STYRELSEN FÖR

**VINTERSJÖFARTSFORSKNING**

WINTER NAVIGATION RESEARCH BOARD

Research Report No 102

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# BRASH ICE CHANNEL RESEARCH

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|---|---|
| Finnish Transport Safety Agency | Swedish Maritime Administration |
| Finnish Transport Agency | Swedish Transport Agency |
| Finland | Sweden |

Talvimerenkulun tutkimusraportit — Winter Navigation Research Reports
ISSN 2342-4303
ISBN 978-952-311-278-0

## FOREWORD

In this report no 102, the Winter Navigation Research Board presents the results of research project Model Channel. The project studied the effect of the ice parameters effect on the results of brash ice channel resistance tests that can be used to determine the machinery power requirement for a vessel with a Finnish-Swedish ice class. FGX model ice with two different flexural strengths and fresh-water ice cubes were examined. It was found, that in order to have consistent and reliable model test results in brash ice channels, unified methods to take into account different test methods are needed.

The Winter Navigation Research Board warmly thanks Riikka Matala and Toni Skogström for this report.

Helsinki

October 2018

| | |
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Aker Arctic

# AKER ARCTIC TECHNOLOGY INC REPORT

# BRASH ICE CHANNEL RESEARCH

8 DECEMBER 2017

**Name of document:**
Brash ice channel research

**Document writer:**
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**Client information:**
**Finnish-Swedish Winter Navigation Research Board**

**Checked by / date:**
Leiviskä T. / 7.12.2017

**Report number:**
A-557

**Type of document:**
Research report

**Revision / Status:**
Rev. A

**Revision remarks:**

**Summary:**

This project is funded by Finnish-Swedish Winter Navigation Research Board.

The power requirement of the Finnish-Swedish ice class rules can be defined by model tests. The tests are to be conducted in an ice channel, the thickness and width of which are defined by the guidelines. However, it has been noticed at Aker Arctic and Aalto University that also model brash ice properties strongly affect the ice resistance of the vessel. The effect of piece size, level ice strength and porosity are areas, which should be investigated as well as the effect of channel making procedures. Investigation should also be made, whether the channel can be reconstructed after first test or not. The target of this project is to define the needed channel properties and production methods.

In this test series, ice channel was made of three different ice types: 500 kPa FGX model ice, 1000 kPa FXG model ice and fresh water ice cubes, which were produced outside the test tank. Multiple ice parameters were measured. Three similar channels were made in each ice field. Tests were conducted with a model if tanker with EEDI bow.

The model test results were compared to results of three different calculation methods.

Comparison to full scale channel tests is necessary in future.

**Keywords:**
1A Channel, ice class rules, FGX ice, ice cubes

**Document number:**

**Project number:**
P30122

**Language:**
English

**Pages, total:**
31

**Attachments:**
A

**Distribution list:**
Client

**Confidential status:**
Confidential

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# ABBREVIATIONS

| | |
|---|---|
| $\lambda$ | Scale factor |
| | |
| $B$ | Breadth |
| $D_P$ | Propeller diameter |
| $F$ | Force |
| $H_i$ | Ice thickness |
| $L_{BP}$ | Length between perpendiculars |
| $n$ | Rotation speed of propeller |
| $R_{ice}$ | Ice resistance |
| $T$ | Draft |
| $V$ | Velocity |
| | |
| *f.sc.* | Full scale |
| *m.sc.* | Model scale |

# 1 INTRODUCTION

The objective of the survey was to study brash ice channel ice parameter's effect to channel resistance in model scale. In addition, objective was to find a reliable procedure to conduct the channel tests with minimal amount of test days.

The project plan consisted of 5 steps:

Step 1: Evaluation of the phenomena in brash ice channel production procedures. The evaluation process concentrates on the channel properties, which have effect on the resistance, i.e. piece size, ice strength, thickness and porosity etc. Also the channel making methods are evaluated and finally a standardized method to measure brash ice channel thickness is developed.

Step 2: Definition of the channel preparation methods is made. The parameters for two different channels are selected. The parameters include: level ice thickness and strength, piece size, porosity and how to achieve the defined porosity in the channel. As the applied procedures concern all ice model test facilities in the world, also the main facilities are asked to comment the procedures and channel properties. In principle this refers to the facilities, which are members of ITTC ice committee.

Step 3: The comments from other facilities are taken into account and the final procedures and properties are defined to be tested. The ice in an old brash ice channel consists typically of somewhat rounded, hard ice blocks of size approximately 30-50 cm, which differ very much from the model ice pieces. Therefore, test could also be conducted in one ice channel made of natural ice frozen in the ice basin or even ice cubes produced outside of the basin.

Step 4: The two channels will be tested in two ice model basins with a model of an existing ship. Tests will be conducted in two defined ice sheets and they will be repeated in each channel once, which refers to tests in four channels both at Aalto University and Aker Arctic and optionally in one channel filled with ice cubes. The channels will be reconstructed after the first two tests and the tests are repeated in all channels at least three times.

Step 5: Reporting and recommendations for procedures to prepare the brash ice channels for the definition of the power requirement with ice model tests according to the Finnish-Swedish ice class rules.

Originally, all tests were to be run in 2016. Due to Aalto ice tank renovation delay, the model test schedule was postponed. Schedule of the project was extended until the end of year 2017, but it was found out that no model test can be conducted at Aalto basin before 2018. Therefore, it was decided that all tests will be conducted at Aker Arctic test basin.

Consequently, the steps were accomplished in the following manner:

Step 1: Step 1 was partly completed already in January 2016. Aker Arctic and Aalto University representatives participated in a kick-off meeting, where the issue was discussed. In the meeting there was also discussion about the guidelines for the Finnish-Swedish Ice Class Rules, which define the verification of a ship's performance for ice classes through model tests. It was noted that some definitions regarding the ice properties and measurements were vague and do not reflect ice tank practice. A questionnaire was prepared for the other ice model basins about the brash ice channel measurement methods, e.g. ice piece size, cohesion.

Step 2: The questionnaire was sent to HSVA, Krylov and NRC-OCRE. Aker Arctic also filled the questionnaire, but the representative of Aalto University informed that they do not actually have standardized procedures for channel tests.

Step 3: The answers to questionnaire were reviewed. The main channel properties, which have effect on the channel resistance but are not included in the guidelines at the moment, were identified from the answers to the questionnaires. They were: piece size, ice strength and cohesion. Also, internal friction angle was mentioned. One problem with these properties is that it is difficult to produce as small ice pieces as should be by the scale and that cohesion or internal friction angle are difficult to measure. It was decided to concentrate first to find the possible measuring methods of these parameters. Next the plan was to evaluate how these parameters affect the channel resistance and with what kind of simple tests it would be convenient to define if the channel is appropriate or not.

Step 4: The tests were conducted in Aker Arctic ice model test basin in three different ice channels with a model of an EEDI-tanker. The parental ice strength was varied, and it was assumed that parental ice strength has an effect to achieved brash ice porosity. Two of the channels were manufactured in FGX-model ice with different target strength (500 kPa and 1000 kPa) and one channel was made of fresh water ice cubes, which had practically infinite strength in model scale. After first channel test, the channel was reconstructed twice.

