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Investigation of Ship Performance Prediction Methods in Pack Ice

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ABSTRACT

The ice performance of a ship is a significant factor to consider during the design phase; therefore, quantitative approaches are essential for understanding a ship's ice performance and improving the prediction accuracy of full-scale ship resistance in ice. This research investigates the full-scale performance analysis of a ship navigating through pack ice. A prediction method for full-scale ship resistance in pack ice is introduced based on the concept of the Direct Power Method. In particular, this study utilises full-scale ice trial data from the IBRV Araon during its Antarctic voyage around the Ross Sea in 2019. A reliable data processing procedure is employed to manage the full-scale trial data, ensuring that the original data remains unbiased. Finally, the full-scale ship resistance in pack ice is calculated based on the speed-resistance and speed-power relationships in open water and icy conditions.

KEYWORDS: Ice performance; Pack ice; Direct Power Method; IBRV Araon; Full-scale ice trial data

INTRODUCTION

Generally, ship resistance in level ice conditions is a fundamental criterion in the design stage of ice-going vessels, and its characteristics provide comprehensive information on whether the ship meets the design requirements under specific ice conditions. However, predicting the speed-resistance and power relations in full-scale conditions remains challenging. The primary challenge arises from the limited information regarding propeller-ice interaction phenomena and the insufficient quantity of measured full-scale data for propeller thrust and torque characteristics during the icebreaking process. Nevertheless, numerous studies have focused on estimating ship performance in ice.

Multiple ship trials were conducted in ice-covered waters to evaluate their performance in icy conditions. Lewis and Edwards (1970) investigated how to predict ice resistance, employing statistical methods with the U.S. Coast Guard (USCG) icebreaker. They then established a semi-empirical relationship that links ice resistance to the characteristics of both the ship and the ice. Nyman (1995) studied full-scale ship resistance in level ice through trials conducted with the Finnish icebreaker Sampo in the Gulf of Bothnia, comparing these findings to model test results obtained from an ice model basin. In addition, some researchers predicted ship resistance in ice by using measurements of ship speed and propulsion power gathered during ice trials, applying Newton's second law and the principle of energy conservation (Madson, 2010; Skår, 2011; Suyuthi et al., 2011; Johansen, 2018). These studies contributed analytical methods for estimating ice resistance while comparing the results with calculation results derived from empirical formulas to verify the accuracy of the predictions. Reimer et al. (2018) developed a technique to evaluate full-scale sea trials and assess ships' performance in ice, using results from ice model tests focused on variations in propeller speed and the effects of propulsion scaling. Li et al. (2020) introduced a new algorithm for estimating ice resistance in ice-floe conditions to improve voyage planning for commercial vessels operating in the Arctic during summer. They compared the fuel consumption results of their ship performance model to full-scale measurements from an ice-class cargo ship operating in the Northern Sea Route. Wang et al. (2021) compiled sea ice data from scientific cruises conducted on the R/V Xuelong, applying the Monte Carlo method to estimate level ice resistance according to the Lindqvist formula.

This study aims to enhance the understanding of full-scale ship performance in ice and to develop a prediction method. During the ice trials of the IBRV Araon, the onboard monitoring system collected operational data from the ship, including engine power, propeller RPM, speed, and heading angle. Additionally, field tests assessed ice properties such as temperature, density, and salinity. An image processing method was implemented to determine ice thickness and concentration. In the KRISO towing tank, resistance and propulsion tests were performed to estimate full-scale open water resistance related to ship speed. Based on the Direct Power Method concept, a straightforward method for predicting pack ice resistance is also introduced. Moreover, this study employed a reliable data processing method that considers the coefficient of variation and the correlation coefficient while applying threshold criteria to the dataset. The research then used the data gathered from pack ice conditions to assess the IBRV Araon's ice performance regarding speed–resistance and speed–power relationships.

