International Journal of Naval Architecture and Ocean Engineering 10 (2018) 794–802

Contents lists available at ScienceDirect

International Journal of Naval Architecture and Ocean Engineering

journal homepage: http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Development of the ice resistance series chart for icebreaking ships

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A R T I C L E I N F O

Article history:
Received 21 July 2017
Received in revised form
2 May 2018
Accepted 3 May 2018
Available online 21 May 2018

Keywords:
Ice resistance series chart
Icebreaking ship
Ice thickness and strength
Stem angle
Correction chart

A B S T R A C T

The ice resistance series charts for icebreaking ships were developed through a series of systematic model tests in the ice tank of the Korean Research Institute of Ship and Ocean Engineering (KRISO). Spencer's (1992) component-based scaling system for ship-ice model tests was applied to extend the model ship correlations. Beam to draft ratio (B/T), length to beam ratio (L/B), block coefficient (C_B) and stem angle (α) were selected as geometric parameters for hull form development. The basic hull form (S1) of twin pod type with B/T of 3.0, L/B of 6.0, C_B of 0.75 and stem angle of 25° was generated with a modern hull design concept. A total of 13 hulls were designed varying the geometric parameters; B/T of 2.5 and 3.5, L/B of 5.0 and 7.0, C_B from 0.65 to 0.85 in intervals of 0.05, and 5 stem angles from 15° to 35°. Ice resistance tests were first carried out with the basic hull form in level ice with suitable speed. Four more tests for C_B variations from 0.65 to 0.85 were conducted and two more for beam to draft and length to beam ratios were also performed to study the effect of the geometric parameters on ice resistance. Ice resistance tests were summarized using the volumetric coefficient, C_V ($=\nabla/L^3$), instead of L/B and C_B variations. Additional model tests were also carried out to account for the effect of the stem angle, ice thickness and ice strength on ice resistance. In order to develop the ice resistance series charts with a minimum number of experiments, the trends of the ice resistance obtained from the experiments were assumed to be similar for other model ship with different geometric parameters. A total of 18 sheets composed of combinations of three different beam to draft ratios and six block coefficients were developed as a parameter of C_V in the low speed regions. Three correction charts were also developed for stem angles, ice thickness and ice strength respectively. The charts were applied to estimate ice resistance for existing icebreaking ships including ARAON, and the results were satisfactory with reasonable accuracy.

1. Introduction

The standard series was derived from a series of models tested in a towing tank. During these tests, the design parameters of one or more parent hulls were varied systematically. The results obtained were cross-paired and presented in a graphical or tabular format. The methodical series is generally attributed to Admiral D.W. Taylor who introduced the well-known Taylor Series in 1910 (Gertler, 1954). This series was regarded as the forerunner to the methodical series. The BSRA Series (B.S.R.A., 1971) and the American Series 60 (Todd and Forest, 1951) were probably the ones among the best known and the most comprehensive. In addition to these, the KND series (Lee et al., 1999) chart of semi-planning hull form was developed and commercialized (see Table 1).

This study aimed at developing ice resistance charts based on model tests for 13 series hull forms in an ice tank of KRISO. The series hull forms were designed varying the geometric parameters such as B/T, L/B, C_B, and stem angle (α), which significantly influence icebreaking performance. The basic hull form (denoted as S1) was designed first, as a twin pod type. Based on this basic hull form (S1), additional twelve series hull forms were obtained applying the systematic hull form variation program named HCAD (Lee, 2000). For B/T and L/B variations, a non-dimensional variation method was applied, and a C_P-curve variation method was used to change C_B. The stem angles were locally modified based on the design draft. B/T of 3.0, L/B of 6.0, C_B of 0.75 and 25° of stem angle were selected as geometric parameters of the basic hull form. Hull forms of single shaft, twin V-strut and R-class bow were also developed, however, only twin-pod type models were considered in this study.

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Peer review under responsibility of Society of Naval Architects of Korea.

https://doi.org/10.1016/j.ijnaoe.2018.05.002

Table 1
Characteristics of the developed series hull forms.

Dimensionless ratio (coefficient)				Stem angle	Main dimensions			Remarks
L/B	B/T	C_B	∇/L^3*10^3	α	LBP	B	T	
6.0	3.0	0.75	6.944	25°	252.0	42.0	14.0	S1
6.0	3.0	0.75	6.944	30°	252.0	42.0	14.0	S2
6.0	3.0	0.75	6.944	20°	252.0	42.0	14.0	S3
6.0	3.0	0.75	6.944	35°	252.0	42.0	14.0	S4
6.0	3.0	0.75	6.944	15°	252.0	42.0	14.0	S5
6.0	2.5	0.75	8.333	25°	252.0	42.0	16.8	S9
6.0	3.5	0.75	5.952	25°	252.0	42.0	12.0	S10
7.0	3.0	0.75	5.102	25°	294.0	42.0	14.0	S11
5.0	3.0	0.75	10.00	25°	210.0	42.0	14.0	S12
6.0	3.0	0.65	6.019	25°	252.0	42.0	14.0	S13
6.0	3.0	0.70	6.481	25°	252.0	42.0	14.0	S14
6.0	3.0	0.80	7.407	25°	252.0	42.0	14.0	S15
6.0	3.0	0.85	7.870	25°	252.0	42.0	14.0	S16

*Single shaft (S6), Twin-V strut (R7), R-class bow (S8) are disregarded but twin-pod type models are only considered in this series hull form variation.

