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Mikko Elo

CAPABILITY OF ENERGY EFFICIENT SHIPS FOR WINTER OPERATIONS ON THE BOTHNIAN BAY

Finnish Transport and Communications Agency

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FOREWORD

In this report no 103, the Winter Navigation Research Board presents the results of the research project on EEDI optimized hull forms. The study is based on model-scale measurements in ice not only in conditions based on the FSICR requirements, but also in other typical winter navigation conditions in the Bothnian Bay. The study includes also an observation voyage on board a typical IA Super product tanker during the most difficult ice conditions.

The EEDI type bow was found to be performing equally well or even better than reference ship in most of the ice conditions. The test results indicate that the ice performance of the EEDI bow is sensitive to the icebraking mode and how the bow pushes brash ice in channels.

The Winter Navigation Research Board warmly thanks Mr. Mikko Elo for this report.

Helsinki and Norrköping

May 2020

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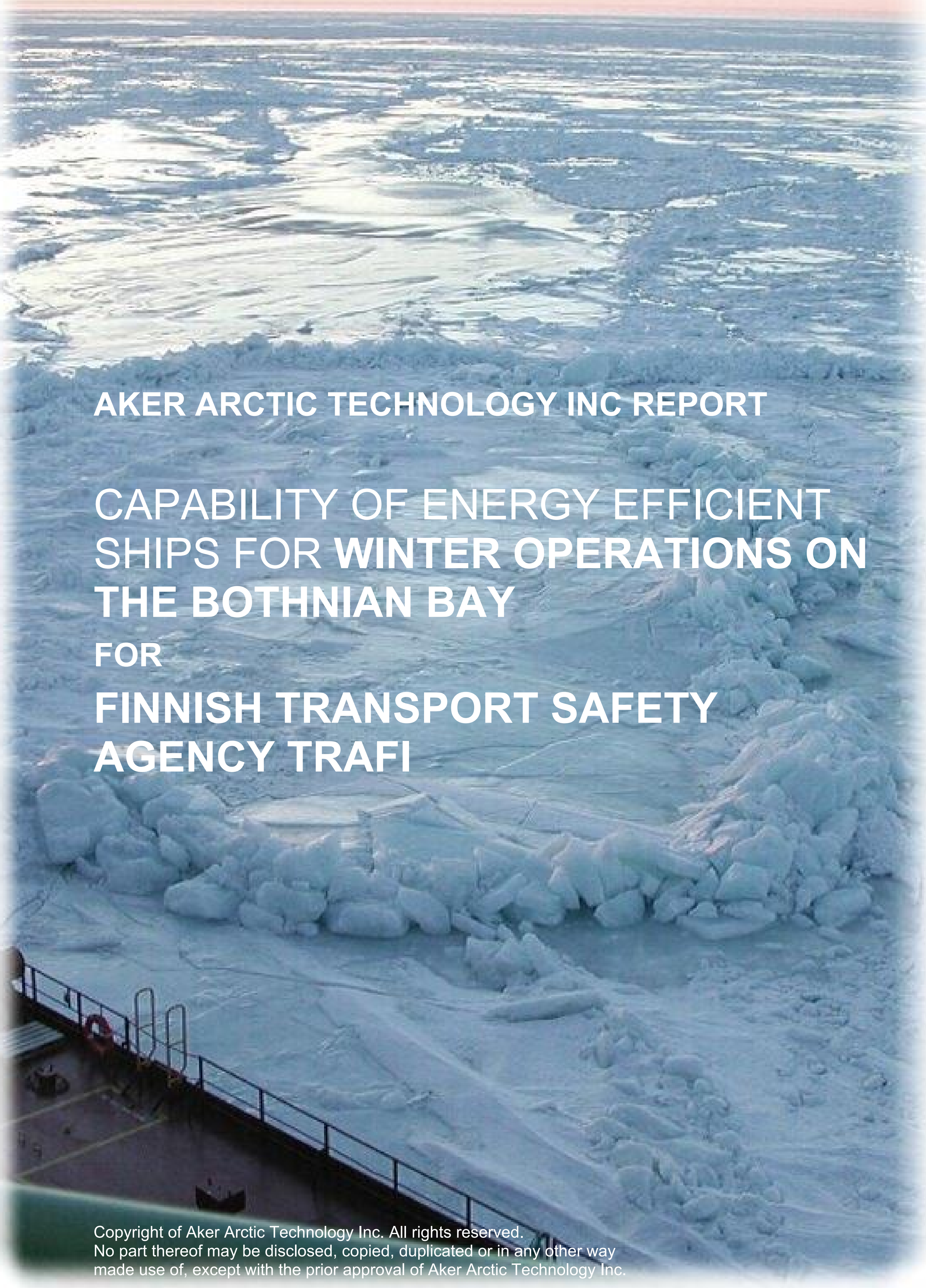

AKER ARCTIC TECHNOLOGY INC REPORT

CAPABILITY OF ENERGY EFFICIENT SHIPS FOR **WINTER OPERATIONS ON THE BOTHNIAN BAY**

FOR

FINNISH TRANSPORT SAFETY AGENCY TRAFI

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Summary:

The target of this study is to find out the capability and possible problems EEDI optimized hull forms have in real winter operations.

This study is based on model-scale measurements in ice of two product tanker models, one with modern EEDI bow form and one with bow form optimised to winter operations in the Bothnian Bay. The models are tested not only in conditions based on FSICR requirements, but their operability is also tested in other typical winter navigation situations, i.e. breaking out from the channel, level ice, broken ice and moderate ice ridges.

The study includes a supplementary observation voyage on board a typical IA Super product tanker. During a normal voyage to Bothnian Bay at the time when the ice conditions were most difficult it was observed how the vessel can navigate in different ice conditions and when and in what kind of conditions ice breaker assistance is needed.

With the same available power as for the Reference ship the EEDI type bow is performing equally well or even better than Reference ship in most of ice conditions. In one condition the EEDI bow performs much worse, the outbreaking from channel, which might be a safety issue during operation.

The ice operability of the EEDI bow should not be generalized because the tested shape was not purely optimized for open water. The ice-going capability was also taken in consideration for this bow shape. The test results indicate that the ice performance of the EEDI bow is sensitive to the icebreaking mode and how the bow pushes brash ice in channels.

Keywords:
Ice performance, ice model tests, FSICR, EEDI.

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ABBREVIATIONS

EEDI ....Energy Efficiency Design Index
FSICR ....Finnish-Swedish Ice Class Rules
MCR ....Maximum Continuous Rating

1 INTRODUCTION

The target of this study is to find out the capability and possible problems EEDI optimized hull forms have in real winter operations.

The Energy Efficient Design Index (EEDI) is nowadays mandatory for new ships. The EEDI will tighten in three phases: Phase 1 on or after 1 January 2015, Phase 2 on or after 2020 and Phase 3 on 1 January 2025 and onwards. The EEDI requirements affect the world shipping and especially the transport regime in the Baltic Sea, where high ice classes are the basis of year-round regular transport. Because the maximum allowed power will be dropped substantially due to EEDI, this will have significant effects on the ice-going capabilities. The EEDI optimized ships do not in practice consider the needs of ice operations.

For the new, energy efficient ships, novel bow forms have been developed. The new bow forms fulfil the minimum engine power requirements of the Finnish-Swedish Ice Class Rules (FSICR) ice class IA. The ice-going capability defined by the FSICR for IA ice class is 1 m thick brash ice channel at a speed of 5 knots. However, for example when the ship is operating in ice in the Bothnian Bay the conditions might change rapidly. The consolidated layer may develop to the ice channel within few hours to IA Super channel and after one day the situation can be even worse. To operate safely and efficiently in the Bothnian Bay in wintertime requires also ability to pass other ships and break out from the channel, if needed. From the operating point of view, it is not enough for an ice-going ship to be able to use only the IA type ice channels and withstand IA class compression forces.

This study is based on model-scale measurements in ice model basin of two product tanker models, one with EEDI optimized bow form and one with bow form optimized for winter operations in the Bothnian Bay. The models are tested not only in conditions based on FSICR requirements, but their operability is also tested in typical winter navigation situations, i.e. breaking out from the channel, level ice, broken ice and moderate ice ridges.

The study includes a supplementary observation voyage on board a typical IA Super product tanker. During a normal voyage to the Bothnian Bay, at the time when the ice conditions were most difficult, it was observed how the vessel can navigate in different ice conditions and when and in what kind of conditions icebreaker assistance is needed.

Also, the open water performance of the bow types was evaluated using CFD analysis.

2 DESCRIPTION OF THE SHIPS

2.1 REFERENCE SHIP

As reference ship for the study M/T Suula/Kiisla was selected. The ship is typical FSICR IA Super vessel with single screw propulsion and bulbous bow. She was built 2005. She operates in the Baltic Sea and visits Bothnian Bay harbours frequently year-round. It was also possible to do full scale observations onboard M/T Suula during one voyage to the Bothnian Bay. The main dimensions of the ship are presented in Table 1.

Table 1: Main dimensions of the reference ship

	Reference ship
L_{OA} [m]	139.75
L_{WL} [m]	135.0
B_{DWL} [m]	21.70
T_{DWL} [m]	8.70
∇_{DWL} [m^3]	19090
Ice class	IA Super
Speed, full load [knots]	16.0

Figure 1: M/T Suula.

2.2 EEDI SHIP

As reference the hull model of the Reference ship was used for the EEDI ship. The mid and stern part, from frame #12.5 to aft, were left as they were in the Reference ship, whereas the bow part was designed close to the shape used in the midsize ice class IA tankers that had to fulfil EEDI phase 1.

Typical EEDI optimized bow forms have vertical or almost vertical stem as well as the bow buttock lines. The bow is sharp, and the bow waterlines have small entrance angles and the bulbous part extends forward only slightly. The bulbous part is often quite slim and narrow and integrated to bow part. Sometimes these bow types are called “axe bows”. Some EEDI bow forms are shown in Figure 2.