Following ice property measurements were conducted in each ice field:

- Parental ice thickness
- Parental ice flexural strength
- Channel thickness
- Porosity
- Internal friction angle
- Ice density
- Friction between ice and model

Measuring procedures are described in Chapter 5 Ice measurements.

Step 5: The test conditions, procedures and results are described and discussed later in this report.

# 2 OBJECTIVES OF THE MODEL TESTS

The objective of the model tests was to study brash ice channel ice parameter’s effect to channel resistance in model scale.

All tests were conducted in an ice channel (1A), the thickness and width of which were defined by the Finnish-Swedish ice class rules. In addition, many other parameters, which are not defined by the rules, were measured.

During the survey, the test channel was made of three different material: FGX model ice with flexural strength of 500 kPa, FGX model ice with flexural strength of 1000 kPa and fresh water ice cubes produced outside the test tank.

The test results varied along the changing material parameters. In order to identify the correct test results, channel resistance equations and full scale channel tests were also studied.

Tests were conducted with the model of a tanker with EEDI bow.

# 3 DESCRIPTION OF THE MODEL

The model was built in scale c.1:25. The tested vessel was a tanker equipped with EEDI bow, one shaft propeller and a rudder. The surface of the model was treated in accordance with the Aker Arctic standard methods.

# 4 TESTS

## 4.1 TEST PROGRAM

Day program is presented in *Table 4-1*. The idea was to vary ice strength and observe the difference in cohesion between ice pieces in channel.

The tests were conducted in three different ice types. In all ice fields, the channel was reconstructed twice after first test run. Two different power levels were used in each channel.

*Table 4-1 Day program by ice type*

| Ice field | Date | Ice type |
|---|---|---|
| 1 | 9.5.2017 | FGX-ice, 500 kPa |
| 2 | 10.5.2017 | Ice cubes |
| 2 | 11.5.2017 | Ice cubes, next day |
| 3 | 12.5.2017 | FGX-ice, 1000 kPa |

In all tests, the channel target thickness and width were the same. Finnish-Swedish Ice Class Rules define exact channel profile but enables the use of average channel thickness $H_{ave}$, which is defined by following equation (1):

$$H_{ave} = H_m + 14.0 \cdot 10^{-3} \cdot B \tag{1}$$

where $B$ is beam of the ship and $H_m$ is 1 meter for ice class IA. Therefore, $H_{ave}$ is 1.4 m in full scale, which equals to 58 mm in model scale.

The width of the channel is also defined 2 x $B$ which is 52 m in full scale and 2.2 m in model scale.

## 4.2 CHANNEL MAKING PROCEDURES

### 4.2.1 ICE FIELD 1, FGX-ICE 500 KPA

FGX-ice was produced with Aker Arctic standard spraying method. The target ice properties are presented in *Table 4-2*.

The channel was prepared by manually cutting the ice into small pieces with a special tool.

*Table 4-2 FGX-ice 500 kPa target properties*

| | f.sc. | m.sc. |
|---|---|---|
| $h_{ice}$ | 0.8 m | 36.0 mm |
| $h_{channel}$ | 1.4 m | 57.7 mm |
| $\sigma_f$ | 500.0 kPa | 21.2 kPa |
| Piece size | 1.0 m | 42 mm |

### 4.2.2 ICE FIELD 2, ICE CUBES

Ice cubes were imported to the tank from a special ice making company. Ice cubes were cylindrical and there was a hole in the middle of each piece (*Figure 4-1*). The length of each ice piece varied between 50 mm and 80 mm. Diameter of the pieces was 30 mm. The ice properties are presented in *Table 4-3*.

The level ice outside the channel was spared from the previous ice field.

The flexural strength of an ice cube could not be measured, but the properties were assumed to correspond to fresh water ice properties. When scaled to full scale, the strength was as high as 23.6 MPa. Ice cubes in model scale were assumed to behave as infinite strong particles and cohesion was assumed to be zero.

*Figure 4-1 Ice cubes*

*Table 4-3 Ice cube channel properties*

| | f.sc. | m.sc. |
|---|---|---|
| $h_{ice}$ | 0.8 m | 36.0 mm |
| $h_{channel}$ | 1.4 m | 57.7 mm |
| $\sigma_f$ | ~23600 kPa | ~1000 kPa |
| Piece size | 1.1 m | 50 mm |

### 4.2.3 ICE FIELD 3, FGX-ICE 1000 KPA

FGX-ice 1000 kPa was produced similar way with ice field 1, but the target flexural strength was set to 1000 kPa instead of 500 kPa. The target ice properties are presented in *Table 4-4*.

*Table 4-4 FGX-ice 1000 kPa target properties*

| | f.sc. | m.sc. |
|---|---|---|
| $h_{ice}$ | 0.8 m | 36.0 mm |
| $h_{channel}$ | 1.4 m | 57.7 mm |
| $\sigma_f$ | 1000.0 kPa | 42.4 kPa |
| Piece size | 1.0 m | 42 mm |

## 4.3 FRICTION CORRECTION

The friction coefficient varied between different ice making procedures. Because objective was to compare Finnish-Swedish ice class rules channels, special interest is given to results, which are corrected to correspond to friction coefficient 0.1.

According to the Finnish-Swedish Ice Class rules, the channel resistance correction is calculated as following:

$$R_{CH(with\ target\ \mu)} = \left[(0.6 + 4 \cdot \mu_{target})/(0.6 + 4 \cdot \mu_{actual})\right] \cdot R_{CH(with\ actual\ \mu)}, \qquad ()$$

where $\mu_{target}$ is 0.1.

*Table 4-5* presents friction coefficients of different ice types. The coefficients were measured during testing period.

*Table 4-5 Measured friction coefficients of different ice types*

| **Ice type** | **Friction coefficient** |
|---|---|
| FGX-ice 500 kPa | 0.044 |
| Ice cubes (natural ice) | 0.028 |
| FGX-ice 1000 kPa | 0.033 |

## 4.4 THICKNESS CORRECTION

In analysis, the thickness of channel was defined by calculating average thickness from 10 meters before the end of valid model test length. In test carried out in FGX-ice, three middle thickness measurements were taken into account, because it was observed that further from center line there was no movement in channel brash ice. In tests conducted in ice cube channel, the ice brash moved at the whole width of channel and so all five lateral measurements were taken into account.

In model scale, the target properties of ice are sometimes not achieved, but the results are corrected to correspond to target thicknesses. Traditionally, the corrected ice resistance is calculated using following equation (2):

$$R_{ice,corrected} = R_{ice} \cdot \left(\frac{h_{target}}{h_{measured}}\right)^{x} \qquad (2)$$

where

$h_{target}$ is target channel thickness

$h_{measured}$ is measured channel thickness

$x$ is a constant based on Aker Arctic experience, in this $x = 1.2$.

This correction method is used in this report results.