Ice resistance tests were carried out in level ice, beginning with the basic hull form, in the low speed regions. Four more tests for C_B variations from 0.65 to 0.85, two for B/T and L/B were conducted to study the effect of the geometric parameters on ice resistance. Additional model tests were also carried out to account for the effect of the stem angle, ice thickness and strength on the ice resistance. Non-dimensional ice resistance coefficients were summarized as a function of the volumetric coefficient (C_V) for various speeds. To develop the ice resistance series charts with a minimum number of experiments, the trends of ice resistance obtained from the model tests were assumed to be similar for different models with other geometric parameters. 18 sheets composed of combinations of three B/Ts and six C_Bs were developed as a parameter of C_V in the low speed regions, and three correction charts were also developed for different stem angle, ice thickness and strength. The developed series charts were applied to predict ice resistance for existing icebreaking ships including ARAON, and the results indicated high correspondence with full-scale data. It is expected that the developed ice series chart can be used in an early design stage of icebreaking ships.

2. Development of series hull forms

2.1. Development of basic hull form

Among the recently developed icebreaking ships, the spoon type hull form with B/T of 3.0, L/B of 6.0 and C_B of 0.75 was selected as a basic hull form (S1) for better icebreaking performance. The fore-body shape of S1 was designed in a straight buttock line and a wide waterline ending shape to improve the icebreaking ability. One of the important parameter for ice resistance is the stem angle. Since a smaller stem angle induces larger bending moment while keeping the horizontal force component smaller, icebreaking ships including S1 commonly have relatively small stem angle of 25° (Riska et al., 1994). The aft-body hull form was first designed based on the twin-POD shape, and then the single screw and twin open-strut stern shape were later developed to compare the icebreaking performance. Additionally, the height of the transom in the stern contour was increased to enable astern ramming. Fig. 1 illustrates the body-plan and C_P curve shape of the developed basic hull form.

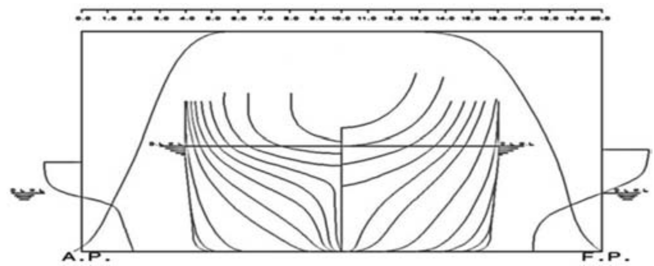

Fig. 1. Body-plan and C_P curve of basic hull form (S1).

2.2. Development of series hull form

Using the aforementioned basic hull form of S1, additional series hull form of S9 and S10 were developed with the B/T of 2.5 and 3.5, respectively. Therefore, the ranges of B/T of the series hull form vary from 2.5 to 3.5. Comparing S9 and S10 with the basic hull form, only the draft was different while other parameters were the same. Therefore, the series hull forms of S9 and S10 were obtained from non-dimensionalized basic hull form using the beam, and the swing method was applied.

The series hull forms of S13, S14, S15 and S16 were developed by changing the block coefficient (C_B) of the basic hull form of S1 to 0.65, 0.70, 0.80 and 0.85, respectively at a constant B/T of 3.0. The swing method was used where the block coefficient of a new series hull form was smaller than that of the basic hull form, and Lackenby's method (Lackenby, 1950) was applied in the opposite case. Fig. 2 shows the C_P curves of the different block coefficient series hull forms with a constant B/T of 3.0.

The series hull forms of S11 and S12 with L/B of 5.0 and 7.0 were developed by varying the basic hull form of S1 with the B/T of 3.0 and C_B of 0.75. The series hull forms varying L/Bs were non-dimensionalized by the length, and therefore, the C_P curve of the developed hull form appears to be the same regardless of the L/B ratio. Additional series hull forms with B/T of 2.5 and 3.5 were not developed because the shape of C_P curve was expected to be similar to that of the B/T of 3.0.

Finally, series hull forms were developed varying the stem angles by changing the bow region locally, and keeping the volume constant, which affects the most significantly on the performance of icebreaking resistance among others. The hull forms of S2, S3, S4, and S5 have angles of 15°, 20°, 30° and 35°, respectively, and were developed using the basic hull form, S1.