Figure 2: Novel bow forms of EEDI time

The objectives to develop the EEDI bow shape was to follow the bow shapes of these novel ships and minimize the open water resistance of the vessel. The displacement, breadth, draught and length overall of the vessel were limiting factors from the Reference ship. When displacement, maximum length, aft- and mid-body are kept same as they are in the Reference ship, there is only about

30 % of total resistance which could be optimized from wave making resistance point of view.

For each developed hull form the open water resistance was evaluated using a CFD tool, including free-surface capturing and viscosity, and the ice performance was evaluated simultaneously with a semi-empirical method, keeping in mind that the vessel has to IA channel capable. Several optimisation rounds were made to bow hull form to get the open water performance to a good level. The hull form of the reference vessel is presented in Figure 3 and the final hull form of the EEDI bow vessel is presented in Figure 4.

Table 2: Main dimensions of the ship with EEDI bow

	Ship with EEDI bow
L_{OA} [m]	140.87
L_{WL} [m]	140.34
B_{DWL} [m]	21.70
T_{DWL} [m]	8.70
∇_{DWL} [m^3]	19090
Ice class	IA

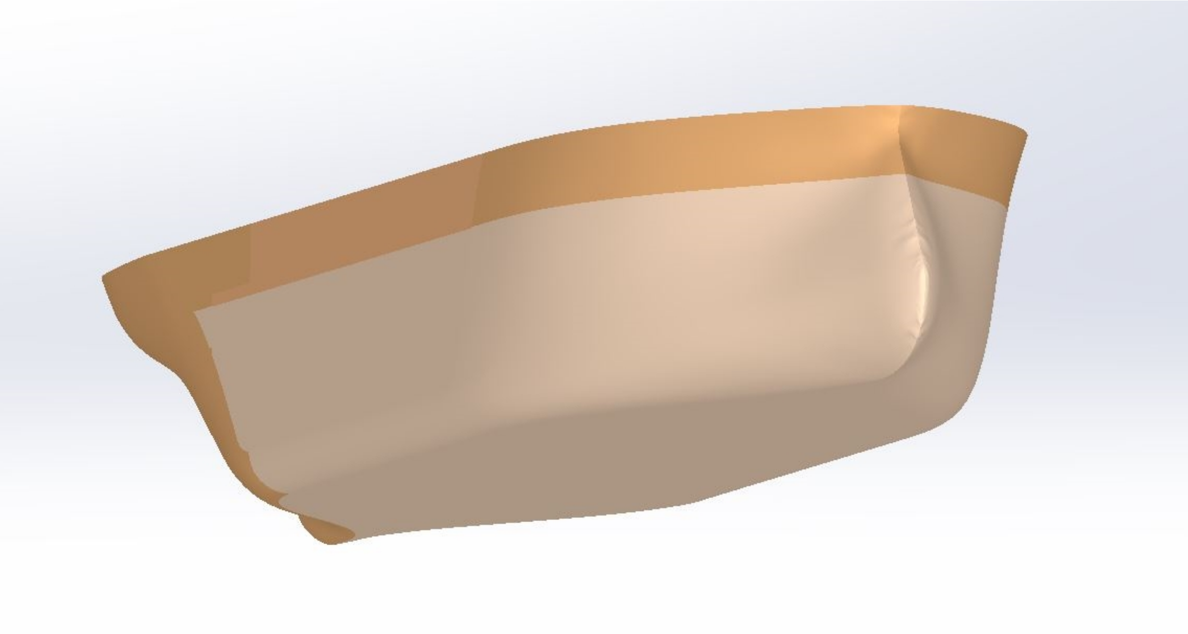


Figure 3: Underwater shape of the Reference ship.

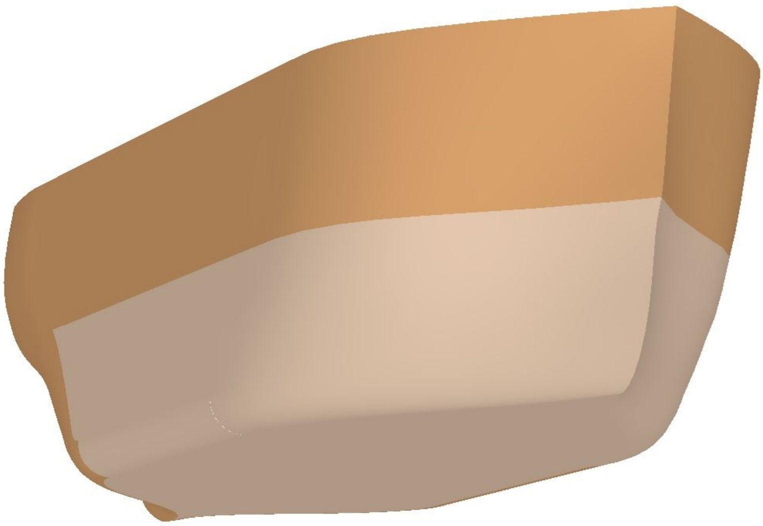


Figure 4: Underwater shape of the EEDI bow vessel.

3 FULL SCALE OBSERVATION

An observation voyage onboard the Reference ship was made in March 2017. The purpose of the voyage was to observe the capability of an ice classed ship to operate and get icebreaker assistance in different ice conditions during trips to/from harbours in the Bothnian Bay during severest part of the winter.

The observation voyage with the Reference ship, IA Super ice class product tanker MT Suula, was done during 12 to 16 March 2017. The voyage was divided into two legs: from Porvoo to Oulu 12 to 14 March and from Oulu to Vaasa 15 to 16 March.

3.1 ICE CONDITIONS

The ice winter 2016-2017 in the Baltic Sea was mild. The maximum ice extent occurred in February when the Bothnian Bay, Quark area and eastern part of Gulf of Finland were covered by ice.

In mid-March, at the time of the observation voyage the route from Porvoo to Quark as well as the route from Quark to Vaasa were ice free except for a narrow landfast ice zone off Porvoo and Vaasa. The Quark area was covered by thin open drift ice.

The Bothnian Bay was covered mostly with 15 to 40 cm thick very close drift ice. During the voyage ice compression was experienced at times due to strong south-westerly wind with speed ranging from 10 to 15 m/s. During the period from 14 to 16 March the ice cover was pushed towards northeast. By 16 March most of the drift ice was compacted in the northern part of the Bothnian Bay, while southern and western parts were almost free of ice.

A jammed brash ice barrier was encountered at the landfast ice edge, close to Oulu 1 lighthouse. The Oulu fairway was covered by a brash ice channel surrounded by landfast ice 45 to 70 cm thick.

Ice charts from mid-March 2017 are shown in Figure 5.

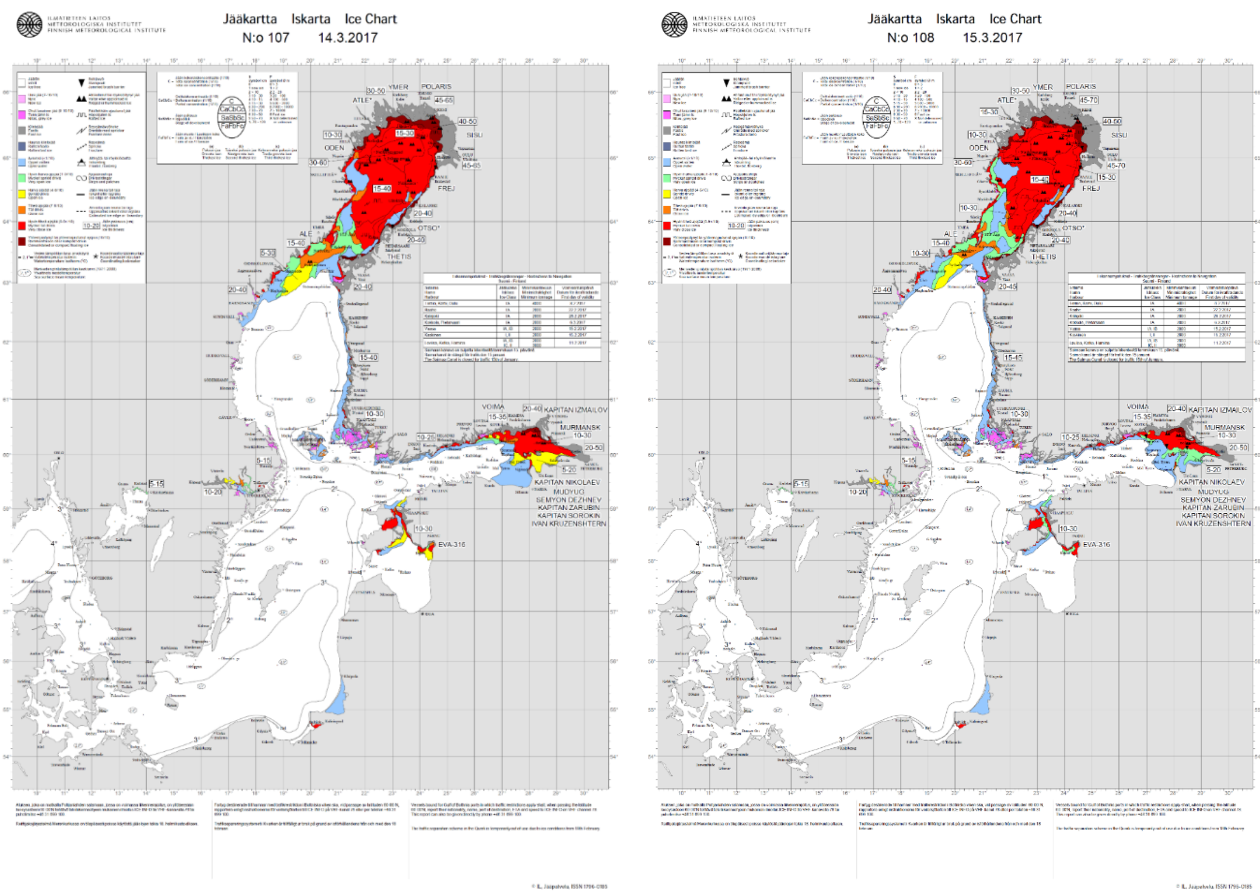


Figure 5: Baltic Sea ice charts 14 and 15 March 2017

3.2 ONBOARD OBSERVATIONS

3.2.1 PORVOO – OULU

The voyage from Porvoo to Oulu was conducted in loaded condition at a draught of about 8.5 m with no trim in harbour condition during 12 to 14 March. An overview of the conditions during the voyage is shown in Figure 6. The Reference ship performance data during the voyage is summarized in Table 3 on page 18.

