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Concept development and experimental investigation of an Arctic trimaran

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ABSTRACT

Modern cargo carriers are noted for their heavy displacement, which leads to increased principal dimensions. Operation of such vessels in the Arctic is more difficult due to complicated ice features requiring large amount of horsepower. One of the most efficient ways to rationally choose the power requirements for a large-size vessel under design is to assess her propulsion performance in operating ice conditions. Most of such vessels can be operated with assistance of icebreakers, which significantly decrease their propulsive power requirements. However, there are no available ships in the current icebreaking fleet that is able to break an ice channel exceeding the breadth of modern cargo carriers. Difficult and economically inefficient tactics of navigation like assistance of two icebreakers should be employed as well as design of powerful and wide icebreakers.

An alternative icebreaker version with three hulls has been produced in this work. The concept was developed based on the earlier investigations of a multi-hull icebreaker performed at the Krylov Centre. A distinctive advantage of this icebreaker is the ability to produce a wide channel in ice at less power consumption as compared with the traditional single hull version. During investigations several options of the most optimum power installation for the icebreaker have been worked out, including LNG type. Model experiments in towing tanks have been conducted to know limiting icebreaking capacity of the icebreaker. These data are also used for verification of the ice propulsion methods for the multi-hull icebreaker.

KEY WORDS: Trimaran; Wide ice channel; Icebreaker assistance; Icebreaker; Powerplant.

INTRODUCTION

A gradual increase in the breadth of cargo vessels, primarily LNG carriers, calls for new methods of their icebreaker-assisted operations. One of the possible options is an escort of heave-tonnage ship with two icebreakers and increased ice-going capacity of cargo carriers or innovative means for making a wide channel in ice. An icebreaker with wide hull is a tool of this kind, which is difficult to design because of the requirement to equip her with a sophisticated powering and propulsion system for ensuring the targeted ice-going capacity. An alternative concept is to combine several smaller hulls under one bridge platform. The subject of this investigation is the multi-hull icebreaker.

The main advantage of the multi-hull icebreaker concept is the width of channel in ice. In making this channel the icebreaker would consume less power than her single hull counterpart of corresponding breadth (Dobrodeev, 2018). Also, it should be noted that the deck is much more spacious as compared with the single hull icebreaker of equal displacement.

The multi-hull icebreaker concept has been developed for quite a long time. In Russia the concept of multi-hull icebreaker began as part of the project for development of a powerful icebreaker to provide for fast shipping through the Northern Sea Route. The Krylov State Research Centre suggested an original design solution alternative to the 120 MW icebreaker (Sazonov, 2014). The full cycle of model tests in ice basin was conducted for three-hull and four-hull versions, also an inter-hull structures were developed. In the recent years, Aker Arctic engineers have also developed an icebreaker able to make a wide ice channel.

The author of this investigation developed a trimaran icebreaker concept for the western sector of the Northern Sea Route and estuaries of Siberian rivers in his Master of Science thesis. This concept like a Krylov Centre version involves three separate hull bridged by a common deck. A certain distinction of this new concept from the idea of Krylov Center is that all icebreaker hulls have classical icebreaking hullforms. Another feature of this investigation is an additional study of the innovative powerplant system meeting all existing and perspective requirements of International Maritime Organization (IMO) regarding environment and noted for a high fuel economy. Model tests were conducted in the Krylov Centre ice basin for verification of the icebreaker propulsion performance in ice.

The paper contains the main results of investigations, suggests and verifies the numerical method for calculation of ice resistance for the trimaran icebreaker.

EXPERIMENTAL INVESTIGATIONS

A 1:50 model was developed and made for experimental investigations. Prior to investigations an assumptions is made that scaling of data to full size is possible with introduction of certain corrections. The choice of scale is determined by the fact that the hull was developed under a Master thesis of St. Petersburg Marine State Technical University. Towing tests were supposed to arrange in the University towing tank intended for laboratory experiments on propulsion of cargo ships and high-speed craft, and this tank has its constraints on the size of tested models.

