angle at current radius, degree; $\varepsilon = C_X/C_Y$ – section drag-to-lift ratio, C_Y – propeller section lift coefficient for current radius.

Angle of attack α for each section is defined by difference between pitch angle φ and induced advance angle β_I (see Figure 1). Pitch angle is found with formula $\varphi = \mathrm{atan}\left(\frac{P}{2\pi r}\right)$ where P – propeller pitch at current radius, m.

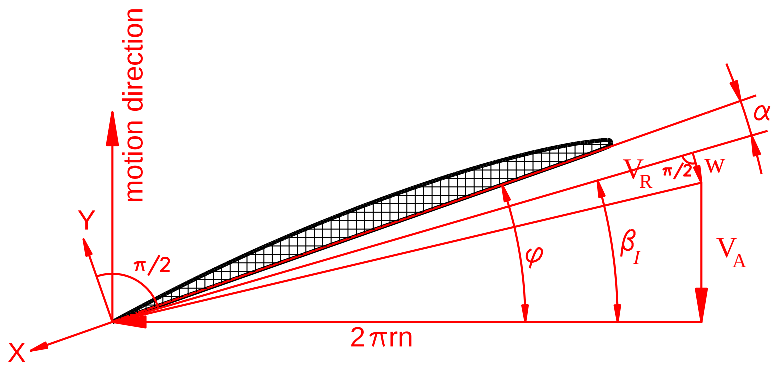

Figure 1. Velocity diagram nearby propeller blade section.
Y and X are lift and drag forces of propeller blade section, respectively

Resultant flow speed v_R is defined from the below relationship:

$$v_R = \sqrt{(2\pi r n)^2 + v_A^2 - w_i^2} \ \ [\mathrm{m/s}] \tag{5}$$

where v_A – propeller advance speed in axial direction, m/s; w_i – (total) induced current speed in blade section, m/s.

Formulae (3) and (4) enable computing propeller thrust and moment coefficients under various propeller operation modes defined by advance $J = \frac{v_A}{nD}$, and obtaining relevant relations – propeller performance curves.

Propeller efficiency may be found through:

$$\eta_0 = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi}. \tag{6}$$

This study offers calculations for performance curves of propeller with known geometry being operated in water and brash ice layer. Four-bladed propeller of B4.70 Wageningen series with disc-area ratio $\frac{A_e}{A_0} = 0.7$ and pitch ratio $P/D = 0.7$ was used as a specimen. Detailed data on geometry and hydrodynamic performance for propellers of this series are available (Ship Theory Handbook, 1985). Ice-going vessels are generally equipped with propellers of different geometry as against to that being operated in open water. Since this study does not analyze propeller hydrodynamic performance but variations thereof in brash ice, then the Wageningen series propeller being selected as the study object is well substantiated.

Basic assumptions

Formulae (3) and (4) are used for calculation of thrust K_T and torque K_Q coefficients for propeller operation in open water and in brash ice layer. At that the below assumptions and simplifications were made:

- Brash ice is assumed to be the Newtonian liquid of higher viscosity.
- Formulae (3) and (4) for open water are developed based on plane section hypothesis. The same hypothesis is used for coefficients' calculation for brash ice operation.
- K_T and K_Q coefficients were calculated for open water using data on distribution of lift force coefficient C_Y over the examined propeller radius offered in Ship Theory Handbook (1985). Angles of attack corresponding to the assumed values of lift force coefficient were determined for each blade section.
- When propeller is operated in brash ice angles of attack for each blade section are the same, i.e. they are equal to relevant values for propeller operation in open water and at corresponding values of advance ratio. In other words, induced flow velocities at each section remain the same at propeller operation both in open water and in brash ice.
- When propeller is operated in brash ice turbulent mode of flow through propeller blade is maintained.

Brash ice density and viscosity

Brash ice density is found with the below formula:

$$\rho_{br} = \rho_w \cdot p + \rho_i \cdot (1 - p) \ \ [\text{kg/m}^3] \tag{7}$$

where ρ_w, ρ_i – density of water and ice, respectively, kg/m^3; p – brash ice porosity expressed in volume fractions.

Assuming that $\rho_w = 1025$ kg/m^3 and $\rho_i = 900$ kg/m^3 brash ice density will be $\rho_{br} = 925$ kg/m^3 for $p = 0.2$ porosity.