However, in this series the model tests were carried out in scantling draft and no ice under hull was observed. Instead, ice was pushed to the sides and in some cases even forward. Possibly a different approach would be needed to evaluate thickness variation. The corrections method could be based on soil mechanics equation for cohesionless granular mass being pushed horizontally (3):

$$R = \frac{1}{2} \cdot \left(\frac{1+\sin\phi}{1-\sin\phi}\right) \cdot (1-n) \cdot \rho \cdot g \cdot \left(\frac{\rho_w}{\rho_i} - 1\right) \cdot t^2 \qquad (3)$$

# 5 ICE MEASUREMENTS

Following ice parameters were measured during the test series:

| | FGX 500 kPa | FGX 1000 kPa | Ice cubes |
|---:|:---:|:---:|:---:|
| Parental ice thickness | x | x | |
| Parental ice flexural strength | x | x | |
| Channel thickness | x | x | x |
| Porosity | x | x | x |
| Internal friction angle | x | x | x |
| Ice density | x | x | x |
| Friction | x | x | x |

## 5.1 PARENTAL ICE PROPERTIES

Flexural strength is measured with in-situ cantilever beam method, as recommended by ITTC, at two locations. Ice thickness was measured in the process. The flexural strength is calculated with the following equation (4)

$$\sigma_f = \frac{6Fl}{bh^2} \tag{4}$$

| where | | |
|---|---|---|
| | $F$ | failure force |
| | $l$ | length of the beam |
| | $b$ | width of the beam |
| | $h$ | ice thickness |

## 5.2 CHANNEL THICKNESS

Channel thickness was measured from center line of the tank longitudinally in one-meter intervals. Every second meter, five measurements were taken, so that in addition to center line, one measurement was taken 40 cm and one 90 cm aside center line, both sides.

## 5.3 POROSITY

Porosity ($p$) of the ice channel was measured by submerging a known amount of ice brash and measuring the ice mass buoyancy. Instrumented device, a box, was submerged through the brash ice channel completely and held steady until the buoyancy force was constant. The force ($F_m$) was measured with the force transducer which was mounted between the box and a motor which drove the box in vertical direction. In addition, the box was submerged in open water to measure only the buoyancy of the box ($N_{box}$). The ice channel porosity was calculated according to Archimedes' principle and equations (5) and (6) are presented below. Total volume ($V_T$) was calculated using the surface area of the submerged brash ice (inside area of the box) and the measured thickness.

$$V_{Ice\ mass} = \frac{F_m + G_{box} - N_{box}}{(\rho_w - \rho_i)g} \qquad (5)$$

$$p = 1 - \frac{V_{Ice\ mass}}{V_{Total}} \qquad (6)$$

| where | | |
|---|---|---|
| | $F_m$ | measured force |
| | $G_{box}$ | weight of the box |
| | $N_{box}$ | buoyancy of the box in open water |
| | $\rho_w$ | water density |
| | $\rho_i$ | ice density |
| | $V_T$ | total volume of the channel inside the box |
| | $V_{ice\ mass}$ | ice mass volume inside the box |
| | $p$ | porosity of the channel |

## 5.4 INTERNAL FRICTION ANGLE

A plate was pushed in brash ice at slow speed (Figure 5-1). The brash accumulates in front of the plate, after which the slope angle $\alpha$ of the brash can be measured. There is a relation between the breaking angle and internal friction angle $\phi$ (equation 7):

$$\alpha = 45 - \phi/2 \qquad (7)$$

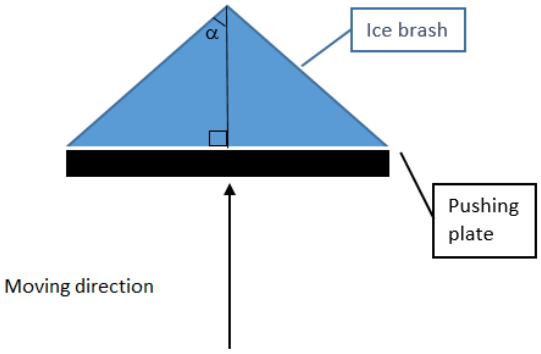

*Figure 5-1 Internal friction test arrangement*

## 5.5 ICE DENSITY

Ice density is measured by defining the weight needed to submerge a freely floating ice sample, which is one of the methods recommended by ITTC. For the measurement, only the scale and the small container is needed. The container is partly filled with the basin water and weighed ($w_1$). The ice sample is lifted from the basin and put into the container on the scale. The weight of the container with freely floating ice is recorded ($w_2$). Then the ice sample is carefully submerged. When the ice sample is completely submerged, balanced, and not in any contact to container walls, the weight is recorded ($w_3$). The ice density is calculated with the formula

$$\frac{\rho_i}{\rho_w} = \frac{w_2 - w_1}{w_3 - w_1}$$

| | | |
|---|---|---|
| where | $\rho_w$ | water density |
| | $\rho_i$ | ice density |
| | $w_1$ | weight of the container filled with basin water |
| | $w_2$ | weight of the container and the ice sample freely floating in basin water |
| | $w_3$ | weight of the container and the ice sample submerged into the basin water |

## 5.6 FRICTION

In the friction test setup, the ice piece is pulled on the test surface with a pulling bracket, which is connected to a force transducer with a wire. The force transducer is pulled with a constant speed of 50 mm/s. Different weights are placed on the pulling bracket to vary the contact force between the ice and the test surface. The tests are done with a water layer on the test surface to reproduce the wet contact between ships side and ice.

## 5.7 ICE MEASUREMENT RESULTS

Ice channel thickness, porosity and equivalent thickness are presented in Table 5-1. The equivalent thickness demonstrates the value of ice mass thickness with 0 % porosity i.e. 100 % ice concentration in the channel.

*Table 5-1 Measured ice channel thickness, porosity and equivalent thickness*

| Date | Ice type | Flexural strength | Test | Average channel thickness | Porosity | Equivalent thickness | Note |
|---|---|---|---|---|---|---|---|
| | | *kPa* | *no* | *mm* | *%* | *mm* | |
| 9.5.2017 | FGX | 500 | I | 55 | 29 | 39 | broken level ice |
| | | | II | 59 | 41 | 35 | reconstructed |
| | | | III | 60 | 45 | 33 | reconstructed |
| 10.5.2017 | Ice cubes | - | I | 66 | 46 | 36 | |
| | | | II | 62 | 49 | 32 | |
| | | | III | 59 | 52 | 28 | |
| 11.5.2017 | Ice cubes | - | IV | 76 | 58 | 32 | reconstructed from previous day |
| 12.5.2017 | FXG strong | 1000 | I | 76 | 45 | 42 | broken level ice |
| | | | II | 68 | 43 | 39 | reconstructed |
| | | | III | 68 | 45 | 37 | reconstructed |

Internal friction angle ($\phi$) measurements are presented in Figure 5-2. There were higher internal friction angles measured in FGX-ice, normal and strong, than in the channel constructed from ice cubes. In FGX-ice channel, measured values were between 23-29 degrees and 12-13 degrees in the channel of the ice cubes.