Table 1.1 – Main data of icebreaker and model

No.	Main characteristics	Symbol	Full-scale icebreaker	Model
1	Length on WL, m	L	152.8	3.056
2	Leading hull length on WL, m	L_1	96.4	1.928
3	Wing hull length on WL, m	$L_{2,3}$	56.5	1.13
4	Breadth on WL, m	B	56.6	1.132
5	Leading hull breadth on WL, m	B_1	23.7	0.474
6	Wing hull breadth on WL, m	$B_{2,3}$	13.8	0.276
7	Leading hull draught at midship, m	T_1	7.6	0.152
8	Wing hull draught at midship, m	$T_{2,3}$	4.5	0.9
9	Transverse distance between wing hull forward perpendicular and leading hull aft perpendicular, m	$B_{1\text{-}2,1\text{-}3}$	21	0.42
10	Ice/hull friction factor	μ	0.05	0.05
11	Propulsion power, MW	P	30	–

All three hulls of the model were manufactured separately using the technology of gluing solid foam plates with further NC-machine processing. After manufacturing the model hulls were painted to apply certain roughness to ensure the required ice/hull friction factor. Immediately before the model tests, the hulls were bridged by frame structure. The wing hulls were installed with five-component dynamometers to measure the longitudinal and transversal components of ice load P_x and P_y and all three components of ice moment M_x, M_y and M_z. Table 1.1 below contains the main data of the icebreaker and her model.

TEST RIG

Experimental investigations of the icebreaker propulsion in ice were performed at the Krylov Centre ice basin as part of SMTU and KSRC collaboration. In addition, a series of towing tests in open water was conducted in the SMTU towing tank.

Krylov's Ice Basin is one of the largest in the world, the length and breadth of its test section is 80 and 10 m, respectively (Timofeev, 2015). A special method of fine-grained (FG) ice preparation was applied in this work to make two ice thicknesses in one ice sheet. It allows us to obtain large volume of experimental data in one day.

Towing tests in the ice basin were done in accordance with the recommendations ITTC 7.5-02-04-02.1. The ice resistance tests were carried out by towing the model at a constant speed through the ice sheet. In addition to five-component dynamometers measuring the ice load on wing hulls, the model was equipped with the towing dynamometer to determine the ice resistance for the total icebreaker (Fig. 1).

Figure 1 – Model test of multi-hull icebreaker in ice basin
(1 –towing dynamometer; 2 – frame bridge to connect hulls;
3 – five-component dynamometer to measure ice load on wing hulls)

For the resistance tests in level ice, the towing force was a result of primary measurements. For determination of net ice resistance it is required to take account of water resistance in ice conditions. It should be noted that there is practically no wave-making component in water resistance when the model is moving in ice conditions.

For this reason, the first phase of experimental investigations dealt with the bare hull tests of the icebreaker. The model was tested in the speed range of 0.07 to 1.45 m/s, which corresponds to full-scale speeds of 1 to 20 knots. The towing resistance of model was scaled to full-size using the method based on the Froude scheme. The method of Froude is based on the assumption that the residual resistance coefficients of the model and the ship are equal. In this case the total resistance coefficient of full-scale ship C_{TS} can be calculated from the formula $C_{TS}=C_R + C_{F0S} + C_A + C_{AP}$, where C_A – correlation coefficient, which can be assumed as 0.4×10^{-3}. Appendage resistance coefficient C_{AP} is not singled out and included into the residual resistance.

Fig. 2 shows the total resistance of ship R_{TS} versus speed V_S.