The results of previous theoretical and experimental studies were used for evaluation of brash ice viscosity coefficients. Landau & Lifshitz (1959) investigated viscosity of mixture consisting of liquid and solid particles. Kinematic viscosity of such mixture (suspension) $\tilde{\nu}$ may be assessed with:

$\tilde{\nu} = (1 + K\phi)\nu \quad [\mathrm{m}^2/\mathrm{s}]$ (8)

where ν – liquid kinematic viscosity, m^2/s; ϕ – volume fraction of spherical particles, K – coefficient of suspension viscosity variation, assumed to be 2.5 for spherical particles as per Landau & Lifshitz (1959).

Significantly higher viscosities were obtained by DeCarolis et al. (2005) during investigation of surface wave propagation in grease ice layer. This medium, as well as brash ice, is mixture of small ice pieces and water. These media are different by particle dimensions: they are significantly smaller in grease ice (~0.4 cm) as compared to brash ice (~50 cm). At the same time, it should be taken into account that the brash ice contains not only individual ice floes of different sizes but also grease ice, which is formed as a result of ice crushing and water crystallization. This suggests that the brash ice viscosity is close to the grease ice viscosity. Kinematic viscosity of grease ice is found with the below formula:

$\tilde{\nu} = \nu(1 - \phi)^{-K} \quad [\mathrm{m}^2/\mathrm{s}]$. (9)

DeCarolis et al. (2005) compared the results of their studies with those obtained through tests in Martin & Kaufman (1981) wave basin aimed at investigation of effective viscosity of grease ice. Good data correlation was obtained. When volume ratio of ice particles in suspension changes from 0.28 to 0.44 parameter K varies within 15 – 20 range that increases kinematic viscosity by 1500 – 10000 times.

The present study offers computational investigations into hydromechanical parameters of propeller blade sections for the following values of liquid viscosity coefficient: ν, 2.5ν and 10000ν where ν is the initial liquid viscosity.

DEFINITION OF HYDRODYNAMIC CHARACTERISTICS OF PROPELLER BLADE SECTIONS

Numerical simulation of flow around the blade sections over radius was carried out by COMSOL Multiphysics® software representing finite-element numerical simulation package. The blade sections corresponded to those of the selected B4.70 Wageningen propeller. Calculations were made for sections at relative radii $\frac{r}{R}$ = 0.3, 0.4,…, 0.9, 0.95. Lift and drag forces of blade at varied angle of attack were estimated, and then lift, drag coefficients and drag-to-lift ratio were found.

The problem of incompressible turbulent air flow around the blade section was solved in two-dimensional formulation using low-Reynolds $k - \varepsilon$ turbulent model. The chord of the calculated profile was 2 meters, the size of the computational domain was 180×180 meters. The number of elements was 111200, the thickness of the first element was $1.84 \cdot 10^{-6}$ m, the distance to cell center in viscous units was $\mathrm{l}_\mathrm{C}^+ < 0.25$ lengthwise the blade. Denser mesh was used for higher density case nearby blade surface, at that the distance to cell center in viscous units was $\mathrm{l}_\mathrm{C}^+ < 0.17$ everywhere.

The numerical model was preliminarily verified using experimental data on the air flow around the NACA 2406 aircraft profile (Jacobs et al., 1935).

The calculation results for blade flow at section $0.6R$ under 4° angle of attack with input viscosity ν and increased viscosity 10000ν are offered in Figure 2 as an example. Significant effect of viscosity variation on blade flow nature can be visually observed. It results in variation of blade hydrodynamic performance parameters depicted in Figure 3.