The ship left Porvoo on 12 March at about 14:00 UTC. At first the ship sailed a short distance in a light brash ice channel in Porvoo fairway before arriving in open water. Then the ship continued sailing westward in the Gulf of Finland in head wind conditions at a speed of 13 to 14 knots with engine power of 3900 kW. The wind was south-westerly with average speed of 10 to 12 m/s.

By the morning of 13 March the ship had reached Åland Sea and it passed Märket lighthouse at 8:00 UTC. The ship continued northward in the Sea of Bothnia in backwind conditions at a speed of about 14 knots with engine power of about 3600 kW. The wind was southerly with average speed of 10 to 12 m/s.

By midnight the ship reached the Quark area and encountered ice. The Quark area was covered by thin open drift ice which didn't slow down the ship. After midnight the ship reached the area of very close drift ice in the Bothnian Bay. During the morning of 14 March the ship continued in the drift ice field northward towards Oulu. The ship was breaking its way through level ice fields with some areas with broken ice and followed fresh channels broken by other ships when possible. However, most of these channels were closed due to strong wind. The average ship speed remained at about 12 to 13 knots while the engine power was gradually increased from 3800 to 6000 kW.

When reaching the area west of Hailuoto the average speed of the ship slowed down although the engine power was increased up to 6500 to 7000 kW. Eventually the ship stopped in about 40 cm thick level ice at 9:15 UTC (Figure 7 A). Evidently, there was ice compression in this area. This was observed visually from the channel behind the ship which was closing within about two ship lengths. Also, the wind speed was ranging from 12 to 15 m/s from south-southwest. After getting loose the ship continued to Holma beacon, where she was given orders to wait for icebreaker (Figure 7 B).

After waiting for 4 hours at Holma beacon the ship continued to Oulu 1 lighthouse behind icebreaker Atle which was heading towards Kemi. During this leg the ship speed was about 12 knots with an engine power of 4600 kW.

At Oulu 1 lighthouse the ship waited for a half an hour for icebreaker Sisu which was bound to assist the ship to Oulu (Figure 8 A). The ship followed the icebreaker through the jammed brash ice barrier at the landfast ice edge. The ship approached the brash ice barrier with an initial speed of about 12 knots and engine power of 6800 kW. However, the ship got stuck and the icebreaker had to cut her loose (Figure 8 B). After the ship was cut loose she followed the icebreaker in a heavy brash ice channel with an average speed of about 10 knots, while the engine power remained at about 6800 kW. When passing Liberta the ship slowed down to less than 5 knots to pick up the pilot.

After transiting through the heaviest part of the brash ice channel the icebreaker went aside, and the ship continued independently to Oulu in the brash ice channel with a speed of about 13 knots and engine power of 6200 kW. The ship arrived in Oulu harbour in the evening of 14 March at 18:45 UTC.

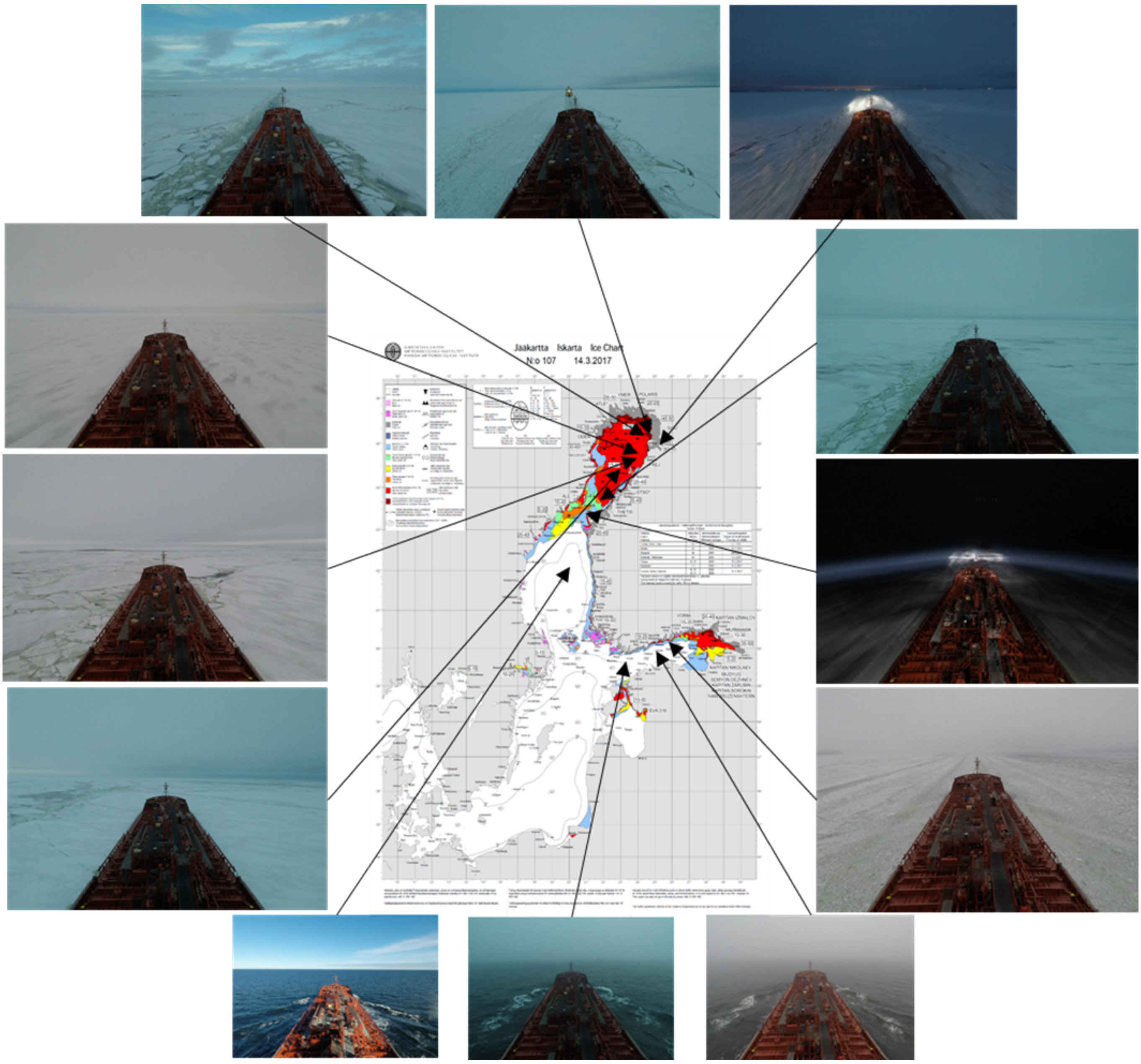
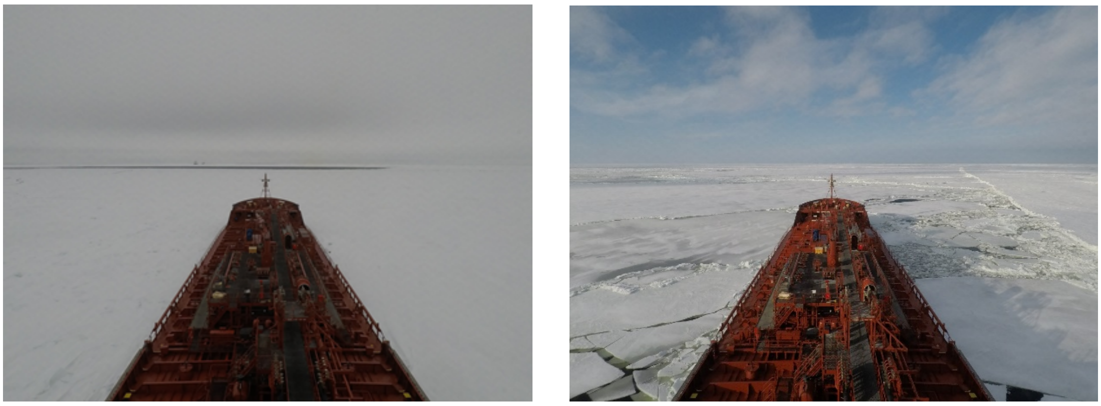


Figure 6: The conditions during the voyage from Porvoo to Oulu



A *B*

Figure 7: Bothnian Bay: Stopped in level ice west of Hailuoto (A), Waiting at Holma beacon (B)

A *B*

Figure 8: Waiting in broken ice at Oulu 1 lighthouse (A), Cut loose by icebreaker Sisu at jammed brash ice barrier at the entrance of Oulu fairway (B)

3.2.2 OULU – VAASA

The voyage from Oulu to Vaasa was conducted in partially loaded condition at a mean draught of about 6.1 m with an aft trim of 0.8 m in harbour condition during 15 to 16 March. An overview of the conditions during the voyage is shown in Figure 9. The Reference ship performance data during the voyage is summarized in Table 4 on page 18.

The Reference ship left Oulu on 15 March at about 11:30 UTC. The ship followed icebreaker Atle in the brash ice channel all the way from Oulu harbour to Oulu 1 lighthouse. At first the speed was 13 to 14 knots with an engine power of about 5600 kW. In the heavy part of the brash ice channel the speed dropped to about 10 knots while engine power was increased to 6500 kW. When passing Liberta the ship slowed down to drop off the pilot. When arriving at the jammed brash ice barrier the ship stopped, and the icebreaker had to cut her loose (Figure 10 A).