SHIP PERFORMANCE PREDICTION METHOD

Determining Open Water Resistance Component

Towing tank tests represent the best approach for assessing a ship's performance in open water, which is essential for evaluating the resistance and propulsion performance of full-scale vessels. Consequently, model tests conducted in calm water can identify the open water resistance component. In addition, the thrust deduction factor can be obtained from the results of the overload test in open water. However, the main component of the total resistance in ice is ice resistance, while the resistance from open water accounts for about 5–10% of this total; thus, open water resistance is minor compared to ice resistance. Therefore, a simplified open water resistance equation, as a function of the ship's speed, is used to predict a ship's performance under full-scale conditions. This study estimated the full-scale open water resistance through model tests conducted in a KRISO towing tank for a model ship of the IBRV Araon (MOERI, 2008). The experimental findings indicate that the full-scale open water resistance, dependent on ship speed, can be expressed as follows:

$$R_{ow} = 0.0157v^4 - 0.3406v^3 + 3.3927v^2 - 3.9367v, \quad (1)$$

In Equation (1), the quantity R_{ow} is expressed in Newtons, and v is measured in knots. This equation is specific only to the IBRV Araon.

Determining Ice Resistance Component

As a ship advances through ice, a significant consideration for ice-going vessels is having sufficient thrust to overcome resistance from the ice under certain conditions. For example, when the ice resistance exceeds the available net thrust, the ship cannot gain momentum to move forward, leaving it stuck in the ice. As mentioned before, a full-scale ice trial can assess a ship's performance in ice. While data from these trials can provide insights, predicting ice resistance remains challenging. Therefore, based on the Direct Power Method, this study presents a straightforward method to predict IBRV Araon's performance in ice-covered waters (ITTC, 2021). First, the delivered power to the propeller, P_{Dms}, can be calculated from the measured shaft power, P_{Sms}, as follows:

$$P_{Dms} = P_{Sms}\eta_S, \tag{2}$$

where η_S is the shaft efficiency, it is assumed to be 0.97 in this study.

Then, the torque coefficient in the ice trial condition, K_{Qms}, can be calculated by the following formula:

$$K_{Qms} = \frac{P_{Dms}}{2\pi\rho_S n_{ms}^3 D^5}\eta_{Rms}, \tag{3}$$

where ρ_S is the seawater density, n_{ms}, and D are the measured propeller rate of revolution and the propeller diameter, respectively, and η_{Rms} is the relative rotative efficiency of the design propeller in the ice trial condition. Herein, the η_{Rms} is assumed to be 1.04 from the resistance and propulsion tests.

In addition, the curves of the thrust coefficient, K_{Tms}, and torque coefficient, K_{Qms}, by the open water characteristic data for the design propeller obtained from the model test in a towing tank are defined as the following formulae:

$$K_{Tms} = a_T J_{ms}^2 + b_T J_{ms} + c_T, \tag{4}$$

$$K_{Qms} = a_Q J_{ms}^2 + b_Q J_{ms} + c_Q, \tag{5}$$

where, J_{ms} is the advance coefficient for the design propeller, a_T, b_T, and c_T are the factors for the thrust coefficient curve and a_Q, b_Q, and c_Q are the factors for the torque coefficient curve.

Therefore, the advance coefficient for the design propeller in the ice trial condition, J_{ms}, is determined using the following formula.

$$J_{ms} = \frac{-b_Q - \sqrt{b_Q^2 - 4a_Q(c_Q - K_{Qms})}}{2a_Q}, \tag{6}$$

where, K_{Qms} represents the torque coefficient in the ice trial, calculated by Equation (5) using the torque coefficient.

If the POD propulsion system lacks a specialised sensor for measuring thrust and torque, obtaining these data will not be possible after it is mounted on the ships. Therefore, the thrust coefficient of the design propeller in the ice trial condition, K_{Tms} is obtained by Equation (4). Thus, the load factor of the design propeller in the ice trial condition, τ_{Pms}, and the thrust of each propeller, T_S, can be obtained as follows :

$$\tau_{Pms} = \frac{K_{Tms}}{J_{ms}^2}, \tag{7}$$

$$T_S = (\tau_{Pms}) {J_{TS}}^2 \rho_S D^4 n_{ms}^2, \quad (8)$$

where, J_{TS} is read off from the full-scale design propeller characteristics.