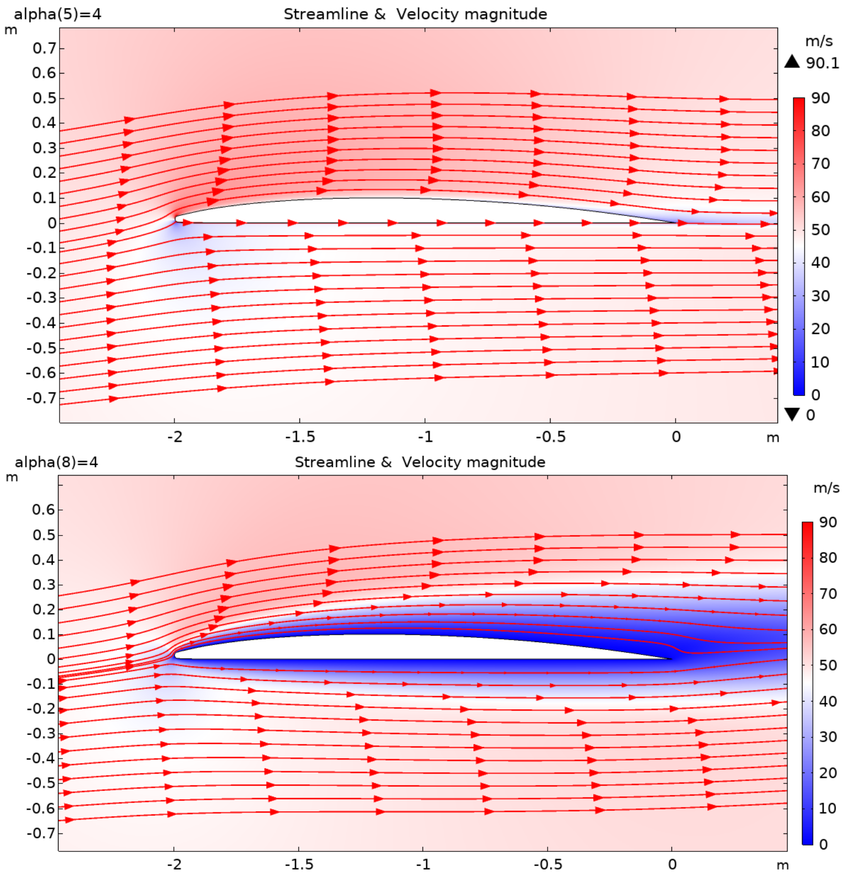

Figure 2. Flow around blade section at 0.6R radius and viscosity ν (top) and 10000ν (down). Angle of attack 4°

Calculation of blades with 2.5ν viscosity coefficient did not demonstrate significant variation in both blade flow patterns and numerical values of their hydrodynamic characteristics as compared to input value of ν viscosity.

DEFINITION OF THRUST AND TORQUE COEFFICIENTS OF PROPELLER OPERATING IN BRASH ICE LAYER

Propeller thrust and torque coefficients were calculated for three advance ratios using the obtained relations $C_Y(\alpha)$ and drag-to-lift ratio of blades $\varepsilon(\alpha)$. Propeller design conditions are given in Table 1.

Table 1. Design working conditions of propeller

Calculation option #	Propeller diameter D [m]	Rotation rate n [1/s]	Velocity v_A [m/s]	Advance ratio J
1	4.0	4.0	3.2	0.2
2	4.0	4.0	6.4	0.4
3	4.0	3.0	6.0	0.5