After passing Oulu 1 lighthouse around 14:30 UTC icebreaker Atle headed towards south along the Finnish coast and the ship followed in the channel broken by the icebreaker with a speed of about 13 knots and engine power of 6100 kW. The surrounding ice field was composed of large level ice floes and broken ice areas. However, there was ice compression in the area west of Hailuoto which slowed down the ship although engine power was increased up to 6800 kW. Eventually, the ship stopped as the ice compression increased and the channel behind the icebreaker closed quickly. At the time the wind speed was 12 to 14 m/s from southwest. In this condition the ship was not able to get loose on its own and the icebreaker had to cut her loose (Figure 10 B).

After the ship was cut loose she continued towards south behind icebreaker Atle with an average speed of about 11 knots and engine power of 5800 kW. The surrounding very close ice field was composed of large level floes.

After passing Nahkiainen lighthouse off Raahe at 19:00 UTC the ice conditions became lighter and the channel behind the icebreaker was nearly ice free. At 22:00 UTC icebreaker Atle turned back to assist northbound ships while the ship continued alone towards Vaasa. The ice conditions were light with open to very open drift ice. The ship reached an average speed of 15.5 knots with engine power of about 5000 kW.

The ship reached open water at about 23:00 UTC before arriving in the Quark area. In open water the ship reached a speed of close to 16 knots with 5000 kW engine power. The wind was westerly with a speed of 10 to 12 m/s. In the Quark the engine power was reduced to about 4400 kW and the speed dropped to 15 knots.

After passing the Quark the ship turned to southeast towards Vaasa with a speed of 15 knots. Due to backwind conditions (westerly wind) the engine power was decreased to about 4200 kW. At 4:15 UTC the ship reached the landfast ice edge off Vaasa. The ship slowed down and followed the light brash ice channel to Vaasa harbour where she arrived in the morning of 16 March at 5:30 UTC.

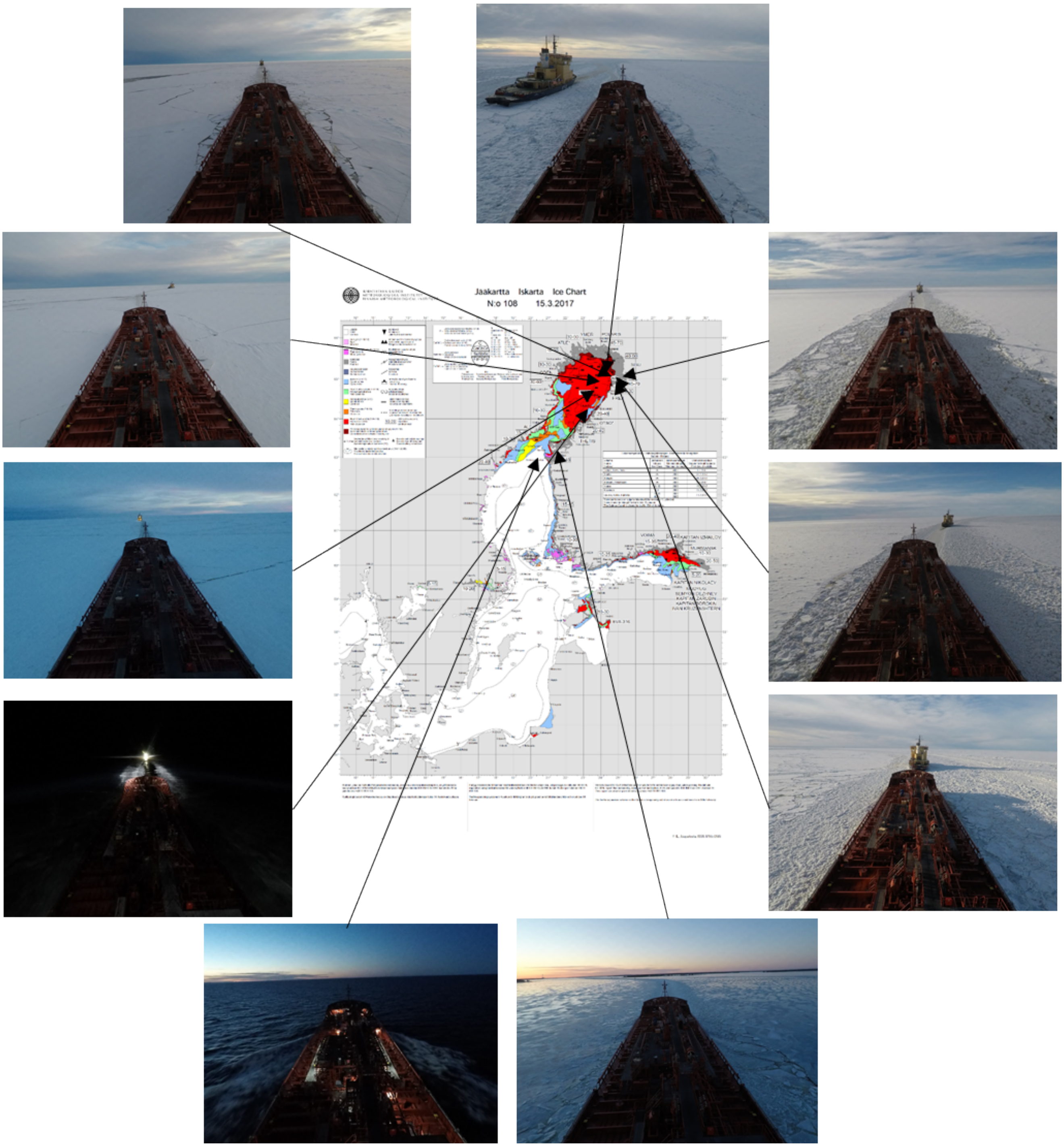


Figure 9: The conditions during the voyage from Oulu to Vaasa


A *B*

Figure 10: Stuck and cut loose by icebreaker Atle at the jammed brash barrier close to Oulu 1 lighthouse (A), Stuck in channel behind icebreaker Atle due to ice compression, Atle coming to cut loose (B)

3.2.3 SHIP PERFORMANCE DURING PORVOO – OULU AND OULU – VAASA LEGS

The ship performance during the observation voyage was analysed based on data obtained from the ship's own data recording system. The following quantities were recorded at 7 to 8 minutes intervals:

- Speed
- Heading
- Main engine power
- Wind speed and direction

The data was combined with ship position and onboard observations and then divided in legs which represent relatively constant conditions. The results of the analysis are shown below in Table 3 and Table 4. The presented numbers are average values calculated over each leg.

Table 3: Performance of the Reference ship during voyage from Porvoo to Oulu

Date	Area	Condition	Wind speed [m/s]	Wind direction	Ship speed [kn]	Heading [deg]	Engine power [kW]
12.03.2017	Gulf of Finland	Open water	11.5	SW	13.5	258	3880
13.03.2017	Northern Baltic Sea Proper	Open water	10.8	SW	13.6	278	3840
13.03.2017	Northern Baltic Sea Proper / Åland Sea	Open water	9.5	SW	13.8	321	3710
13.03.2017	Bothnian Sea	Open water	11.0	SW	14.1	12	3590
13.03.2017	Quark	Open ice	10.0	S	14.0	47	3620
14.03.2017	Bothnian Bay	Thin level ice	12.0	S	13.1	40	3800
14.03.2017	Bothnian Bay	Level ice, broken ice, fresh and closed channel	12.5	S	12.5	69	4350
14.03.2017	Bothnian Bay	Level ice, broken ice, fresh and closed channel	12.1	S	13.3	36	5450
14.03.2017	Bothnian Bay	Level ice, ice compression	13.2	SW	8.7	101	6140
14.03.2017	Bothnian Bay	Newly broken channel, following an icebreaker	12.8	S	11.4	61	4560
14.03.2017	Oulu fairway	Heavy brash ice barrier, heavy brash ice channel, assisted by an icebreaker	11.7	S	8.5	104	5930
14.03.2017	Oulu fairway	Brash ice channel	11.8	S	12.9	126	6220

Table 4: Performance of the Reference ship during voyage from Oulu to Vaasa

Date	Area	Condition	Wind speed [m/s]	Wind direction	Ship speed [kn]	Heading [deg]	Engine power [kW]
15.03.2017	Oulu fairway	Brash ice channel, assisted by an icebreaker	13.4	SW	13.5	304	5620
15.03.2017	Oulu fairway	Heavy brash ice channel, heavy brash ice barrier, assisted by an icebreaker	12.6	SW	7.5	264	5540
15.03.2017	Bothnian Bay	Level ice, broken ice, ice compression, assisted by an icebreaker	12.8	SW	13.2	218	6120
15.03.2017	Bothnian Bay	Large level ice floes, assisted by an icebreaker	14.0	W	10.7	195	5820
15.03.2017	Bothnian Bay	Broken ice field, following an icebreaker in a nearly ice-free channel	13.9	W	15.0	233	5320
15.03.2017	Bothnian Bay	Very open ice	11.6	W	15.5	227	5040
15.03.2017	Bothnian Bay	Open water	11.4	W	15.8	229	5040
16.03.2017	Quark	Open water	12.5	W	14.8	230	4410
16.03.2017	Quark / Bothnian Sea	Open water	9.7	W	15.0	136	4220

3.2.4 CREW EXPERIENCE

As a part of the observation voyage the operational aspects and ship performance were discussed with the ship crew on a general level. The main conclusions are presented below.

The performed observation voyage was a typical voyage to the northern part of the Bothnian Bay during a mild ice winter. However, significant ice compression is not experienced during a typical voyage.

During mild winters the ship typically operates independently in the Bothnian Bay. Icebreaker assistance is only needed in brash ice channels in Oulu and Kemi-Tornio fairways. In severe winters the ship may need icebreaker assistance in the entire Bothnian Bay.