From the calculated thrust of the design propeller, taking into account the thrust deduction factor, *t,* the effective thrust, T_{eff}, to overcome the pack ice resistance, R_{pack}, can be expressed as follows:

$$T_{eff} = (1 - t) T_S - R_{ow} \quad (9)$$

where t is the thrust deduction factor of 0.14, it was determined using the resistance and propulsion test results.

Prediction of Ship Performance in Pack Ice

Full-scale ice trials were performed around the Ross Sea region of Antarctica in November and December 2019 in various ice conditions, including pack ice, ridged ice, and level ice. This study used the data obtained from pack ice conditions to estimate the ship's ice performance in both speed–resistance and speed–power relationships. This section provides an overview of the ship trials, property measurements of an ice sheet, and ship performance prediction results.

1. Overview of the ice trials

The IBRV Araon, Korea's first icebreaker, was built in 2009. It can break ice continuously at a speed of 3 knots in 1.0 meters of level ice, with a flexural strength of at least 630 kPa. The vessel is powered by twin azimuth propulsion units, which are operated by a diesel-electric propulsion system providing 10 MW of power. Key features of the IBRV Araon are listed in Table 1.

Table 1. Principal characteristics of the IBRV Araon

Parameters	Value
Length between perpendiculars (m)	95.0
Breadth (m)	19.0
Design draft (m)	6.8
Maximum draft (m)	7.62
Displacement (ton)	7,664
Propulsion capacity (kW)	10,000
Propeller diameter (m)	4.0
Speed in open water at the design draft for 100% power level (knots)	16.7

Network cameras were mounted at the bridge, bow, stern, and parallel regions during the ice trials to obtain images. The image obtained from the bridge was used to determine the ice concentrations (Kim et al., 2023), and the ice thickness could be derived using an image processing method (Kim and Nam, 2016), which was taken from the ship's parallel regions. Figure 1 shows the sample bridge view image of sea ice conditions during the ice trials, and Figure 2 shows the results of the ice thickness prediction. In addition, ship operation data, such as power outputs, propeller revolutions, speeds, propulsion unit angles, heading, and draughts, were obtained from the VDR and AMS on the ship. The strength characteristics may depend on several parameters, including salinity, density, and temperature; the field measurements, therefore, were carried out to obtain the strength properties of the ice. During the field measurements, the snow depth was recorded using a measuring stick, while the thickness of the ice was determined by ice drilling (using a 2-inch auger). Ice specimens for measuring physical properties were then cored with a 3-inch coring device in the field. The temperatures of the ice cores were measured by inserting a thermistor probe into each core at intervals of 10 cm along the depth. Based on this data, the flexural and compressive strength of the ice was calculated using empirical formulas (Timco and Frederking, 1990; Timco and O'Brien, 1994). The average calculated flexural and compressive strengths based on the ice cores' salinity, temperature, and density profiles were 257 kPa and 3.88 MPa, respectively (see Figure 3 and Table 2).