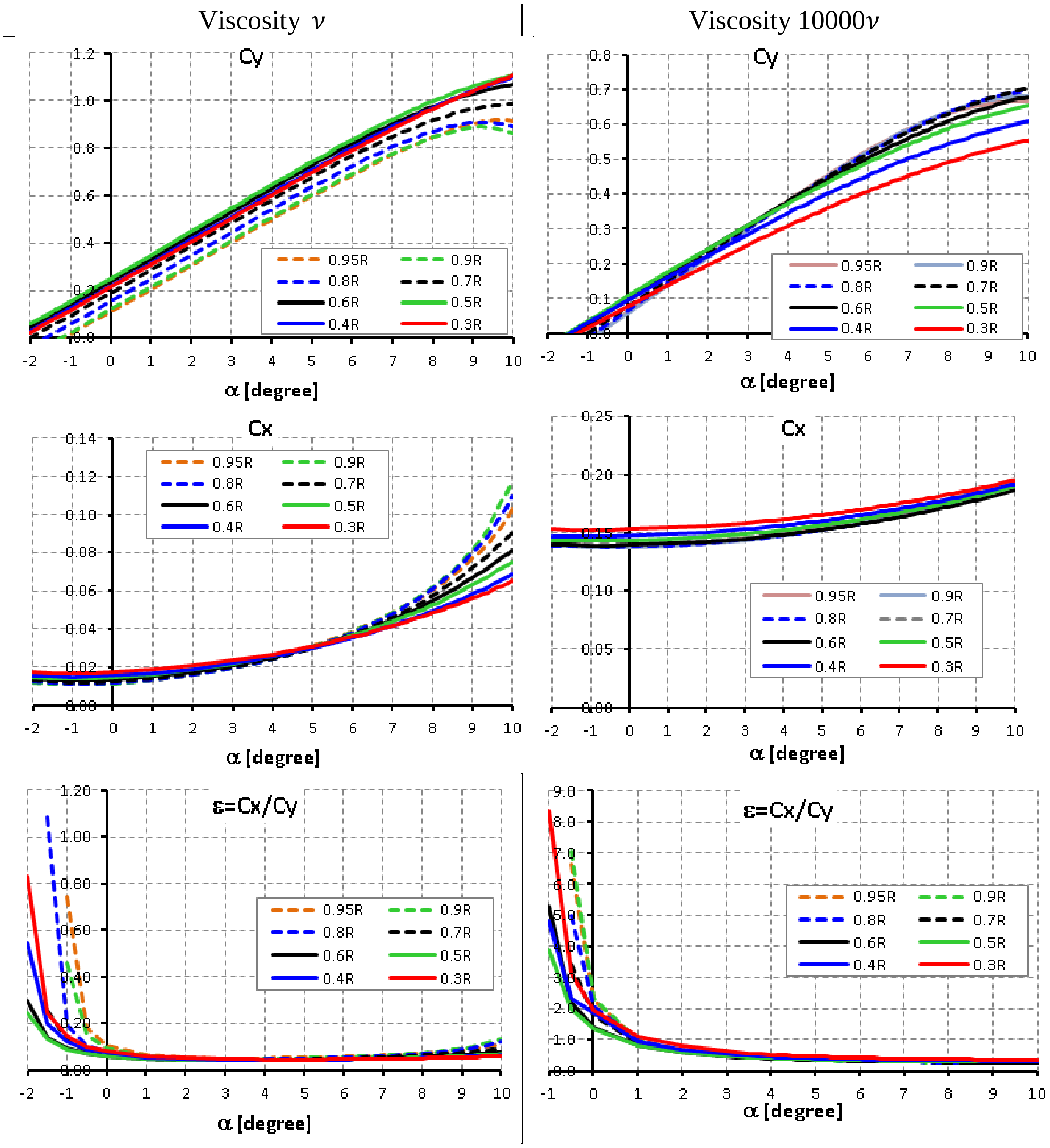

Figure 3. Hydrodynamic characteristics of propeller blade sections at different viscosities

Thrust and torque coefficients were calculated for propeller being completely immersed in liquid with specified kinematic viscosity. Calculations were for two cases: initial kinematic viscosity $\nu = 1.51 \cdot 10^{-5}$ m²/s and the same increased by 10000 times, i.e. at $\nu = 1.51 \cdot 10^{-1}$ m²/s.

Thrust and torque coefficients of propeller immersed in brash ice to a certain depth h_{br} (see Figure 4 to the left) were assessed through the below formulae:

$$K_T(h_{br}) = \left[K_{T\,br} \cdot A_{br} + K_{T0} \cdot \left(\frac{\pi D^2}{4} - A_{br}\right)\right] \cdot \frac{4}{\pi D^2} \tag{10}$$

$$K_Q(h_{br}) = \left[K_{Q\,br} \cdot A_{br} + K_{Q0} \cdot \left(\frac{\pi D^2}{4} - A_{br}\right)\right] \cdot \frac{4}{\pi D^2} \tag{11}$$

where $K_{T\,br}$, $K_{Q\,br}$ – thrust and torque coefficients of propeller completely immersed in brash ice, respectively; K_{T0}, K_{Q0} – thrust and torque coefficients in open water, respectively; A_{br} – propeller disk area immersed in brash ice to depth h_{br}, m^2.

The curves indicating variations in propeller hydrodynamic parameters followed by increase of relative depth of propeller immersion into brash ice are given in Figure 4 to the right. It is well seen that propeller thrust coefficient reduces and torque coefficient increases during the immersion that results in increase of power consumed for propeller rotation.