3. Ice resistance tests and analysis

3.1. Model ship and test conditions

A series of ice resistance tests on all models were carried out in

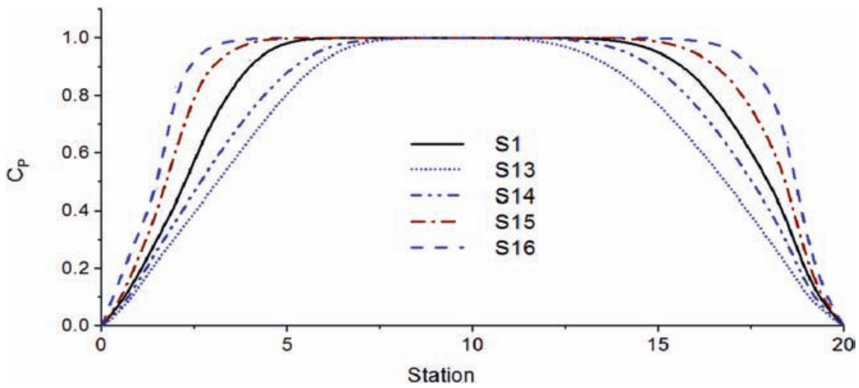

Fig. 2. C_P curves of series hull forms of different C_B with B/T = 3.0.

the ice tank of KRISO. The KRISO ice tank has the dimensions of 42 m in length, 32 m in width and 2.5 m in water depth. The maximum speed of an electronically controlled towing carriage is 3.0 m/s. Images from one of the tests in the ice tank at KRISO are shown in Fig. 3. Wooden ship models with a scale ratio of 42 (1/42, approx. 6.0 m in length) were manufactured considering the test conditions in the ice tank. The surfaces of the models were gel-coated using Magnesium Silicate in order to satisfy the standard friction coefficient of the ice-hull.

The towing point of the model ship was chosen at the center of buoyancy so that pitch and heave motions (trim and sinkage) are released. The towing guide device was also installed on the bow to prevent the yaw and sway motion. All ice resistance tests conducted in this study were performed and various measured values were obtained by a computerized data acquisition system.

3.2. Ice resistance series tests

In order to develop the series charts of ice resistance, a series of model tests in level ice was performed at design draft. The speed range was from 2.0 to 5.0 knots considering the development range of the series chart. Furthermore, additional resistance tests for the basic hull were also carried out varying the ice thickness, ice strength and stem angles to obtain the correction charts of the three parameters.

In the ice resistance tests, Cauchy number (C) and Froude number (F_n) of the model and the prototype hull form were set to be equal to meet the dynamic similarity of the strength of the level ice (Ashton, 2004).

Froude number and Cauchy number is defined as follows.

$$F_n = \frac{v}{\sqrt{gL}} \quad (1)$$

$$C = \rho v^2 \big/ E \quad (2)$$

where,

L: ship length
g: Gravitational acceleration
ρ: mass density
v: Flow velocity
E: Modulus of elasticity
g: Gravitational acceleration

Spencer's method (Spencer, 1992; Spencer and Jones, 2001), shown below, was applied in order to compute ice resistance components in level ice from resistance and self-propulsion tests in the low speed range.

$$R_{Ts} = R_{OW} + R_B + R_C + R_{BR} \quad (3)$$

where,

R_{Ts}: Total ice resistance [N]
R_{OW}: Open water resistance [N]
R_B: Ice buoyance resistance [N]
R_C: Ice clearing resistance [N]
R_{BR}: Icebreaking resistance [N]

Different from the traditional resistance test procedure, full scale resistance of series hull forms was extended from the model test results following the recommendations of Spencer and Jones (2001) and Riska et al. (1994). In this study, the total ice

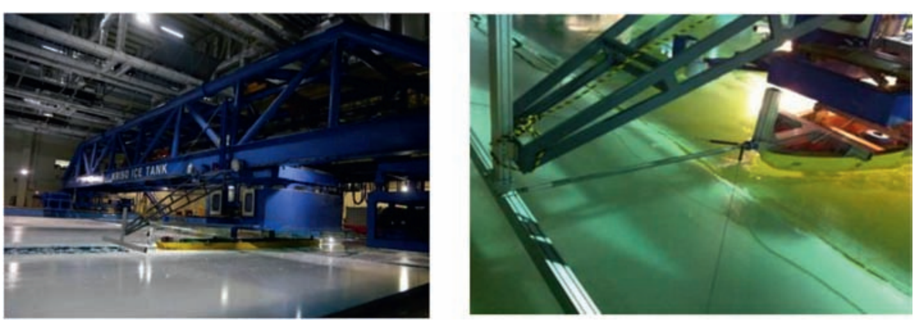

Fig. 3. KRISO ice tank (left) and test scene for the series chart (right).