Figure 1. Ice conditions in the Ross Sea during the IBRV Araon ice trials

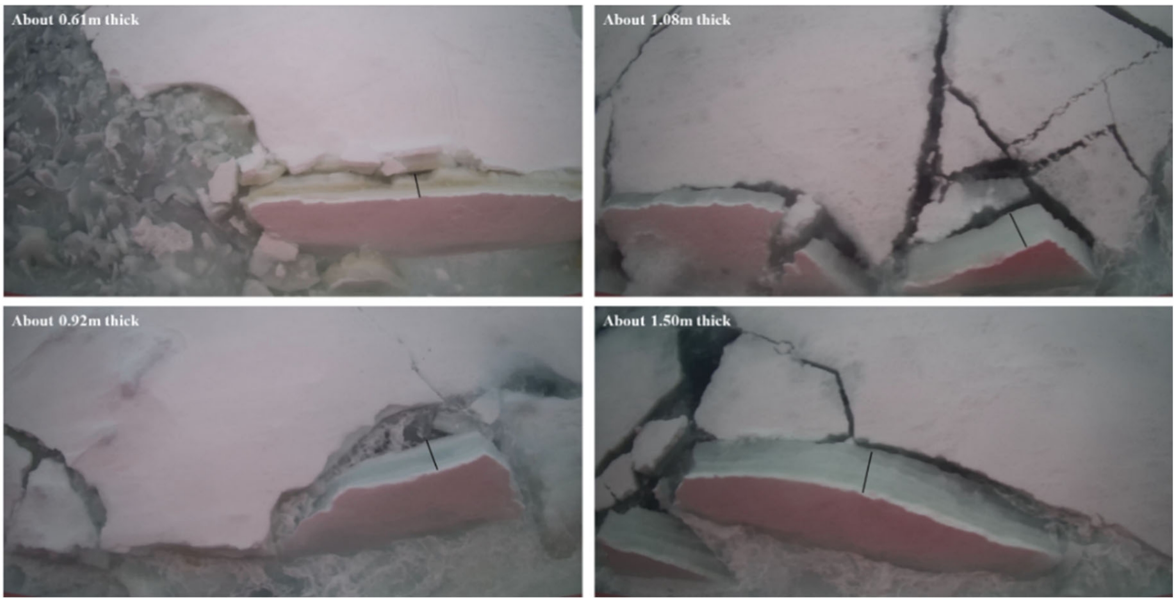

Figure 2. Predicted ice thickness using the image processing method. Herein, the black line denotes the thickness of the broken ice floe

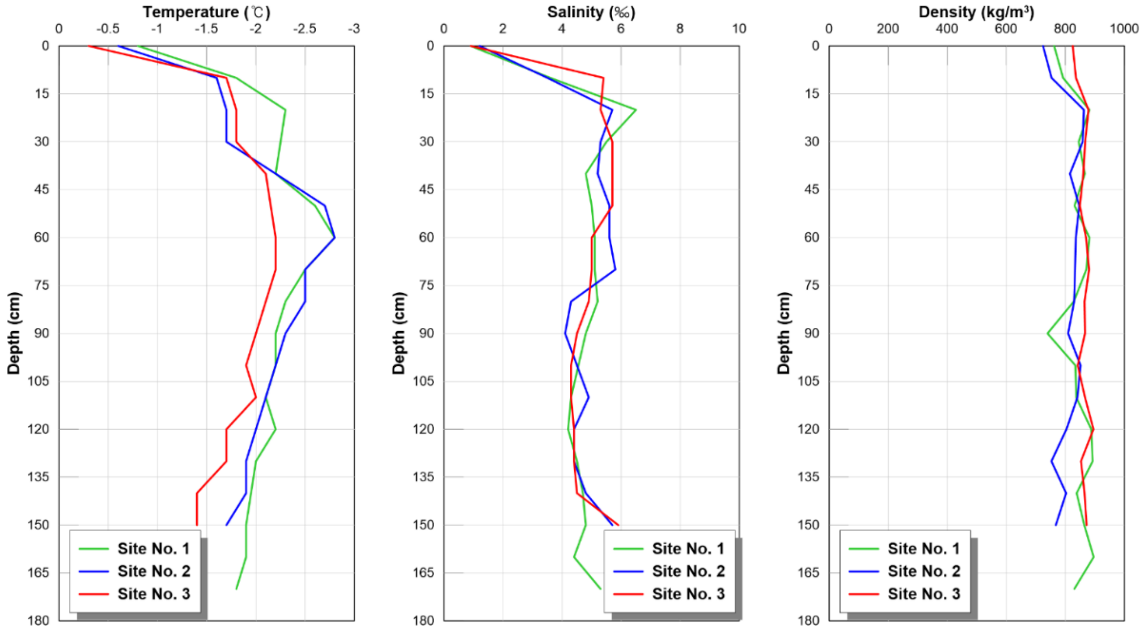

Figure 3. Plots of the measured temperature, salinity, and density profiles along the depth

Table 2. Calculated compressive and flexural strengths of the ice

Site No.	Compressive strength of sea ice (MPa)	Flexural strength of sea ice (kPa)
1	4.42	291
2	4.18	272
3	3.04	209
Average	3.88	257