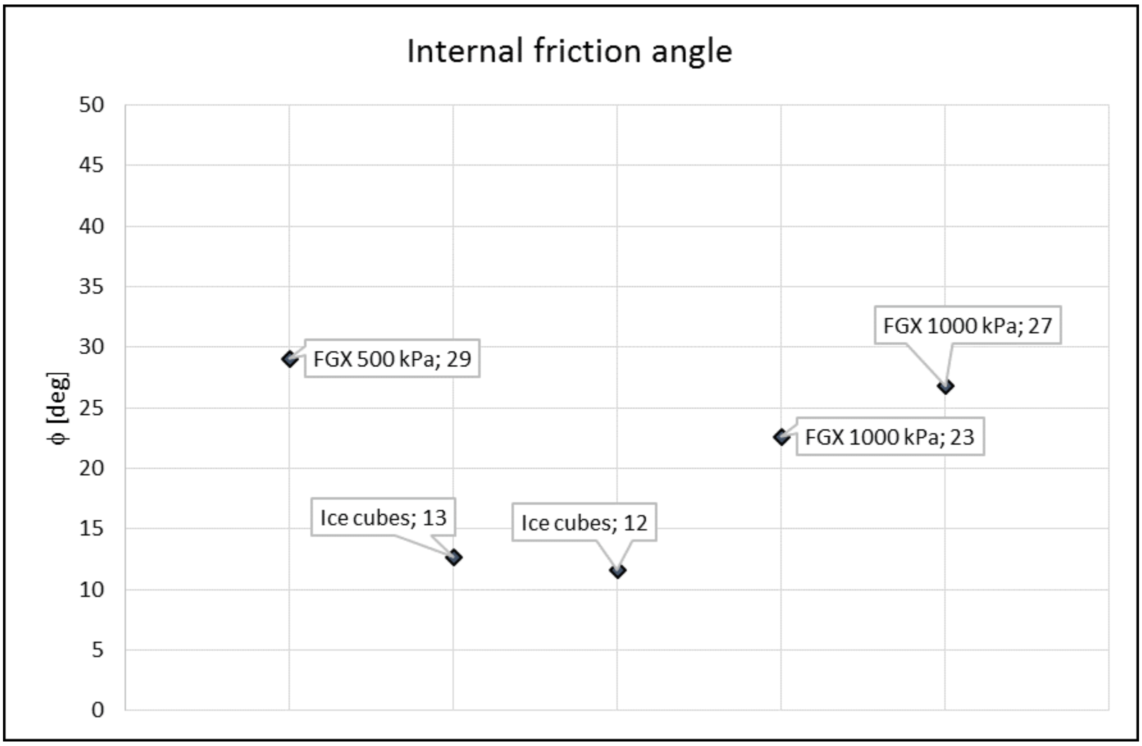

*Figure 5-2 Internal friction angle measurements in FGX-ice and in the channel of ice cubes*

# 6 COMPUTATIONAL METHODS

Ship channel resistance evaluation methods have been under development from 80's. The equations are typically divided into terms, which measure certain physical phenomenon between ice and the vessel. In this project, the channel resistance was calculated using three different methods: Finnish-Swedish ice class rules, Wilhelmson's method and Lindqvist's equation.

In calculations, the constants were chosen so that they corresponded to model test conditions. The calculated resistances are presented together with friction and thickness corrected model test results in Figure 7-4.

## 6.1 FSIC

Finnish-Swedish ice class rules calculate channel resistance with equation, which takes into account the consolidated layer of the ice channel for 1A Super vessels. The equation calculates the ice resistance at speed of 5 knots. There is no speed component in the formula.

$$R_{ch} = C_1 + C_2 + C_3 \cdot \left(H_f + H_m\right)^2 \cdot \left(B + C_\Psi \cdot H_f\right) \cdot C_\mu + C_4 \cdot L_{PAR} \cdot \left(H_f\right)^2 + C_5 \cdot \left[\frac{LT}{B^2}\right]^3 \cdot \frac{A_{wf}}{L}$$

- $C_1$ and $C_2$ take into account a consolidated upper layer of the brash ice and are to be taken as zero for ice classes 1A, 1B and 1C.
- $H_f = 0.26 + (H_m \cdot B)^2$
- $H_m = 1.0$ for ice class 1A
- $L$ = length of the ship between the perpendiculars [m]
- $B$ = maximum breadth of the ship [m]
- $T$ = actual ice class draught of the ship [m]
- $C_\Psi = 0.047 \cdot \Psi - 2.115$, and $C_\Psi = 0$ if $\psi \leq 45°$
- $C_\mu = 0.15 \cdot \cos(\varphi_2) + \sin\Psi \cdot \sin\alpha$, $C_\mu$ is to be taken equal or larger than 0.45
- $C_3 = 845 \frac{kg}{m^2 s^2}$
- $C_4 = 42 \frac{kg}{m^2 s^2}$
- $C_5 = 825 \frac{kg}{m^2 s^2}$
- $A_{wf}$ = area of the waterline of the bow [$m^2$]
- $\Psi = \tan^{-1}\left(\frac{\tan(\varphi_2)}{\sin\alpha}\right)$
- $\alpha$ = the angle of the waterline at B/4 [degrees]

- $\varphi_2$ = the rake of the bow at B/4 [degrees]

## 6.2 WILHELMSON

Wilhelmson channel resistance calculation method is based on former method of Malmberg, but he added the speed effect into formula in the form of Froude number.

$$R_{ch} = \frac{1}{2} \cdot \mu_B \cdot \rho_\Delta \cdot g \cdot H^2 \cdot K_p \cdot \left[\frac{1}{2} \cdot \left(1 + \frac{H_m}{H_f}\right)\right]^2$$

$$\cdot \left(B + 2 \cdot H \cdot \tan(\Psi) \cdot \cos(\alpha)\right) \cdot \left(\mu_H \cdot \cos\Psi + \sin\Psi \cdot \sin\alpha\right)$$

$$+\mu_B \cdot \rho_\Delta \cdot g \cdot K_0 \cdot L_{PAR} \cdot H^2 \cdot \mu_H$$

$$+C \cdot \rho_\Delta \cdot g \cdot H_m \cdot A_{wf} \cdot {F_n}^2$$

- $C = \left(\frac{LT}{B}\right)^3$
- $\mu_b$ = 1-n
- *n = porosity*
- $\rho_\Delta = \rho_w - \rho_i$
- g = 9.81 m/s$^2$
- $b = H \cdot \tan\Psi \cdot \cos\alpha$
- $\Psi = \tan^{-1}\left(\frac{\tan(\varphi_2)}{\sin\alpha}\right)$
- $H_m$ =Thickness of the brash ice in mid channel [m]
- $H_f$ = Thickness of the brash ice layer displaced by the bow [m]
- H = Thickness of the brash ice layer displaced by the bow [m]
- $K_0 = \frac{\vartheta}{1-\vartheta}$
- $F_n = \frac{v}{\sqrt{g \cdot L_{wl}}}$

## 6.3 LINDQVIST

Lindqvist equation is developed for calculating ice resistance in level ice. The equation consists of four components: crushing, bending, sinking of ice and velocity effect. In order to calculate channel resistance, some assumptions were done:

- Crushing and bending strength of ice were assumed to be zero in broken ice

- The channel was assumed to be evenly 1.364 m thick

If $R_b$ and $R_c$ are taken as zero, the formula alters to following form:

$$
\begin{aligned}
R_{ice} = R_s \cdot \left(1 + 9.4 \cdot \frac{v}{\sqrt{gL}}\right) \\
= \rho_{\Delta} g H_{ice} B \cdot \Bigg[ T \cdot \frac{B+T}{B+2T} + \mu \\
\cdot \left(0.7L - \frac{T}{\tan(\varphi)} - \frac{B}{4\tan(\alpha)} \right. \\
\left. + T\cos(\varphi)\cos(\psi)\sqrt{\frac{1}{\llbracket(\sin\rrbracket\,\varphi)^2} + \frac{1}{(\tan\alpha)^2}}\right) \Bigg] \cdot \left(1 + 9.4 \cdot \frac{v}{\sqrt{gL}}\right)
\end{aligned}
$$

# 7 MODEL TEST RESULTS

Model test results are presented in following figures:

- Figure 7-1 plain test results with no corrections
- Figure 7-2 test results with friction correction
- Figure 7-3 test results with thickness correction
- Figure 7-4 test results with friction and thickness correction

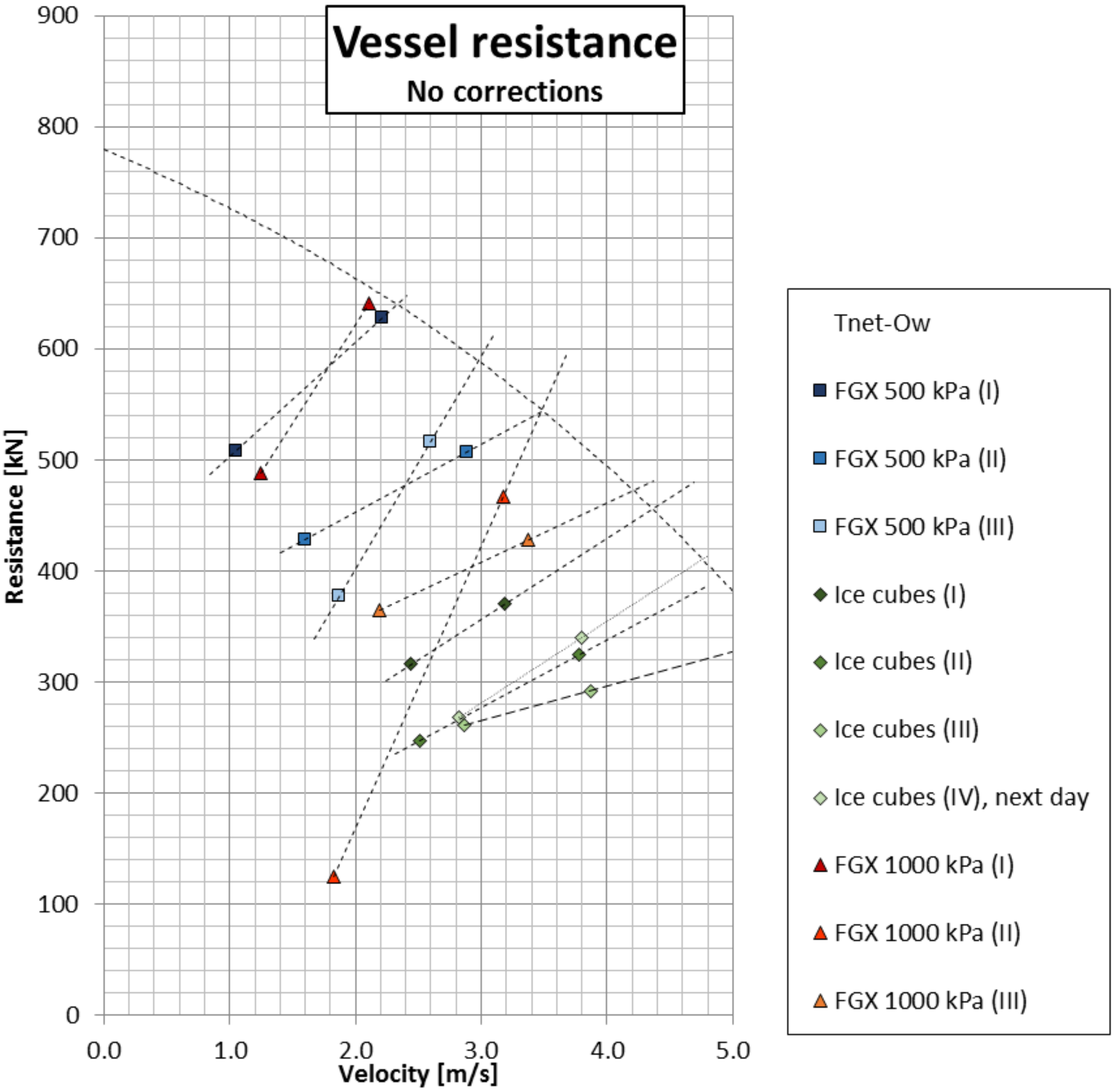

*Figure 7-1 Model test results with no corrections*

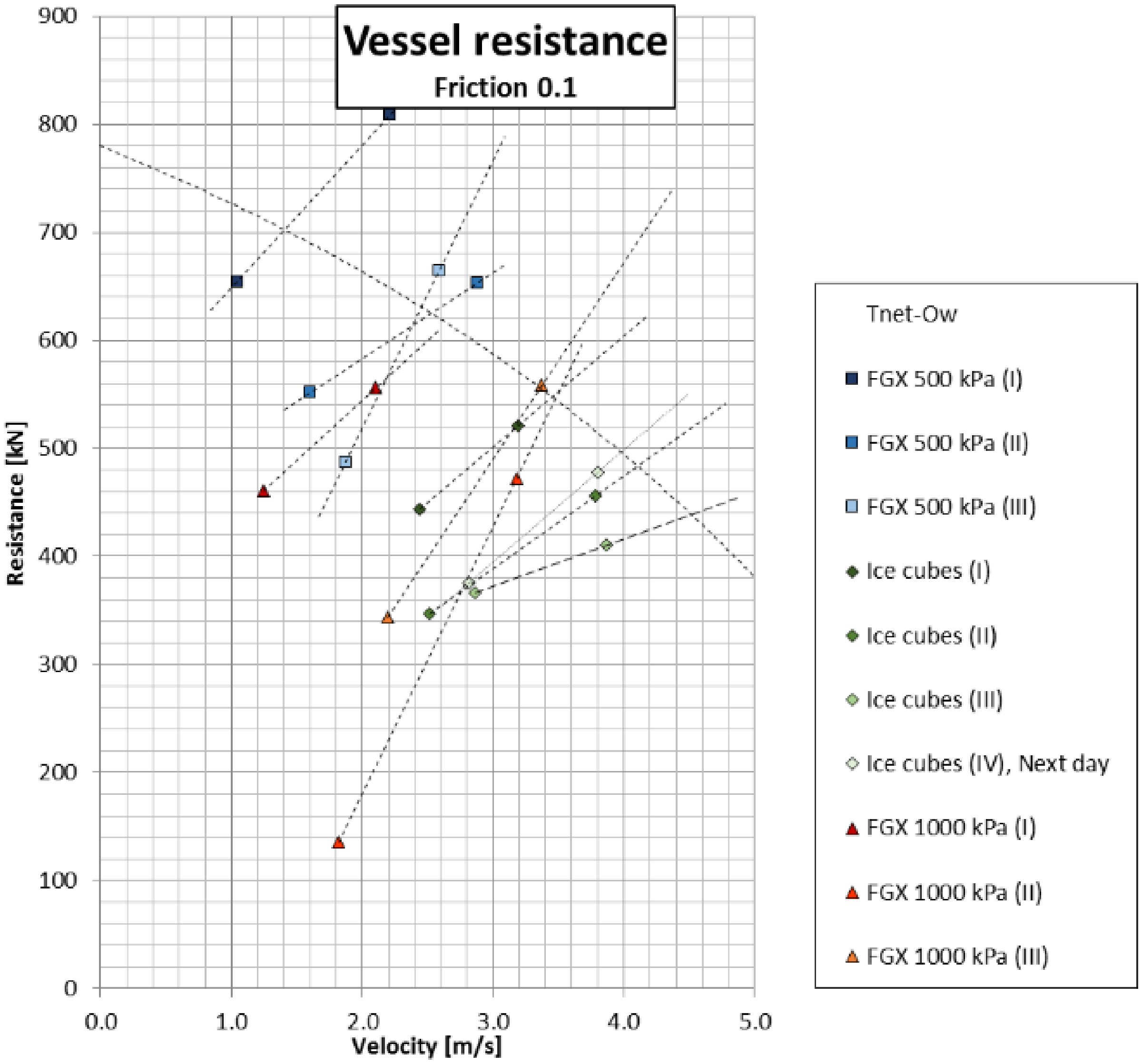

*Figure 7-2 Model test results with friction correction ($\mu = 0.1$)*

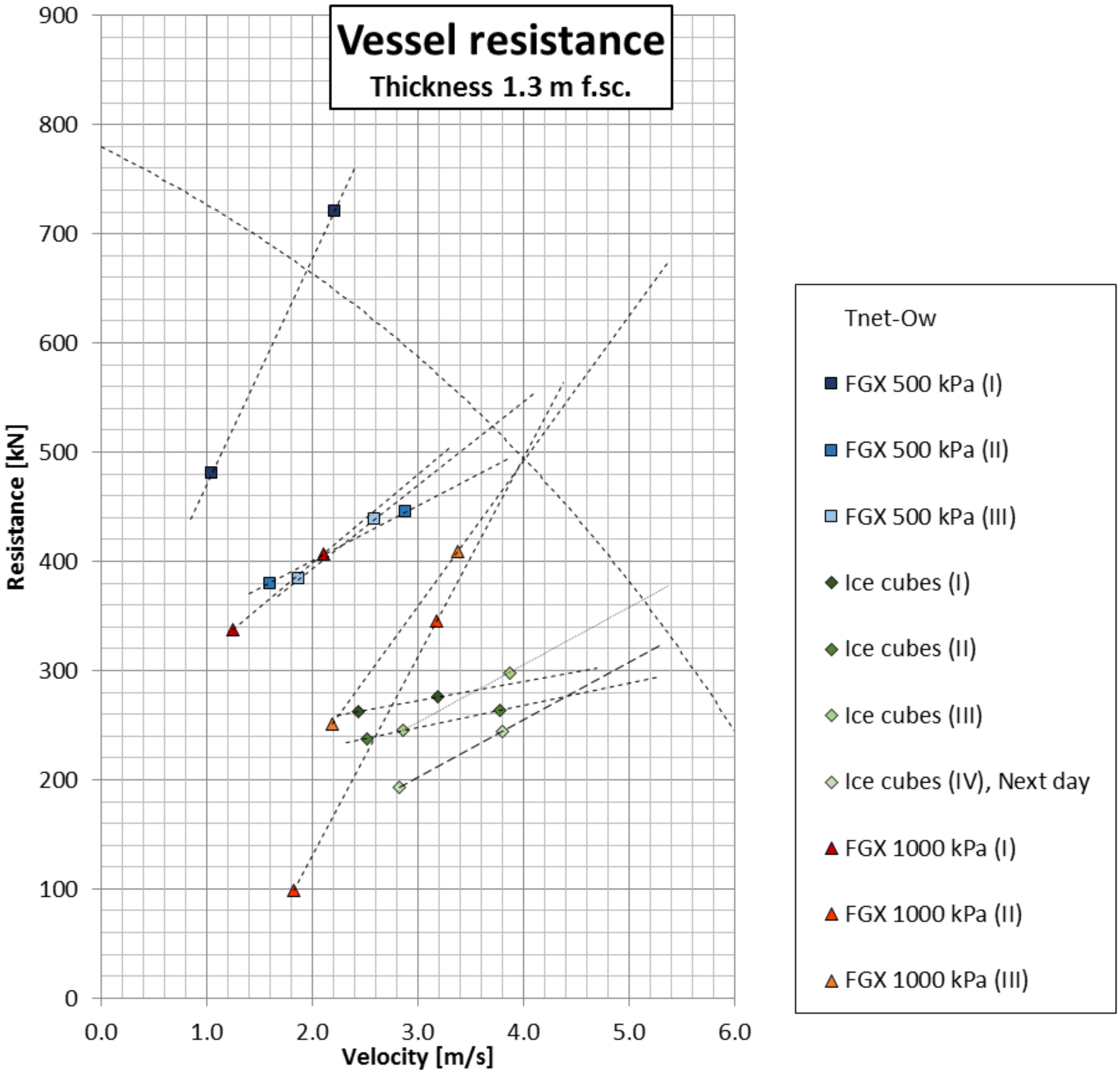

*Figure 7-3 Model test results with thickness correction ($H_{ch}$ = 1.3 m F.Sc.)*