In general, the manoeuvring capability in ice is considered rather sufficient in loaded condition. Manoeuvring in partially loaded and ballast conditions is more challenging as the bulbous bow splits the ice and easily steers the ship aside.

Breaking out of channel is considered difficult, especially in partially loaded and ballast conditions. During the observation voyage there was one ‘breaking out of channel’ event in loaded condition, where the Reference ship was overtaking another ship. In this case the Reference was able to break out of channel within a reasonable distance.

4 MODEL TESTS

4.1 THE TESTED MODELS

Two different bow forms were tested: an EEDI bow designed to fulfil the requirements of low open water resistance and as a reference the original bow of the Reference ship. The tested concepts were using the same stern configuration. The tests were performed at the design draught T=8.7 m.

The used model scale was 1:20.079. The target model-ice friction coefficient was 0.05.

The estimated bollard pull value of the ship is 932 kN at MCR of 8450 kW, on which the ice going predictions has been made.

The main characteristics of the tested ships are shown in Table 5 The models are shown in Figure 11 and Figure 12.

Table 5: Main characteristics of the ships

	Reference ship	EEDI bow
L_{OA} [m]	139.75	140.87
L_{WL} [m]	135.0	140.34
L_{BP} [m]	132.2	137.6
B_{DWL} [m]	21.70	21.70
T_{DWL} [m]	8.70	8.70
∇_{DWL} [m^3]	19090	19090
$D_{propeller}$ [m]	5.1	5.1

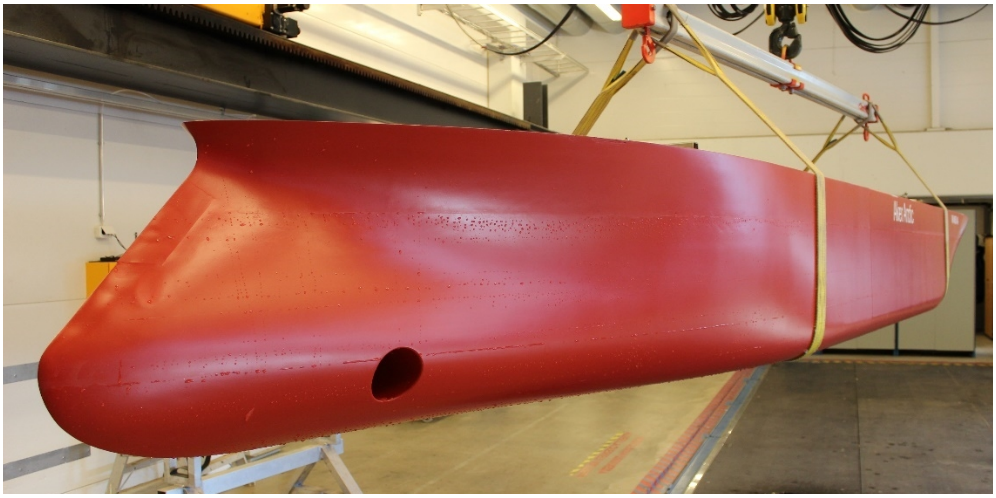


Figure 11: Model of the Reference ship

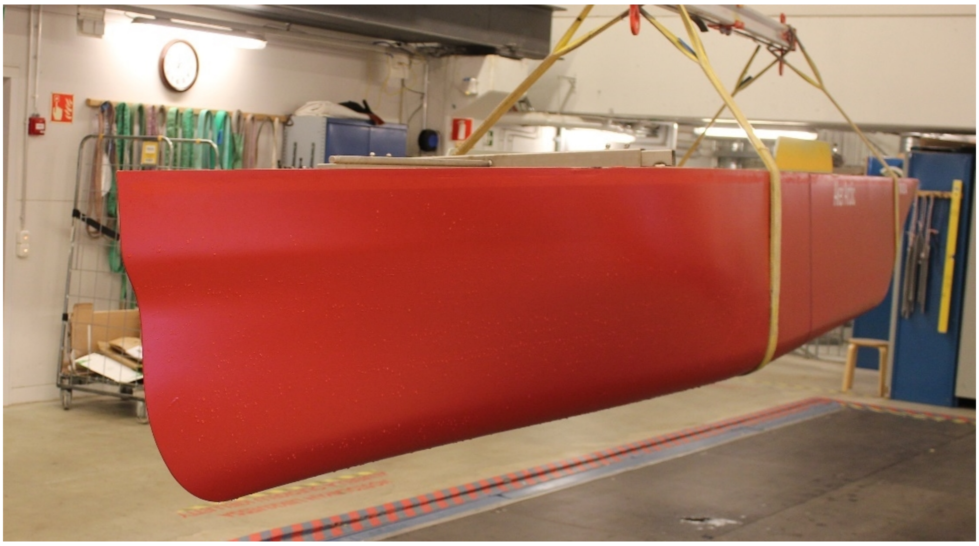


Figure 12: Model with EEDI bow

4.2 TEST PROGRAM

The main purpose of the model tests was to investigate and compare the operational use of power and achieved speeds in different ice conditions during transit voyage with the Reference ship. The result of these observations was then tried to make conclusions how a new type of bow shape might be able to operate in ice.

The tests were made in different ice conditions and were partly corresponding to ice conditions observed during the voyage with the Reference ship.

The two concepts were tested in same ice conditions which were the following:

- Level ice, two different thicknesses, corresponding to 0.35 m and 0.5 m thick ice.
- Brash ice channel (Figure 13) according to Finnish-Swedish Ice Class Rules (FSICR) for ice class IA. FSICR define exact channel profile but enables the use of average channel thickness H_{ave}, which is defined by following equation:

$$H_{ave} = H_m + 14.0 \cdot 10^{-3} \cdot B,$$

where B is breadth of the ship and H_m is 1.0 m for ice class IA and IA Super. For this ship H_{ave} is then 1.30 m. The difference between IA and IA Super channel is a 0.1 m thick consolidated layer. The width of the channel is also defined as 2 x B which corresponds to 43.4 m in full-scale.

Figure 13: Brash ice channel, ice class IA

- Heavily consolidated brash ice channel, thickness corresponding to FSICR
- Pack ice (Figure 14), two different thicknesses, corresponding to 0.35 m and 0.5 m thick ice, floe size 50 m.

Figure 14: Pack ice field

- Triangular ridge in level ice field (Figure 15). The ridge thickness corresponds to 5 m.

Figure 15: Triangular ridge in level ice field

- The manoeuvring tests were done as breaking out from own channel. The tests were only performed into one level ice thickness 0.35 m.

4.3 TEST RESULTS

Generally, the test results were surprising. The EEDI bow performed much better than expected. This is, most probably, due to the hull form design with a small icebreaking edge at the waterline. On the other hand, the level ice tests showed that the EEDI bow is sensitive to the icebreaking mode. Sometimes the EEDI bow breaks the ice by bending which leads to a relatively low ice resistance. Sometimes the icebreaking happens by crushing or by cutting the ice which results in reduced ice going capability. The crushing and cutting mode might by more representable for the bow shapes with a vertical stem.

4.3.1 LEVEL ICE

The results of the level ice tests are shown in Figure 16 (Ice resistance) and Figure 17 (Ice going capability). The net thrust curves for the ships are presented for engine power levels corresponding to 50 %, 75 % and 100 % of MCR.

The ice breaking cycle of the EEDI bow is very instable and therefore the icebreaking capability in level ice is strongly dependent on in which mode the EEDI bow breaks the ice. When the ice is broken in bending mode a speed close to 2.5 knots was achieved with the EEDI bow. Notable is that when the icebreaking happens in crushing mode the icebreaking capability at 2 knots is less than 0.3 m. The test results also indicate that the speed in 0.35 m ice, in bending mode, would be about the same as in 0.5 m thick ice.