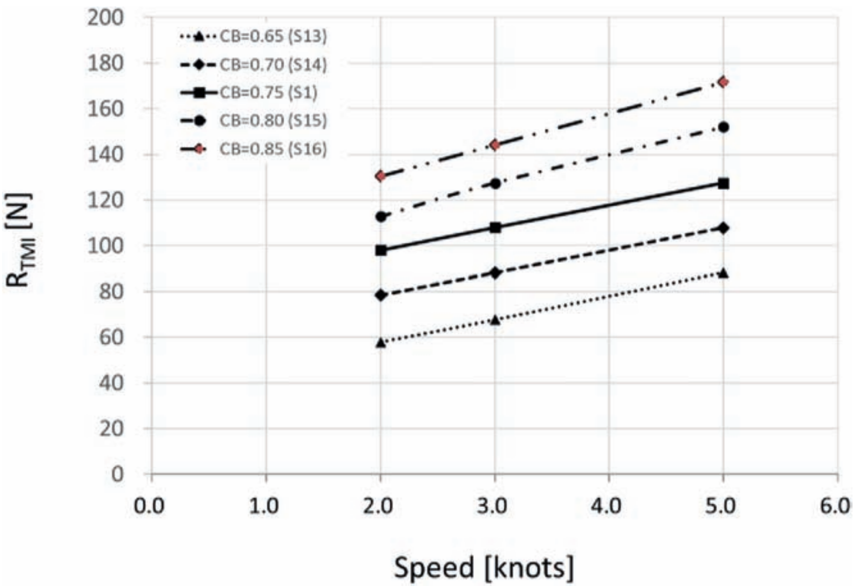

Fig. 4. Ice resistance test results of series hull forms for C_B variations *(B/T = 3.0, L/T = 6.0, α = 25°)*.

resistance coefficients were obtained using the following equation.

$$C_{Ts} = R_{Ts} \Big/ \frac{1}{2} \cdot \rho_s \cdot V_s^2 \cdot S_s \quad (4)$$

where,

C_{Ts}: Total ice resistance coefficient [−]
R_{Ts}: Total ice resistance [N]
ρ_s: Density of the ice $[kg/m^3]$
V_s: Ship speed [m/s]
S_s: Surface area of the ship $[m^3]$

The total ice resistance, R_{TS},of Eq. (4) was modified considering the correction factor due to ice strength to the measured value in the model test.

3.3. Analysis of the ice resistance series tests

Ice resistance tests for the series hull forms were performed, and the comparative analysis was carried out considering the block coefficient (C_B), L/B, B/T and stem angle (α) variations.

Fig. 4 demonstrates the ice resistance of the hull forms for different C_B values, and the results show that the ice resistance increases as C_B increases. Fig. 5 indicates the total ice resistance of the model (R_{TM}) varying L/Bs and the resistance reduces as L/B increases. Based on these results, the effect of L/Bs can be analyzed to estimate other values by interpolation. The ice resistance test results were analyzed in ice resistance forces, as L/B variations turned out to be larger than C_B variations.

Ice test results of series hull forms for B/T variations are shown in Fig. 6. From the figure, it is found that ice resistance increases as B/T increases. In order to develop ice resistance correction charts based on stem angles, ice thickness and strength, extra model tests

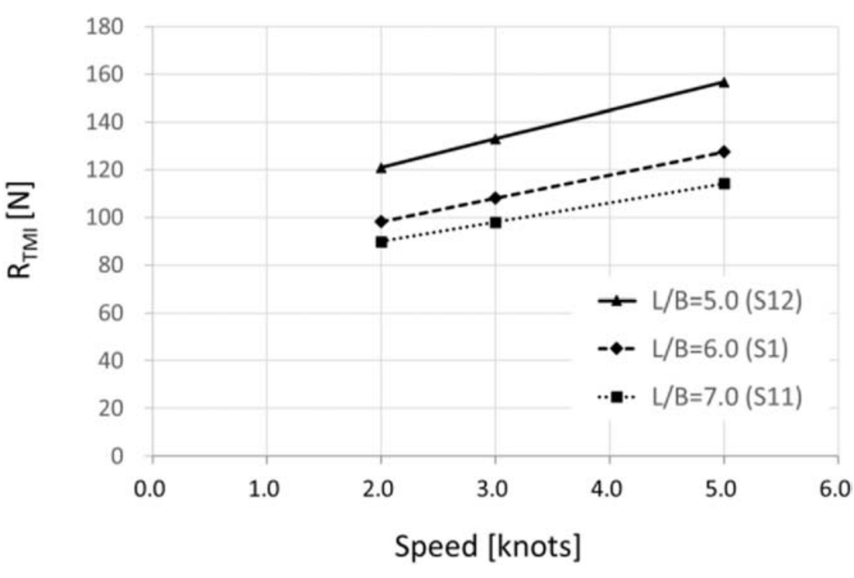

Fig. 5. Ice resistance test results of series hull forms for L/B variations *(B/T = 3.0, C_B = 0.75, α = 25°)*.