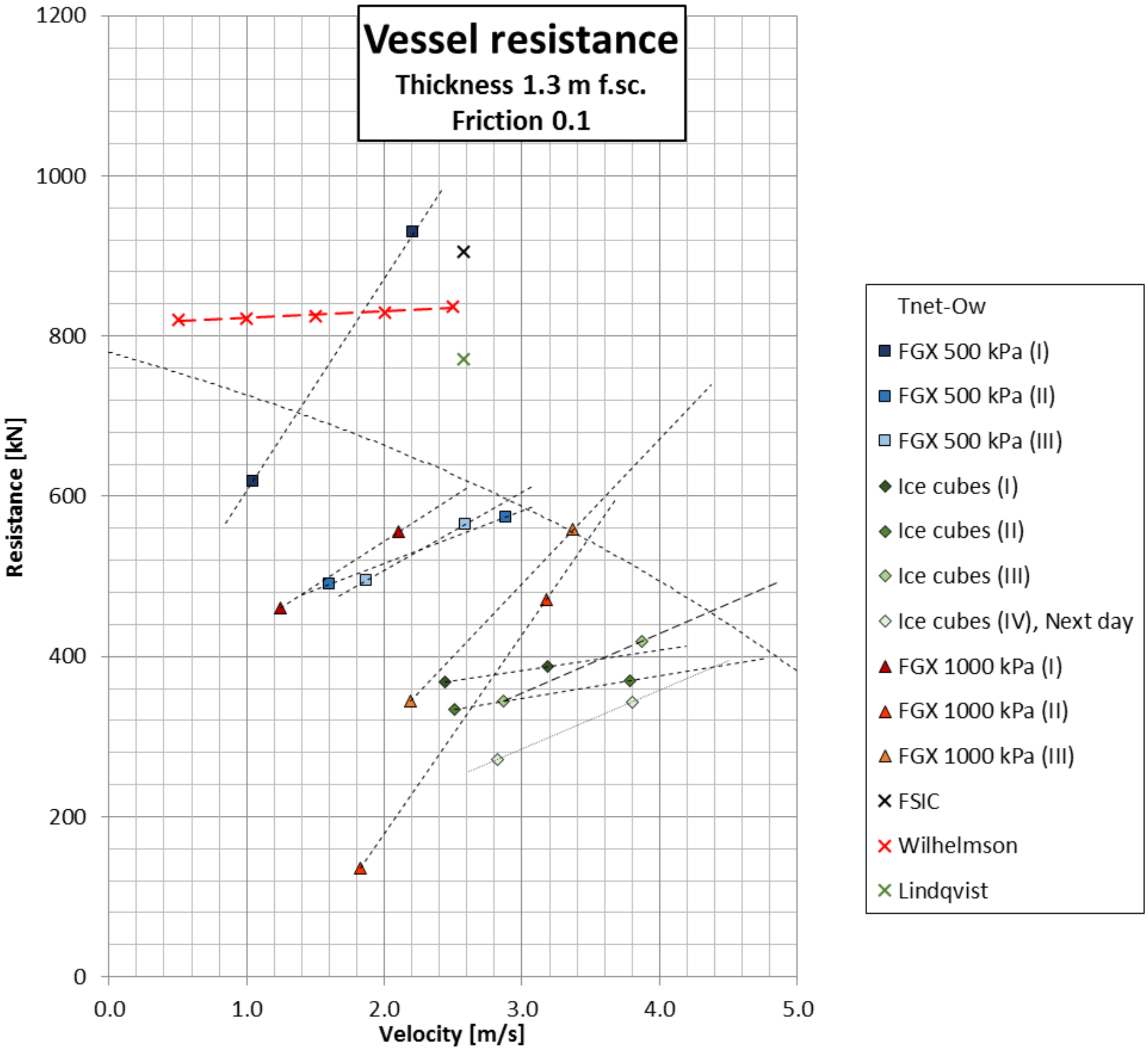

*Figure 7-4 Model test results with friction and thickness correction, presented together with calculation methods*

# 8 PICTURES OF CHANNELS

It was observed in tests that visually the channel made of ice cubes corresponded to reality better than channels made of soft FGX-ice. The channel made of ice cubes closed realistically one ship length behind the model as it advanced in the channel. Pictures of channels behind the model in channels made of different ice are presented in Figure 8-1 - Figure 8-3.

*Figure 8-1 Channel behind the model, channel made of FGX ice, 500 kPa*

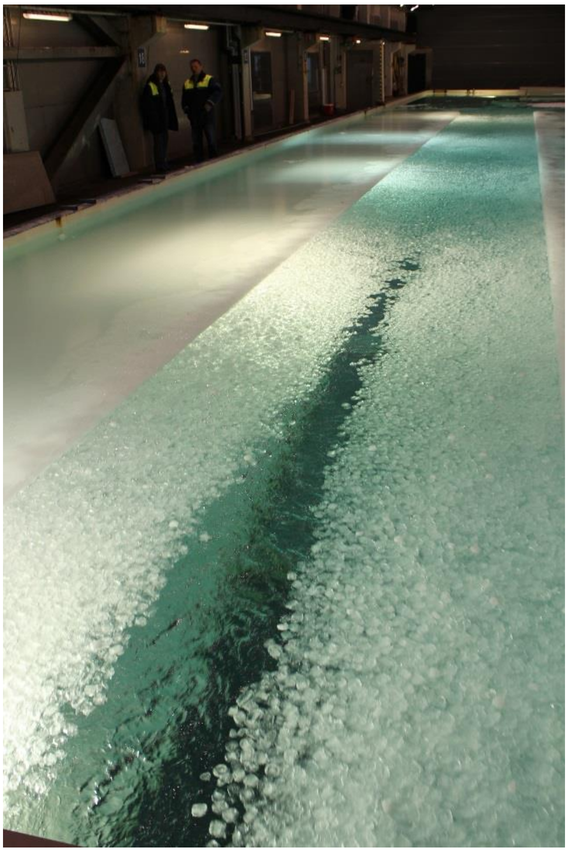

Figure 8-2 Channel closes nicely behind the model in ice channel made of ice cubes

Figure 8-3 Channel behind the model in ice channel made of FGX-ice, 1000 kPa

# 9 FULL SCALE REFERENCES

In order to choose correct model test method, full scale references are necessary. It is preferable to conduct full scale test with a vessel equipped with EEDI bow.

# 10 FRICTION CORRECTION EVALUATION

According to rules, the friction coefficient of model is to be corrected to correspond to an old hull (see chapter 4.3). In order to study the accuracy of the method, a tanker (not the same model, which was tested in actual project) model was first tested in 1A channel (ice type was FGX ice, 1000 kPa) with friction coefficient of 0.044 (Aker Arctic standard for freshly painted hull 0.05 ± 0.01), after which the model surface was treated with sand paper so that the friction coefficient became 0.095.

Correcting friction coefficient from 0.044 to 0.1 according to the equation increases ice resistance 29 % and from 0.95 to 0.1 increases ice resistance 2 %, so the effect is remarkable.

It was observed that with no calculational corrections, the ice resistances were closer to each other without correction, but got further after applying the correction, see *Figure 10-1*.

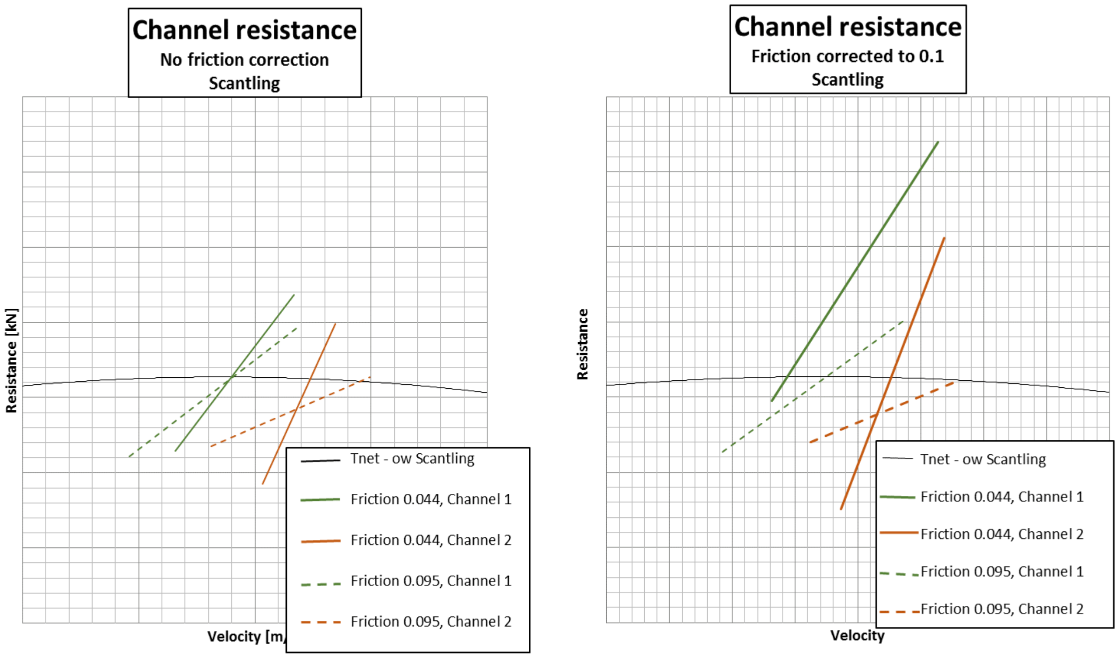

*Figure 10-1 A tanker channel test results in 1A channel tests (channel reconstructed once), conducted with two different model friction coefficients. Figure in the left presents the test results with no calculational friction correction (defined by guidelines) and the figure in the right are same test results after friction correction.*