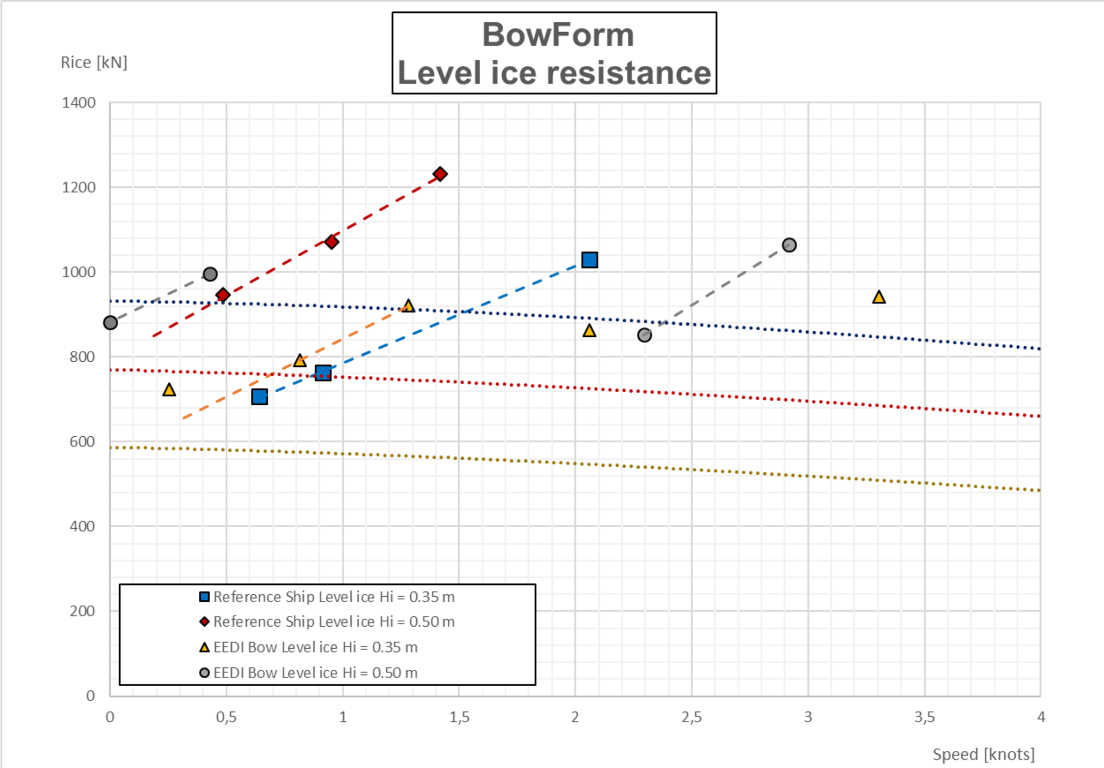


Figure 16: Ice resistance in level ice

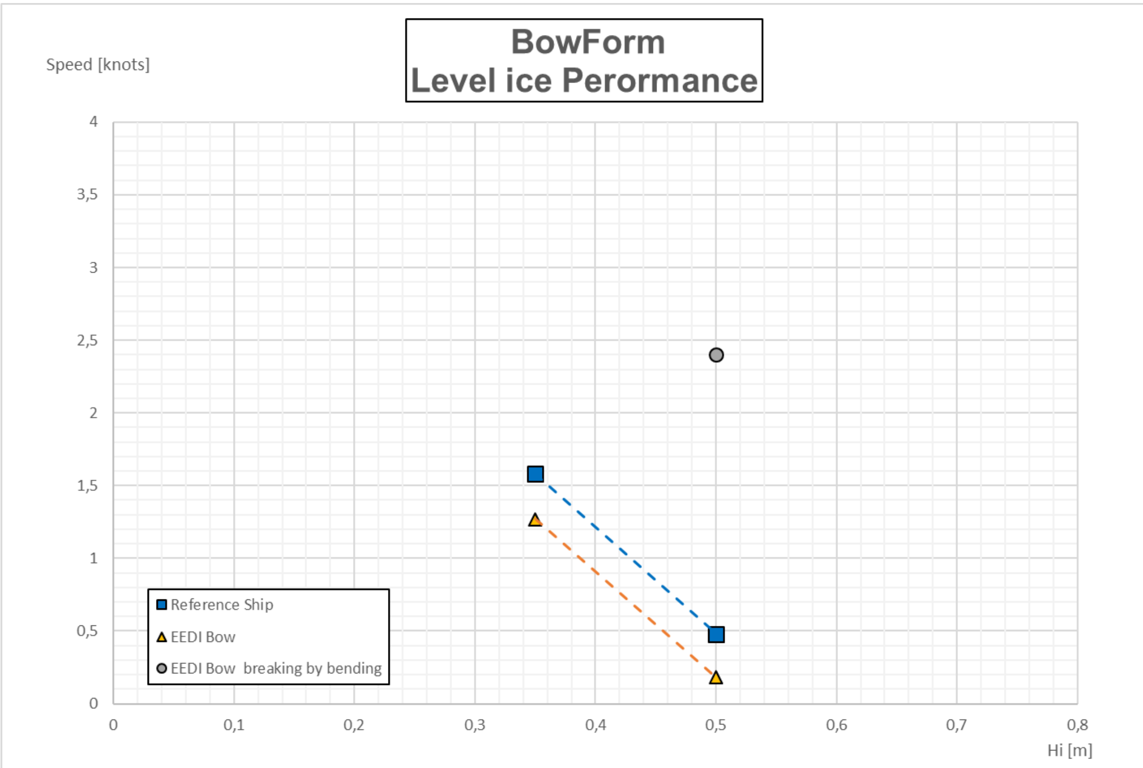


Figure 17: Estimated ice going capability in level ice with engine power corresponding to 100 % of MCR.

The photos below show the differences between the icebreaking modes. The Reference ship breaks the ice upward and no breaking happens along the side after the bulbous bow (Figure 18). The EEDI bow breaks the ice either by bending with some crushing observed at the stem (Figure 19) or by crushing and cutting (Figure 20).

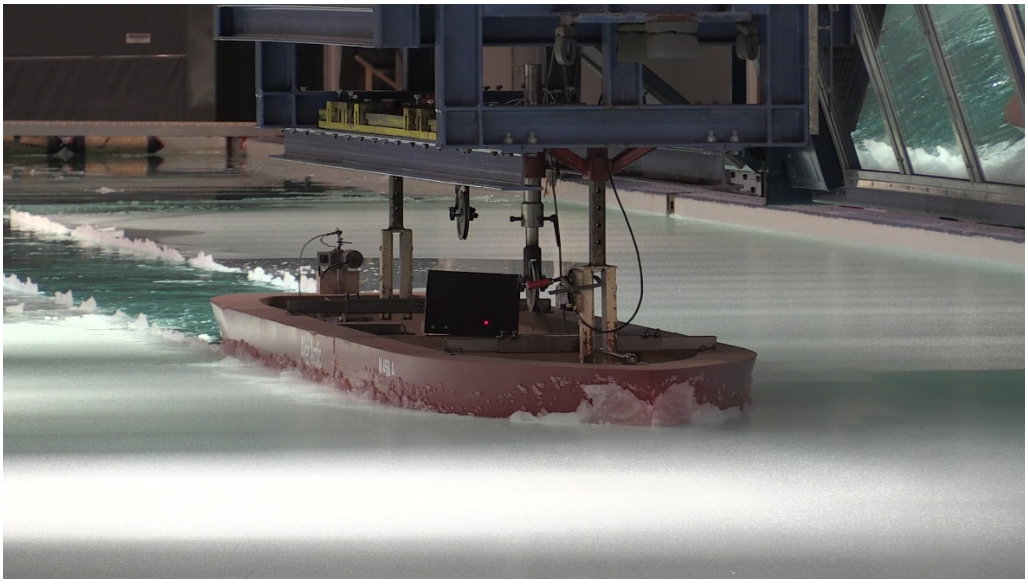


Figure 18: Level ice breaking with the Reference ship

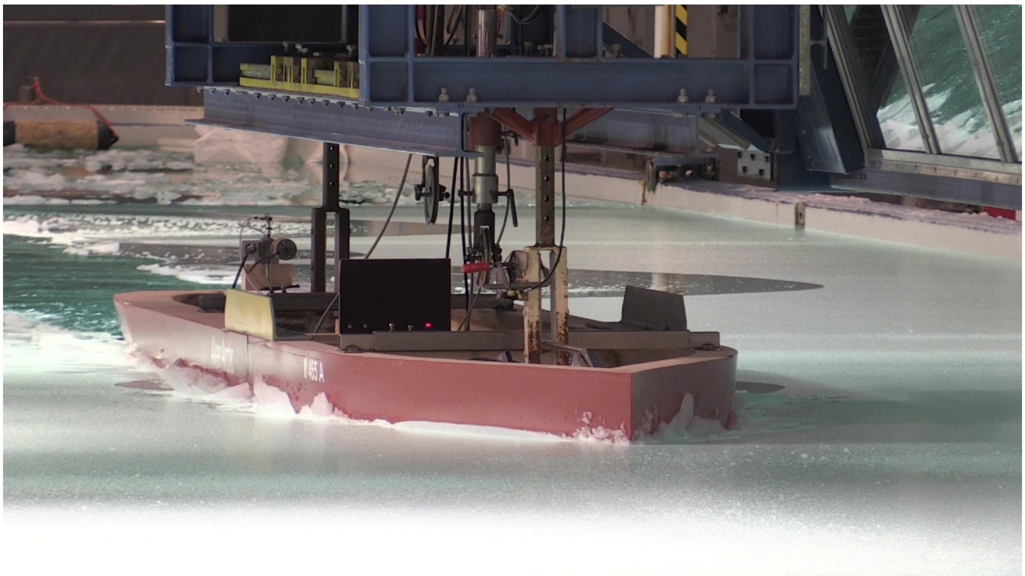


Figure 19: EEDI bow breaking the ice, in this case, by bending

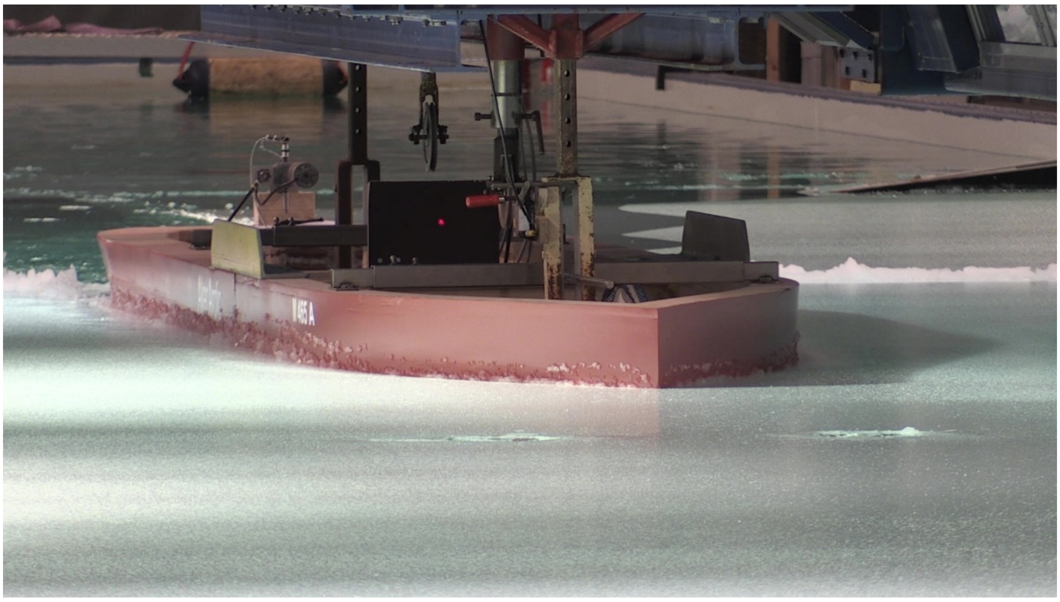


Figure 20: EEDI bow breaking the ice, in this case, by crushing and cutting

4.3.2 BRASH ICE CHANNELS

According to model scale results in FSICR IA brash ice channels both tested concepts would fulfil the speed requirement of 5 knots, even with power of 50 % of MCR (corresponds to an engine power of about 4225 kW). The test results might be somewhat optimistic because the power requirement calculated according to the equation defined in the FSICR would be about 5500 kW for the Reference ship.