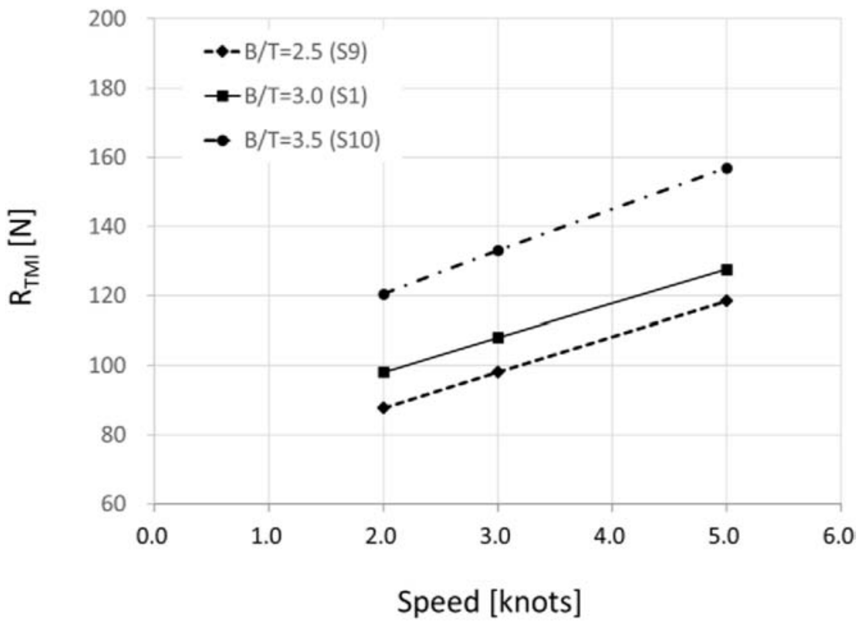

Fig. 6. Ice resistance test results of series hull forms for B/T variation (L/T = 6.0,C_B = 0.75, α = 25°).

were performed, varying the parameters for a minimum number of model tests. Extra tests were also performed with the ice strength kept constant at 600 kPa, while ice thickness varied from 0.5 m to 2.0 m in the steps of 0.5 m. Other tests were also carried out for ice thickness of 1.0 m, and ice strengths of 500 kPa, 700 kPa, and 800 kPa. Results are discussed in the next section.

4. Series chart development for prediction of ice resistance coefficients

4.1. Development of ice resistance series chart

The basic hull form was selected for the geometric parameters of C_B 0.75, L/B 6.0, a stem angle 25° and B/T 3.0 to develop the series charts estimating ice resistance coefficients. Model tests were carried out for the basic hull and extra tests were performed at the same block coefficient varying L/B of 5.0 and 7.0, and B/T of 2.5 and 3.5 at the speed of 2, 3, and 5 knots. The experimental results for various parameters showed reasonable accuracy except in a low speed region due to non-uniform ice thickness and strength and measurement errors etc.

To obtain the series chart for different speeds, the volumetric coefficient (C_V) was changed and total resistances were measured, whereas B/T and C_B were kept constant. The ice resistance coefficients were also uniformly interpolated from the Froude number of 0.01–0.05 in intervals of 0.01. The experimental data were rearranged as a function of C_V at various speeds as shown in Fig. 7.

Five model tests were carried out to develop five sheets by varying C_B from 0.6 to 0.85 in intervals of 0.05 while keeping other parameters constant. Two more model tests for L/B of 5.0 and 7.0 were carried out and the resistance characteristics were rearranged as a function of C_V.

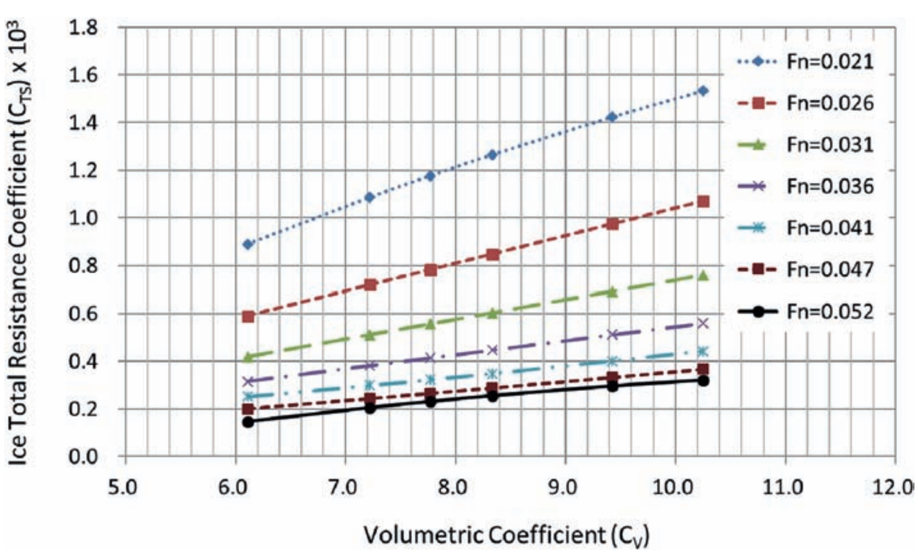

Fig. 7. C_V correction chart of the total ice resistance coefficients for B/T = 2.5 and C_B = 0.75.