2. Data processing for analysis of the ship's ice performance

A ship sailing in ice-covered waters usually avoids severe ice conditions as much as possible; thus, an ice pilot can adjust the propulsion unit angle to navigate the vessel safely through the ice field. In these situations, the heading angle can change dramatically. Consequently, this intentional operational condition was excluded from the analysis through the correlation coefficient analysis between the propulsion unit angle and the heading angle. In addition, analyses of ship performance in ice should be conducted under constant ship speed, propulsion power, and unit angle; thus, the coefficient of variation (CV) was calculated. It shows the extent of the data's variability in a sample relative to the population mean and is a relative measure of variability for comparing different data series. The CV can be written as:

$$CV = \frac{\sigma}{|\mu|} \tag{10}$$

This study proposed data selection and analytical process criteria to determine stable conditions during the ice trials as follows:

1) The correlation coefficient between the heading angle and the propulsion unit angle should be less than 0.4 to remove intentional actions taken to avoid heavy ice conditions.

2) The engine output should be greater than 30 % of the maximum continuous rating (MCR) to prevent being stuck in ice and maintain continuous icebreaking. The CV values for the engine output should be less than 0.1.
3) The CV values for the propeller speed corresponding to the main engine capable of continuous icebreaking should be less than 0.1.
4) The CV values for the ship's speed through water (STW) should be less than 0.2.
5) The CV values for the heading angle should be less than 0.2 for a specific duration of time.

Proposed threshold values are smaller than in previous studies, but the processed data shows sufficiently steady-state conditions (Madson, 2010; Skår, 2011; Suyuthi et al., 2011; Johansen, 2018). Accordingly, the proposed CV criteria and correlations can help determine appropriate event sections when evaluating the performance of a ship through the ice. Figure 4 shows the collected dataset's CV values and correlation coefficients. Five datasets were used in the data processing procedure. As mentioned above, the thickness of the ice was determined using image analysis. Figure 5 shows a histogram of the ice thicknesses measured from the five event data sets. The maximum ice thickness retrieved from the image processing method was approximately 2.75 m, and the mean ice thickness was about 1.35 m from the ice thickness histogram.

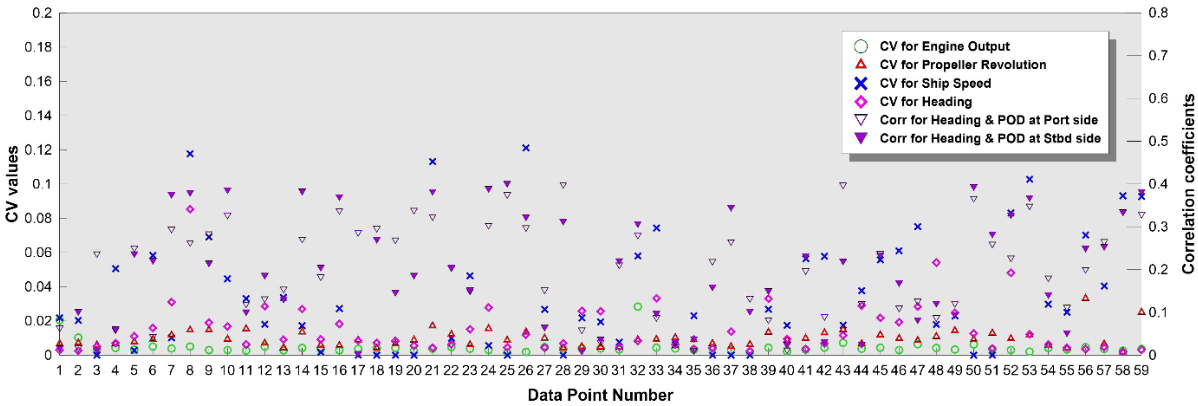

Figure 4. Distribution of the CV values and correlation coefficients for the selected parameters for the full-scale data