The results of the brash ice channel tests are shown in Figure 21. The results include a friction correction according to the FSICR guidelines, where the test results are corrected to correspond to a ship-ice friction coefficient of 0.1.

Photos from the brash ice channel tests are presented in Figure 22 and Figure 23.

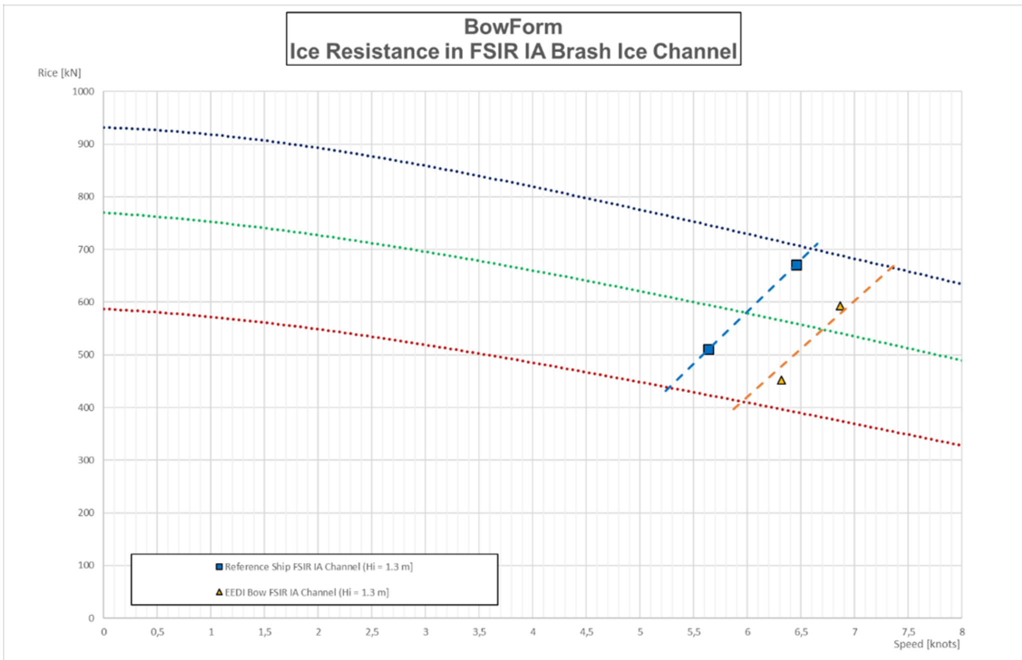


Figure 21: Ice resistance in FSIR IA brash ice channel

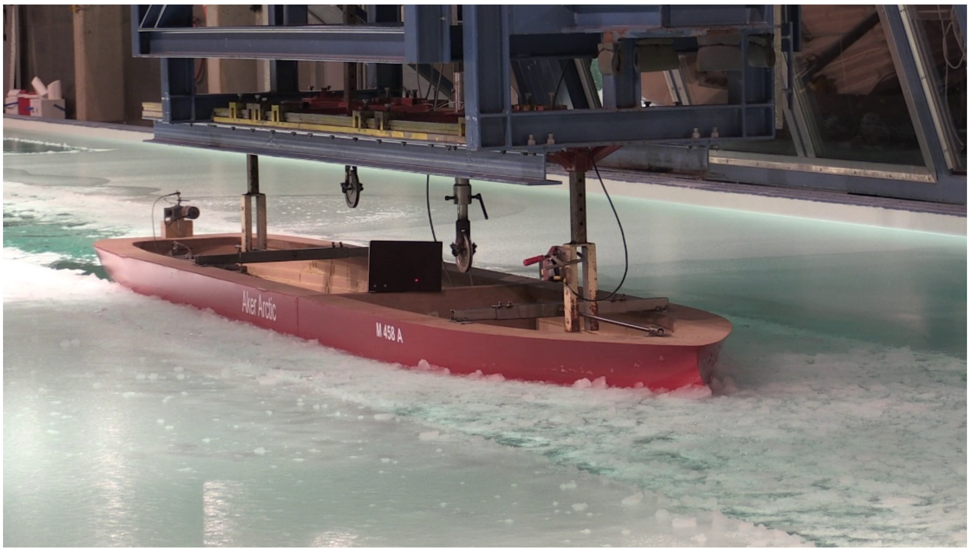


Figure 22: FSICR IA brash ice channel, Reference ship

Figure 23: FSICR IA brash ice channel, EEDI bow

The tests in consolidated brash ice channel were attended to be done in accordance to FSICR IA Super channel. However, due to difficulties in controlling the thickness and strength of the consolidated layer the tested channel was much more difficult than expected. Thus, the results are presented for a consolidated brash ice channel. In this case no friction correction is made to the test results. The results of the consolidated brash ice channel are shown in Figure 24.

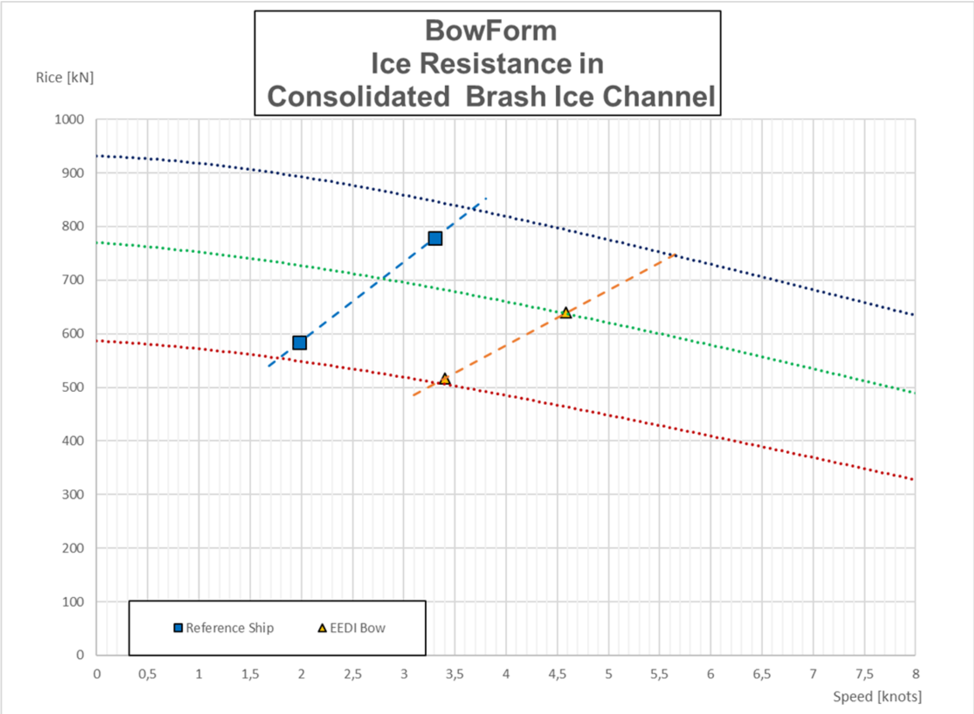


Figure 24: Ice resistance in consolidated brash ice channel

4.3.3 PACK ICE

The speeds achieved in pack ice are quite high. The EEDI bow achieved a speed of about 6 knots using only about 60 % of installed power in 0.35 m thick pack ice. Notable is also that the ice resistance of the EEDI bow is clearly lower than of the Reference ship. The results of pack ice tests are shown in Figure 25.

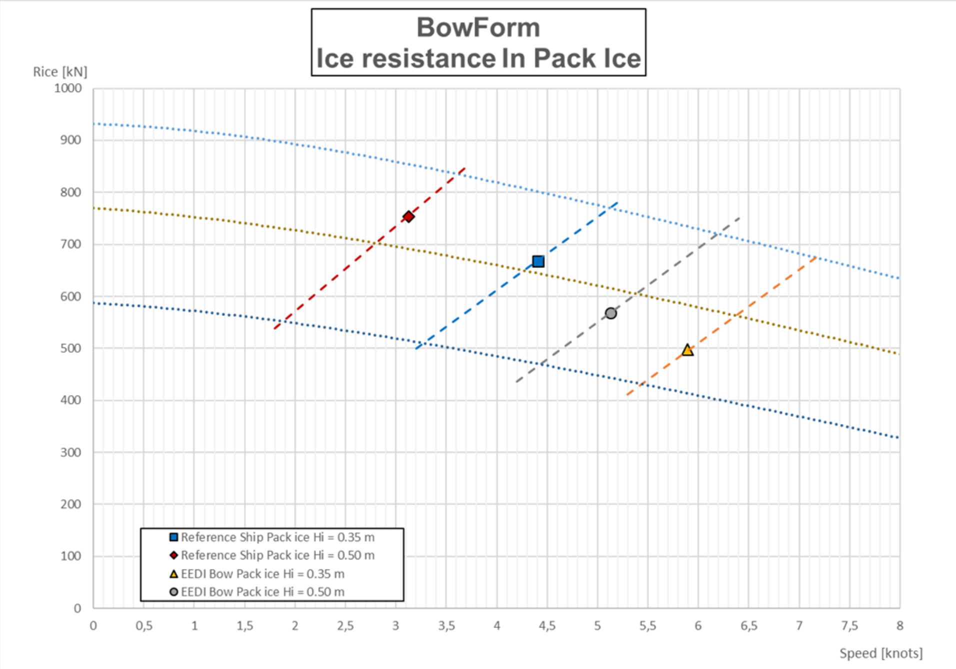


Figure 25: Ice resistance in pack ice

Visual observations showed that the EEDI bow was splitting the ice floe more effectively than the Reference ship. This leads to a better ice performance in the tested pack ice conditions. Photos from the pack ice tests are presented in Figure 26 and Figure 27.