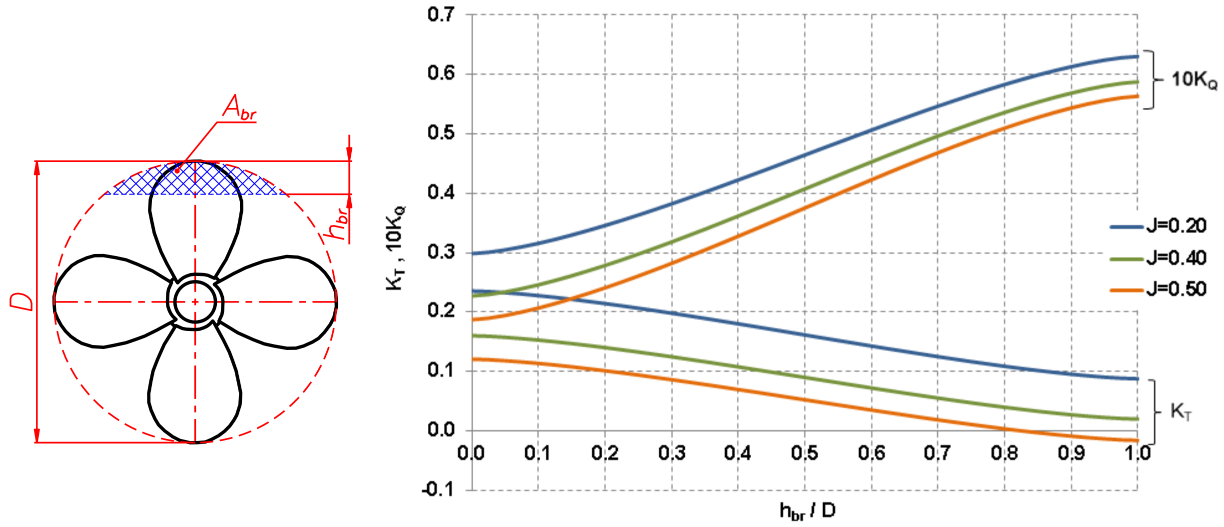

Figure 4. Variation of thrust and torque coefficients depending on propeller disk immersion into brash ice and advance ratio

The Figure 5 presents propeller performance curves in open water and at immersion into brash ice to $h_{br} = 0.2D$ depth. Reduced propeller efficiency at partial immersion into brash ice may be observed: thrust coefficient reduces by ~10-15%, while torque coefficient increases by ~15-30%. Reduction in propeller efficiency becomes more significant with increased advance.

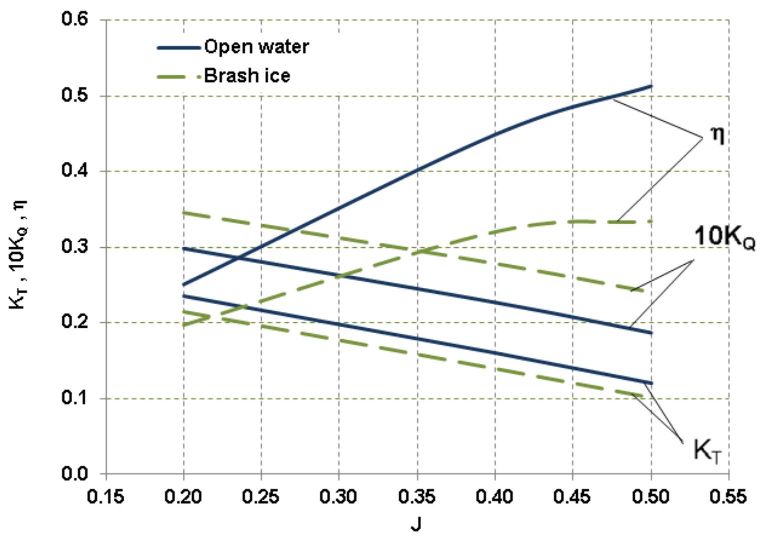

Figure 5. Variations in performance curves of propeller during immersion thereof into brash ice to $0.2R$ depth

The calculation results were compared with model test results of ship performance in ice presented by Wang et al. (2009). The Figure 6 depicts relative variation in propeller thrust and torque coefficients depending on advance ratio during propeller immersion into brash ice to $0.2D$ depth. The calculated curve demonstrates that the effect of brash ice on propeller performance is stronger when advance ratio is increased: drop of thrust coefficient and increase of torque coefficient become more intensive.