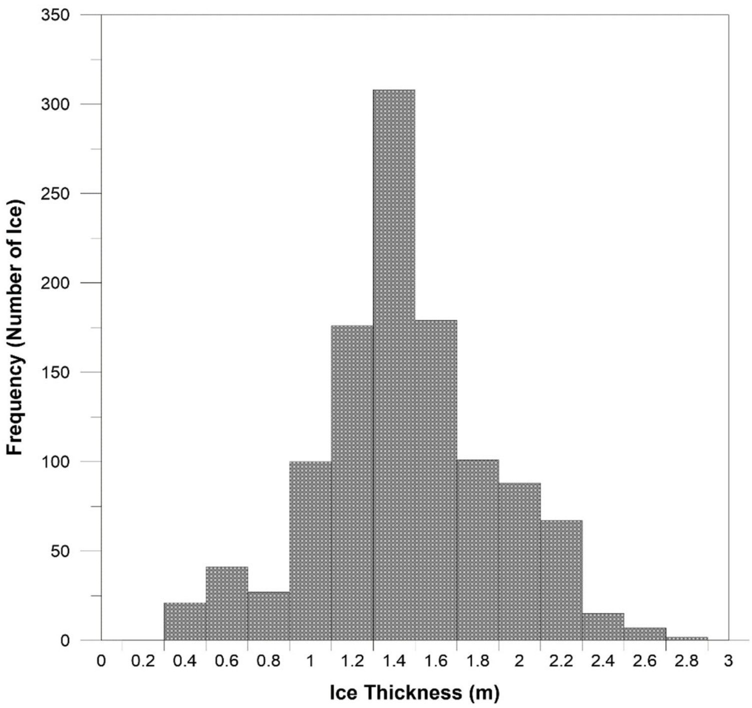

Figure 5. Histogram of ice thicknesses in five test events. The bin width of ice thickness was 0.2

Table 3. Information on ice conditions derived from bridge and side-view images

Statistic	Ice thickness (m)	Ice floe size (m)	Ice concentration (%)
Mean value	1.35	3.87	83.5
Coefficient of variation	0.305	0.224	0.029

3 Speed–resistance and speed–power relationships

The calculated open water resistance and pack ice resistances from Equations (1) and (9) according to ship speed are presented in Figure 6. Herein, the light blue dot markers indicate the pack ice resistance calculated by Equation 9, while the purple solid line represents the open water resistance derived from Equation 1. The results revealed a trend of ship resistance in pack ice with slightly exponential growth. Also, the speed at which the ship could proceed under certain ice conditions could be determined by the relationship between ship resistance in pack ice and available net thrust. Herein, the available net thrust for IBRV Araon was proposed in a previous study (Jeong et al., 2020). The attainable ship speed was about 13.9 knots, indicating good icebreaking performance under the 1.35 m thickness and 83.5 % concentration conditions (see Table 3).

One of the most significant considerations for an ice-going ship is the speed–power relationship, which relates to ice resistance. During the ice trials, the collected data for the power output against the corresponding speed were plotted as a speed-power curve (see Figure 7). Herein, the delivered power in pack ice was much higher than in open water. The average level of the delivered power was about 68.6 % during the ice trials. The required power in pack ice was 5.6 times higher than in open water at a ship speed of 10 knots.