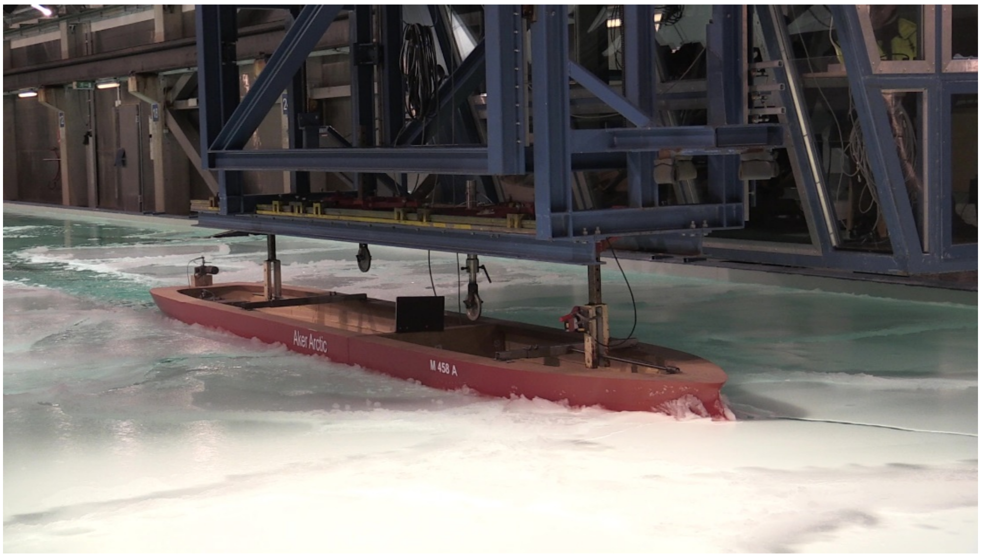


Figure 26: Pack ice, Reference ship

Figure 27: Pack ice, EEDI bow

4.3.4 TRIANGULAR ICE RIDGE

Both models were able to cross the tested ridge, thickness with a steady speed of about 0.7 to 0.8 knots with a power corresponding to about 100 % of MCR. The achieved speed while crossing the ridge was almost the same as in the surrounding level ice, and only a small speed reduction was observed. Photos from the ridge tests are presented in Figure 28 and Figure 29.

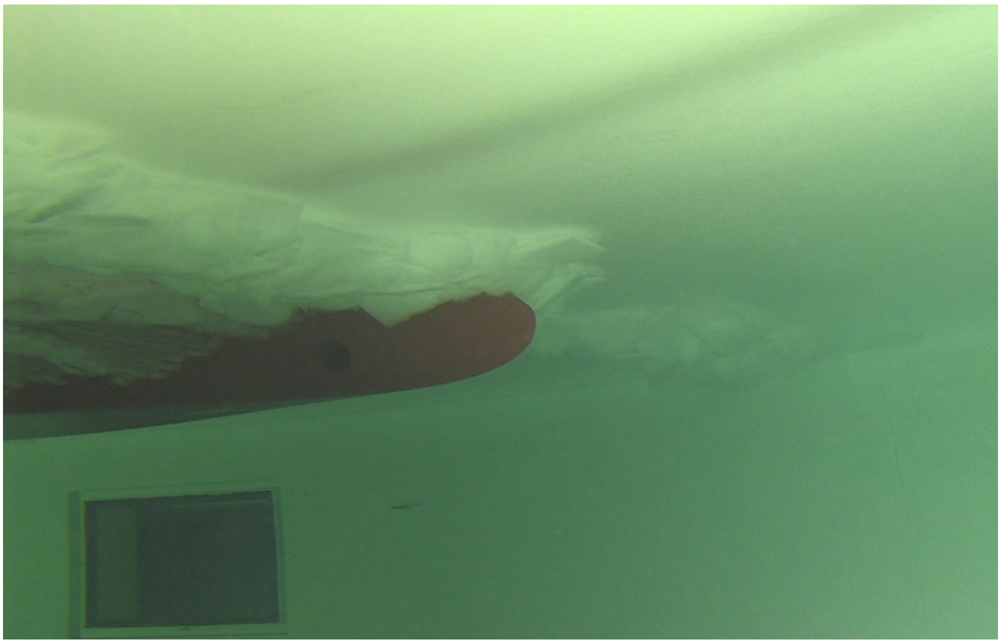


Figure 28: Reference ship penetrating through a small ridge

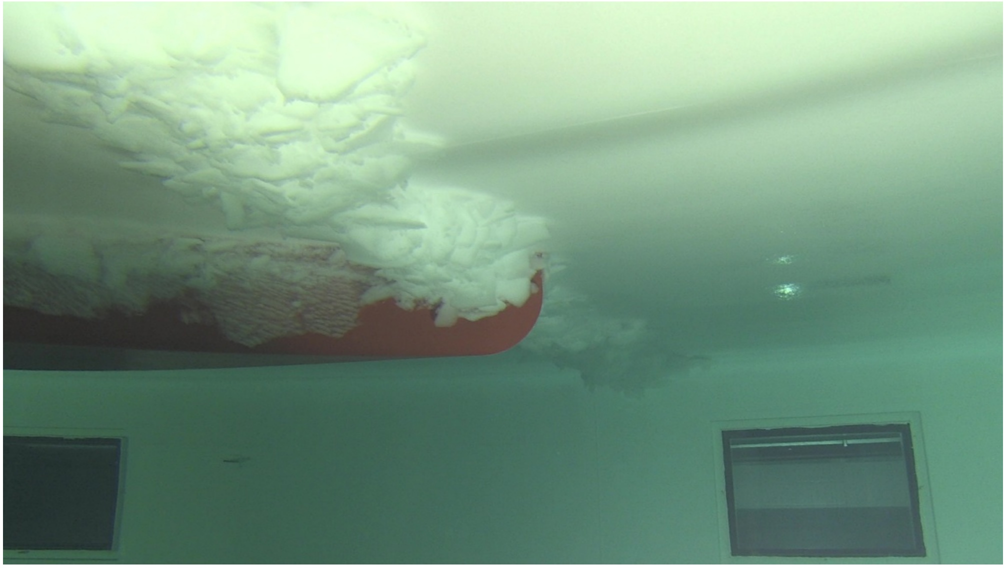


Figure 29: EEDI bow penetrating through a small ridge

4.3.5 MANOEUVRING TESTS / BREAKING OUT OF CHANNEL

The breaking out of channel tests were performed with a power corresponding to about 70 % of MCR. The initial outbreaking speed in the channel was about 5 knots at the time the rudder was turned. A rudder angle of 45 degrees was used.

Neither of the models was able to break out of the channel within the test length which corresponds to a full-scale distance of about 500 m.

During the test the models behaved differently. The Reference ship model was breaking a steadily widening channel and would have eventually break out at some point. However, this couldn't be confirmed in the model tests.

The model with EEDI bow was not able to widen the channel and when turning towards and hitting the channel edge the model bounced to the opposite side of the channel and was not able to break out.

Photos from the outbreaking tests are presented in Figure 30 and Figure 31.

Figure 30: Attempt to break out from channel with Reference ship

Figure 31: Attempt to break out from channel with EEDI bow

5 SUMMARY AND CONCLUSIONS

The target of this study was to find out the operability in ice of EEDI type bows that are usually equipped with a vertical stem. The research started with following an existing vessel, the Reference ship, on a transit voyage through ice in the Bothnian Bay. During this voyage the performance of the ship was observed in different encountered ice conditions. The experiences from this voyage were used as a basis for developing an ice model test program. Model tests were performed with two models: the Reference ship and a ship with an EEDI bow. Similar tests were done with both ships.

The observation voyage with the Reference ship to the Bothnian Bay was done in March 2017. The winter 2017 was mild and most of the voyage was done in open water or light ice conditions. More severe ice conditions occurred only in the northern part of the Bothnian Bay.

One of the most important findings is that the used power levels were about half of the installed power most of time i.e. in open water and light ice conditions. Only in the most severe ice conditions the used power level was more than 60 % of the MCR. The speed of the ship was mostly more than 10 knots when moving both independently and in icebreaker assistance. However, in the most severe ice conditions the ship got stuck, namely at the jammed brash ice barrier close to Oulu 1 lighthouse and in compressive ice west of Hailuoto where icebreaker assistance was needed.

A short summary of the speeds and power usage during the observation voyage is presented below.

- In open water at service speed (13.5 to 14 knots) the Reference ship uses power of 3600 to 3900 kW.
- In light ice conditions at power level of 4000 to 5500 kW the speed was about 13 knots.
- Behind an icebreaker in newly broken channel the speed was about 13 knots at a power level of 4600 kW
- In heavy brash ice channel, assisted by icebreaker, the speed was about 10 knots at power levels of 6500 to 6800 kW.
- When taking in account stopping at jammed brash ice barrier and reduced speed during pilot pick-up/drop-off, the average speeds in heavy brash ice channel, assisted by icebreaker, were 7.5 and 8.5 knots at average power levels of 5500 and 6000 kW, respectively.

The model tests were intended to be done in ice conditions similar to those experienced during the observation voyage. However, due to restrictions in model ice properties (ice thickness and ice strength) it was not possible to model exactly the ice conditions during the observation voyage. However, the model test results present an estimate of the ice performance of EEDI type bows, which can be used to assess the operability in real ice conditions by comparing the results of the EEDI bow and the Reference ship to each other.

Based on the model test the EEDI bow is performing equally well as or even better than the Reference ship in almost all tested conditions with the same available engine power. However, in one condition, outbreaking from channel, the EEDI bow performs much worse which might be a safety issue during operation.

The ice operability of the EEDI bow should not been generalized because the tested shape was not optimized only for open water. The ice-going capability was also taken in consideration for this bow shape during the optimization process. The test results indicate that the ice performance of the EEDI bow is sensitive to the icebreaking mode and how the bow pushes brash ice in channels.