During testing it was observed that the friction affected the ice build-up at the vessel side: when the model friction coefficient was 0.095, the brash ice height at the vessel side was visibly higher than when the friction coefficient was 0.044, see pictures from the ballast tests, *Figure 10-2 - Figure 10-5*.

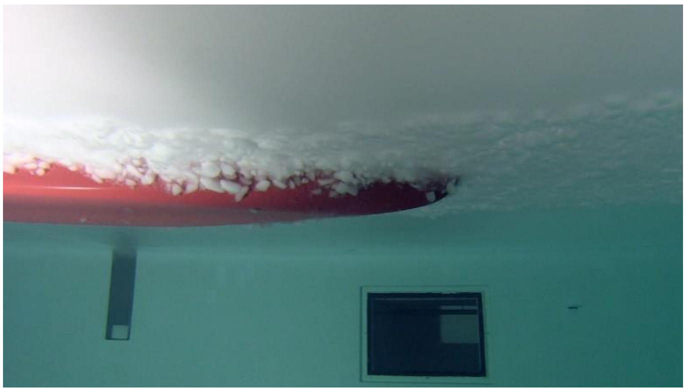

*Figure 10-2 Ballast, Friction coefficient 0.044, Channel 1*

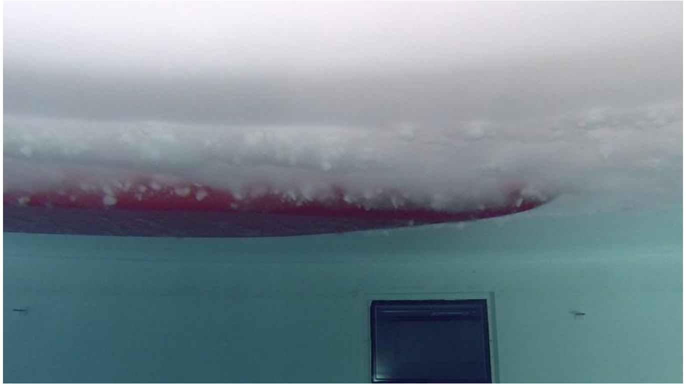

*Figure 10-3 Ballast, Friction coefficient 0.044, Channel 2*

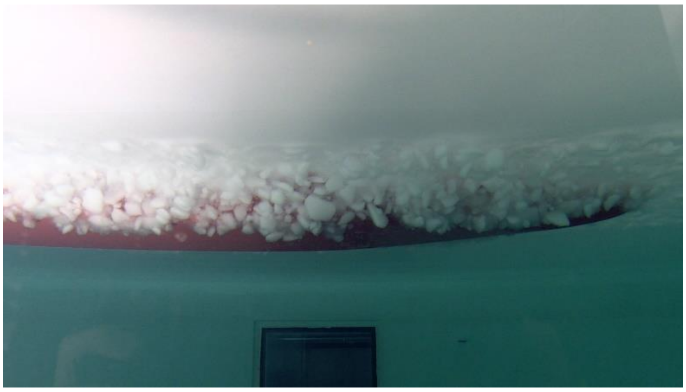

*Figure 10-4 Ballast, Friction coefficient 0.095, Channel 1*

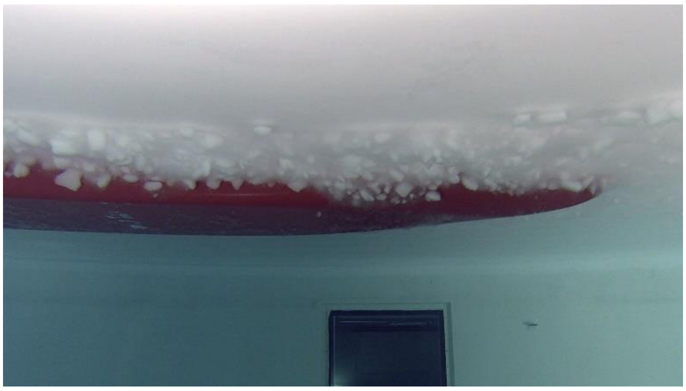

*Figure 10-5 Ballast, Friction coefficient 0.095, Channel 2*

# 11 CONCLUSIONS AND DISCUSSION

The test results vary widely as the material parameters varied between the tests. Test results varied also between the original and reconstructed channel. Below are some observations done during the testing:

- In tests conducted in FGX ice, the channel resistance in original channel is always higher than in second and third test conducted in reconstructed channel, even if the channel thickness in all tests was the same. It was observed in porosity measurements that the amount of ice was ~10 percentage less in second and third test runs compared to first test run.
- In tests conducted in channel made of ice cubes, there was no similar difference in measured ice resistance between the first and later test runs, after thickness correction was done
- Visually the tests conducted in channel made of ice cubes was the most realistic, because the channel closed after the vessel stern as the vessel advanced approximately one vessel length
- Calculated resistances are closest to test results conducted in traditional method with FGX ice with flexural strength of 500 kPa
- Highest channel resistances were measured in 500 kPa FGX ice. As the parental ice flexural strength rises and the ice pieces in channel become more separate, the ice resistance decreases. The cohesion between ice pieces decreases concurrently.
- According to the rules, the friction coefficient of a ship varies from 0.05 for new ships to 0.15 for corroded hull surface. The model test results have to be corrected to correspond to target friction coefficient 0.1 so that also a not-freshly-painted vessel is able to achieve speed of 5 knots. The friction coefficient of Aker Arctic models is typically $\mu = 0.05$ or even below, which leads to a significant increase in channel resistance. The issue was studied by conducting 1A tests with a tanker model with two different friction coefficients and correcting the results to friction coefficient of 0.1. The ice resistance was smaller, when the model friction was higher and therefore the correction effect was smaller.

Following issues need to be studied more:

- This test series was conducted with a tanker with an EEDI bow, which is optimized in open water conditions. The behavior of different channel ice with an icebreaking bow is unknown.
- Due to wide variation in model test results, more full-scale test results of existing vessels are required.
- Calculated thickness correction, which is made to model test results is developed for icebreaking vessels. Typically, in those cases the ice is sunk under the hull. No ice was observed under the hull of vessel, which was studied in this project. The correction method could be altered so that the

added resistance of thickness variation is due to ice being pushed sideways from the hull and not under it.

- Friction coefficient correction method in ice channels need to be studied more.