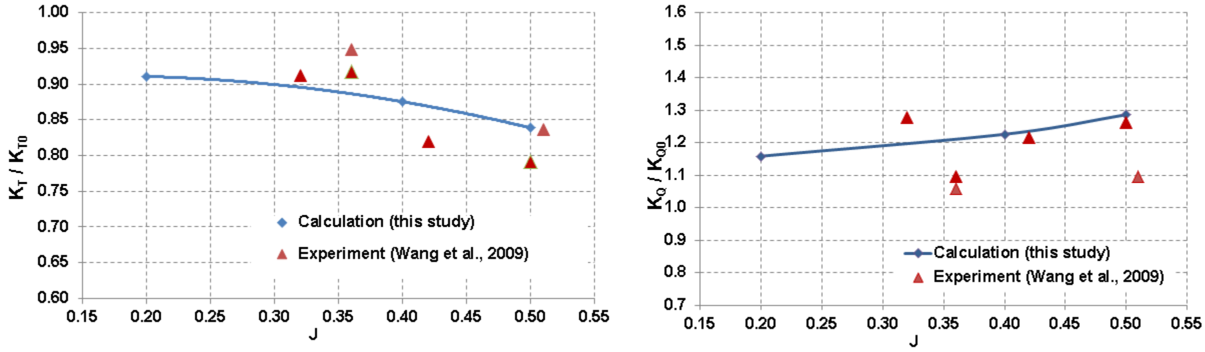

Figure 6. Relative variation of thrust and torque coefficients at propeller immersion in brash ice to 0.2D depth

The diameter of propeller used for the experiment (Wang et al., 2009) was 0.22 m, the latter was immersed into brash ice to 0.046 m depth. Notwithstanding that other parameters of propeller are not indicated the Figure proves that calculation results are well correlated with experiments.

Table 2 shows the change in the propeller thrust and moment when it is operating in the brash ice with a thickness of 0.2D. The values were calculated using the described approach taking into account the change in the medium density and viscosity. The operating modes of the propeller correspond to those given in Table 1.

Table 2. Change in thrust and moment of isolated propeller operating in open water and in the brash ice with a thickness of 0.2D

Calculation option #	Open water thrust [kN]	Thrust in brash ice layer [kN]	Change in thrust [%]	Open water moment [kN·m]	Moment in brash ice layer [kN·m]	Change in moment [%]
1	988	887	-10	501	581	14
2	672	580	-14	381	468	21
3	285	236	-17	177	227	27

CONCLUSIONS

Propeller performance, namely performance curves obtained for open water, varies when it is operated in brash ice. The approach offered in the paper enabled theoretical evaluation of thrust and torque coefficient variation of propeller immersed in brash ice, either in full or in part. A propeller of the Wageningen series B4.70 with known geometry was studied.

Variation in propeller hydrodynamic parameters is dictated by significant increase in viscosity of operating medium – brash ice as against to water. There is reason to believe that the brash ice viscosity is close to the corresponding value of grease ice. Earlier studies into grease ice viscosity revealed that this value may exceed water viscosity by 10000 times.

The offered computational pattern contributed to identification of relationship between propeller thrust and torque coefficients and propeller advance ratio and depth of immersion into brash ice. The brash ice effect increases with increased depth of propeller immersion therein and increased advance ratio.

The research results revealed that if propeller is immersed into brash ice to a depth equal to 20% of its diameter thrust coefficient reduces by ~10-15%, while torque coefficient increases by ~15-30%. These theoretical evaluations are well correlated with results of model tests for icebreaker performance carried out in ice basin. Nevertheless, the results concerning the effect of the viscosity changes on the propeller hydrodynamic characteristics require further refinement in two ways: 1) the brash ice viscosity should be checked, 2) the initial viscosity in the calculation should be determined by the water viscosity instead of the air viscosity.

The presented approach may be used for propellers which geometry is different from the Wageningen series since the study does not address thrust and torque coefficients themselves but variations thereof during propeller operation in open water and in brash ice.

This study does not contain complete calculations of the ship's performance in brash ice. In addition to the propeller performance, it is necessary to take into account the change in the ship resistance and in the hull efficiency factors (wake fraction and thrust deduction fraction). The influence of brash ice on the latter factors is beyond the scope of this work.

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