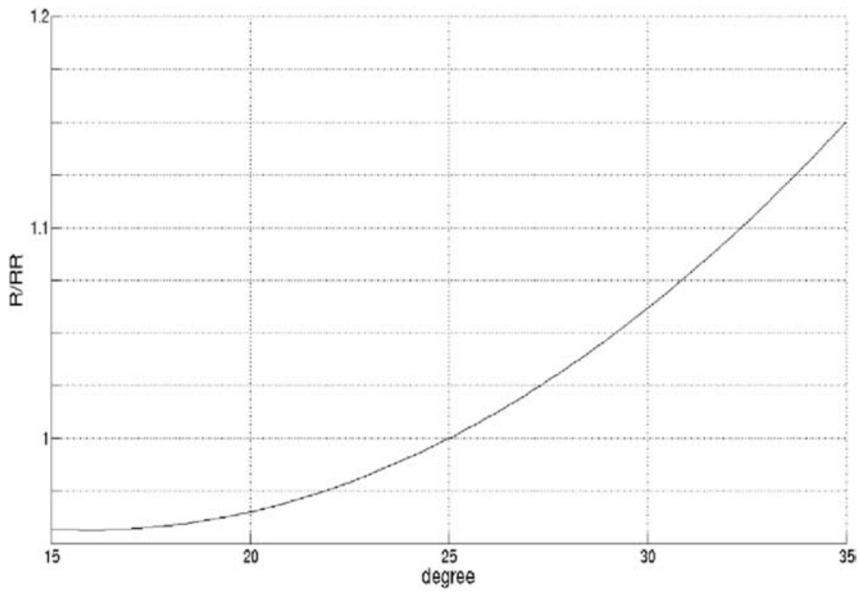

Fig. 8. Stem angle series chart.

The series chart of C_B of 0.6 was obtained by extrapolation of the test data. Therefore, six charts for B/T 3.0 and various C_B from 0.6 to 0.85 in intervals of 0.05 were developed. Additional model tests were performed for two more hull forms varying B/T of 2.5 and 3.5 while other parameters were kept the same as the basic hull form. In addition, six more sheets varying B/T values were also developed assuming that the trends of the ice resistance were similar to those obtained for other C_B and L/B values. Therefore, a total of 18 sheets were developed as a combination of C_B and B/T values.

4.2. Correction chart for stem angle, ice thickness and strength

Ice resistance series charts were developed at 25° of stem angle, and therefore, four more hull forms varying only stem angles from 15° to 35° in intervals of 5° were developed and tested. From the experimental results, it was found that ice resistance increases as stem angle increases as shown in Fig. 8. The vertical axis of Fig. 8, R/RR, denotes the ratio of the ice resistance of the corresponding hull form to that of basic hull form with stem angle of 25°.

Fig. 9 and Fig. 10 show the correction chart for ice strength and ice thickness, respectively. From the experimental results for various ice strengths and thicknesses, it was found out that the ice resistance coefficient increases as the ice strength and thickness increase. Ice resistance for different ice strength and ice thickness can be estimated by using the figures in the similar manner described in the previous section.

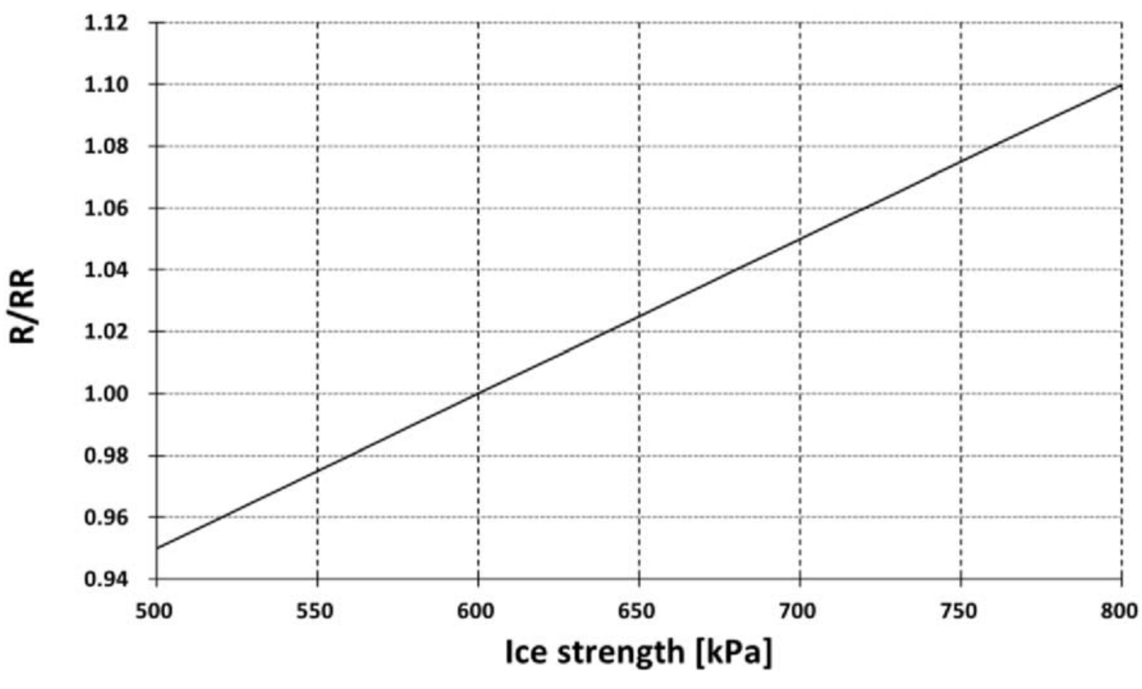

Fig. 9. Correction factor due to ice strength.