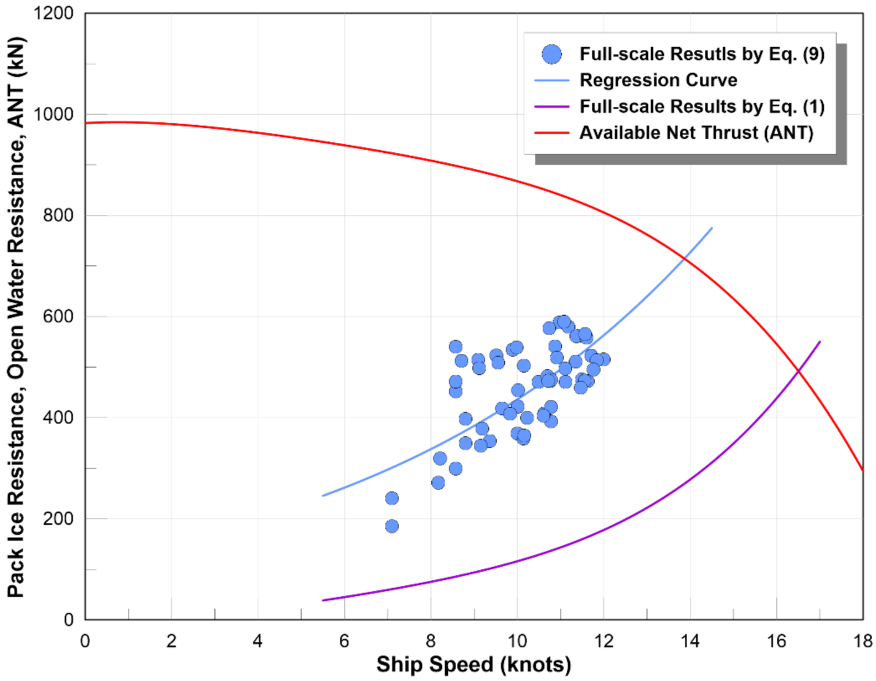

Figure 6. Predicted full-scale ship resistance components vs. ship speed

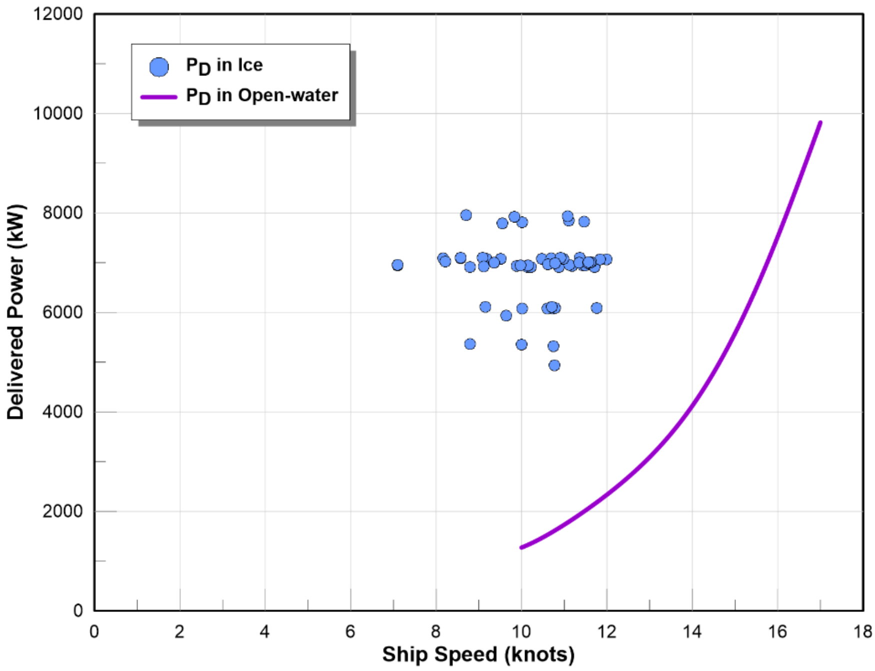

Figure 7. Comparison of delivered power in ice and open water conditions

CONCLUSIONS

This paper presents the full-scale results of the IBRV Araon's ship performance in ice in the Ross Sea, Antarctica, in 2019. During the ice trials, operational and environmental data were collected using the developed onboard monitoring system, which included ship speed, propulsion power, and ice conditions. This study proposes a method to enhance predictive accuracy and prevent misinterpretation of a ship's performance during ice trials. Consequently, preprocessing monitoring data to identify steady-state conditions is essential for eliminating disturbances from the original full-scale data. Specifically, the criteria for data selection and the threshold values for each parameter indicate that they can improve performance predictions in ice-covered waters.

In this study, the ship's resistance characteristics in pack ice appeared to follow an exponential distribution as ship speed increased. In particular, the average ratio of pack ice resistance was roughly 3.8 times higher than that of open water resistance. To overcome this resistance, the propulsion power required in ice was more significant than that needed in open water. During the ice trials, the average power requirement in pack ice was approximately 5.6 times higher than in open water at a ship speed of 10 knots. Therefore, this difference could provide critical insights into power requirements for overload operations and may prove valuable during the design phase. Furthermore, this approach could be a conceptual framework for predicting a ship's full-scale performance and provide valuable information for evaluating ship resistance in pack ice.

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