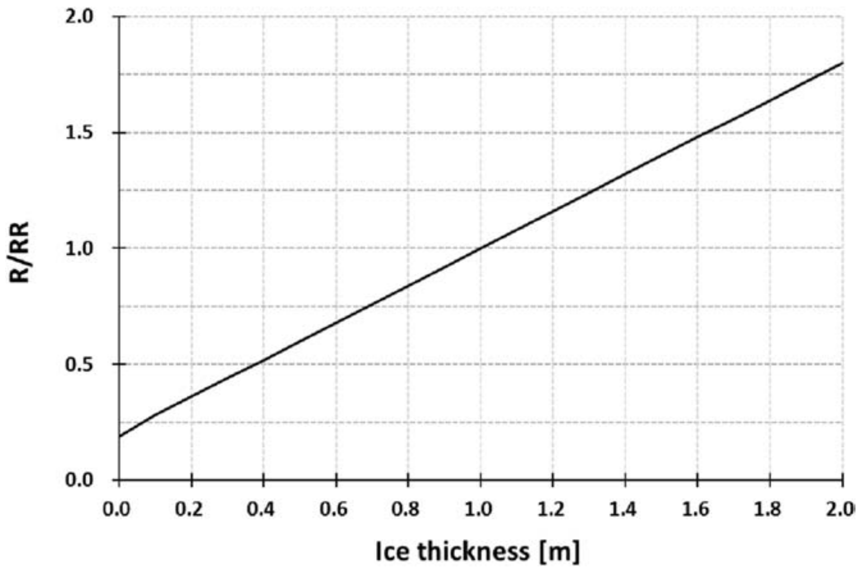

Fig. 10. Correction factor due to ice thickness.

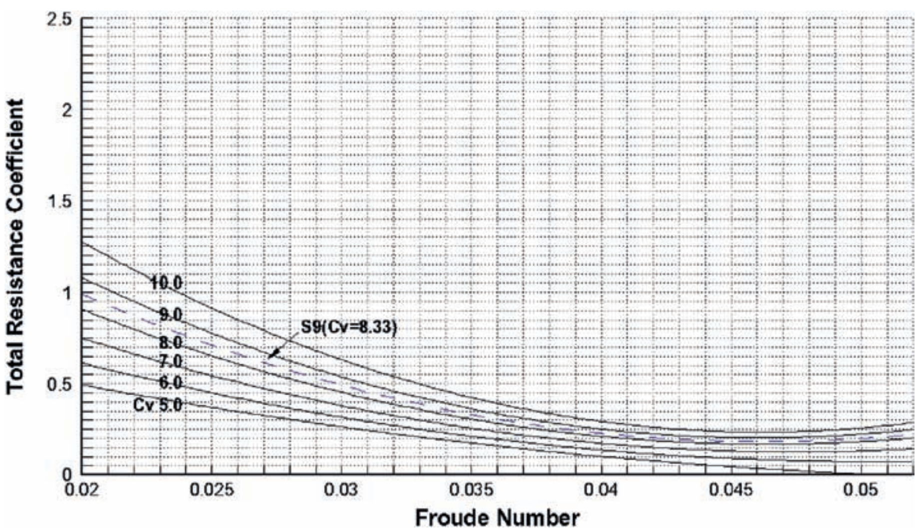

Fig. 11. Verification of series chart for S9 (B/T = 2.5,C_B = 0.75, L/B = 6.0).

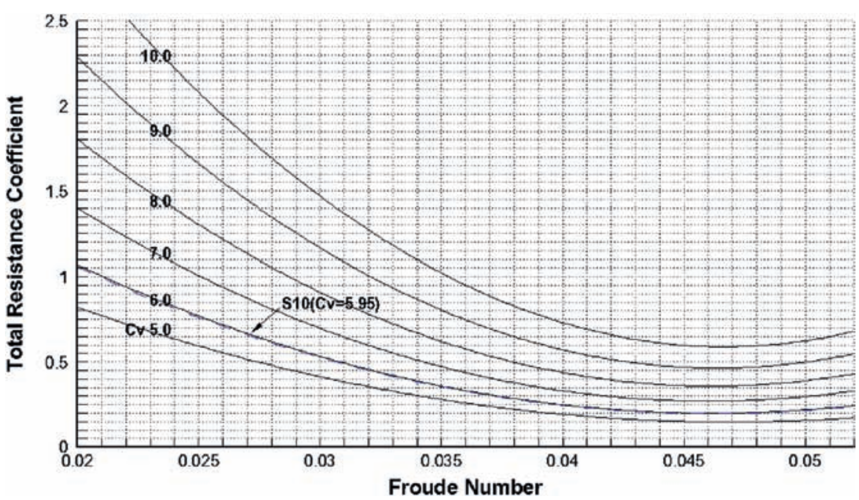

Fig. 12. Verification of series chart for S10 (B/T = 3.5, C_B = 0.75, L/B = 6.0).

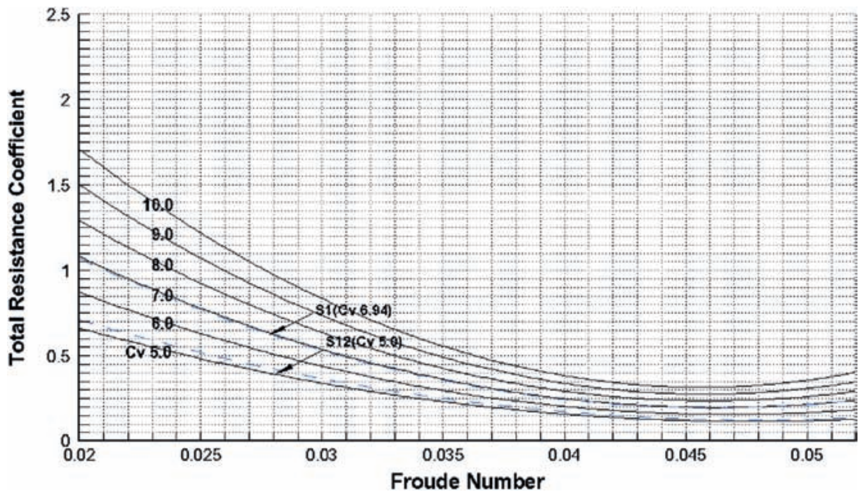

Fig. 13. Verification of series chart for S1 (B/T = 3.0, $C_B = 0.75$, L/B = 6.0) and S12 (B/T = 3.0, $C_B = 0.75$, L/B = 5.0).

4.3. The application of the series chart

The developed series charts were validated by plotting the ice resistance coefficient on the series chart. For some typical cases, sample computed results were obtained for different values of B/T, C_B and L/B as shown in Figs. 11–14. Once the geometric parameters were given for specified hull form, the volumetric coefficient was calculated and the total resistance coefficients were obtained for various Froude numbers as a function of the volumetric coefficient. As shown in the figures, the developed series charts showed high correspondence to the conventional series of hull form for the changes in B/T, C_B and L/B.

The ice resistance coefficient of ARAON was also computed using the developed series charts. Since the B/T and C_B of ARAON was 2.79 and 0.6, respectively, therefore, two sheets of B/T of 2.5 and 3.0 with C_B of 0.6 were used to obtain the ice resistance of ARAON. The computed resistance coefficient was 0.37 while the actual value was 0.217 at a speed of 3.0 knots. The reason for this large error is the low resistance coefficient of ARAON, because the dimensions of ARAON were too small to apply the charts. However, the developed charts provide the icebreaking resistance of large icebreakers with reasonable accuracy at the initial design stage.

5. Conclusions

This study aimed a developing ice resistance charts based on model tests carried out in the KRISO ice tank. Length to beam (L/B) ratio, beam to draft (B/T) ratio, block coefficient (C_B), volumetric coefficient (C_V) and stem angle (α) were selected as parameters that highly affect icebreaking performance of the series hull forms. A total of 13 hull forms were designed to develop ice resistance series charts by using the aforementioned parameters which will be used to design icebreakers.

18 sheets of ice resistance series charts were developed to estimate the resistance of icebreaking ships quickly and efficiently in the early design stage. The estimation method was developed by using the volumetric parameters for three B/T values; 2.5, 3.0, and 3.5, as well as six C_B values ranging from 0.6 to 0.85 with the intervals of 0.05. Considering variations of the stem angle, ice thickness and ice strength, three correction charts were also developed, and therefore, a total of 21 sheets of ice resistance series charts were developed.

Applying newly developed ice resistance series charts for the existing icebreakers, the estimated values showed high correspondence both quantitatively and qualitatively. The ice resistance series charts in this study will be used in designing the icebreaking

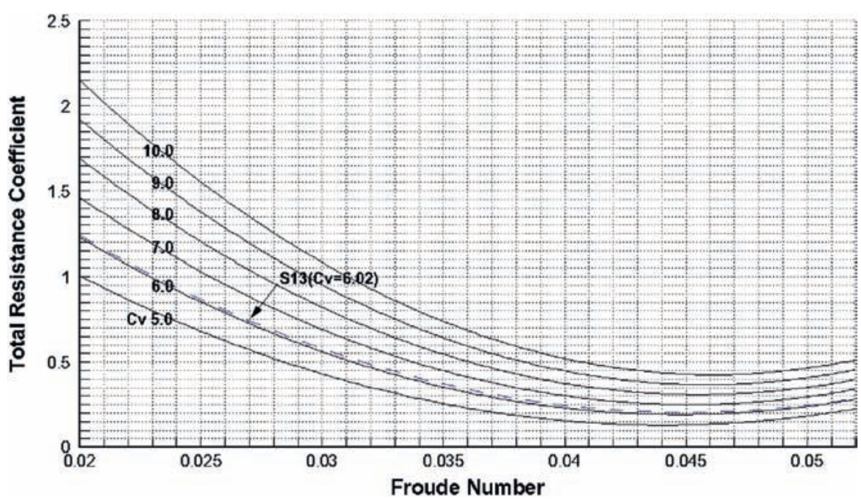

Fig. 14. Verification of series chart for S13 (B/T = 2.5, $C_B = 0.75$, L/B = 6.0).

hull form and compared with full-scale ice resistance measurement data in the near future.

Acknowledgements

This work was carried out within the scope of the principal R&D program (Enhancement of the resistance performance and establishment of the station-keeping test assessment method for ships in ice-covered water, Project No. PES9452), partially supported by Korea Research Institute of Ships & Ocean Engineering (KRISO) and also partially by the research fund of Chungnam National University. All supports are gratefully acknowledged.

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