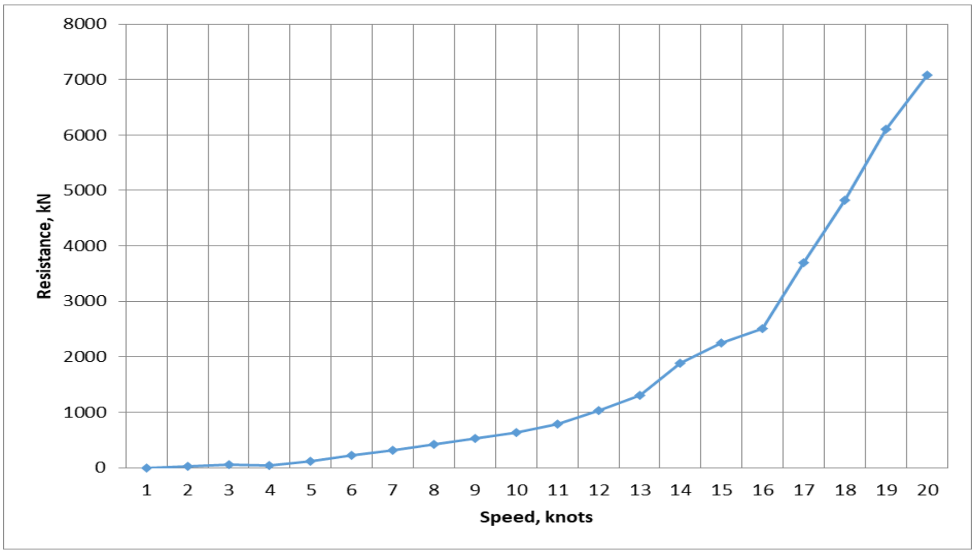


Figure 2 – Towing resistance R_{TS} versus speed V_S

The main wave-making centers in ship motion are hull areas in way of stem and sternpost with pronounced longitudinal camber, which gives rise to sharp peaks of hydrodynamic pressure. Divergent bow waves of icebreaker hulls have different structures. They are of standard configuration for the middle hull. For wing hulls they are different because of interferences with cross waves generated by the leading hull. The wave interference occurs and, therefore, the wave-making resistance is increased. The analysis of model test data has shown that when the ship reaches 16 knots there is a positive effect of wave interference in space between hulls. This effect reduces the icebreaker resistance R_{TS}.

RESULTS OF OBSERVATIONS IN MODEL TESTS IN ICE BASIN

The expected area of the icebreaker navigation is the Kara Sea and the Gulf of Ob. Average thickness of ice in these waters is 1.67 m, the flexural strength of ice in the river is in most cases above the widely used value of 500 kPa to describe the first year ice and equals to 780 kPa (Oganov, 2018). Based on this data, it was decided to assess the limiting ice-going capacity using model tests of the icebreaker hull in continuous level ice of 1.5 m and increased flexural strength of 600 kPa in full scale.

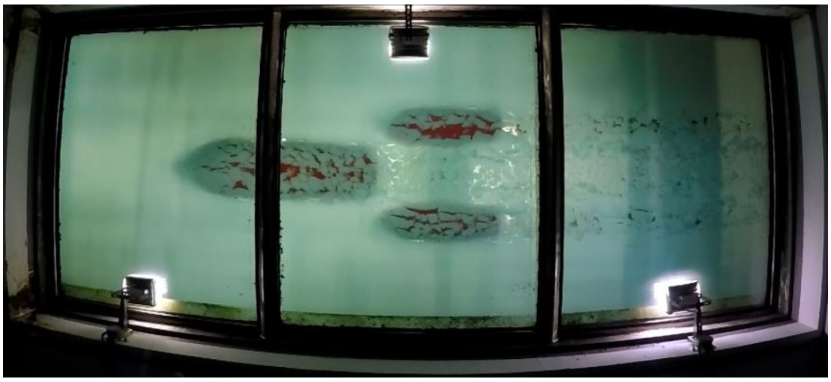


Figure 3 – Ice breaking by model hulls at 0.36 m/s (5.0 knots full-scale)

In the course of the experiment, several important observations were made regarding the trimaran hulls interaction with ice.

The middle hull breaks ice by classical bending of ice sheet, while the wing hulls in addition to the said mechanism are able to break off some ice fragments into the channel laid by the leading hull (Fig. 3). Let us consider the ice failure in more detail.

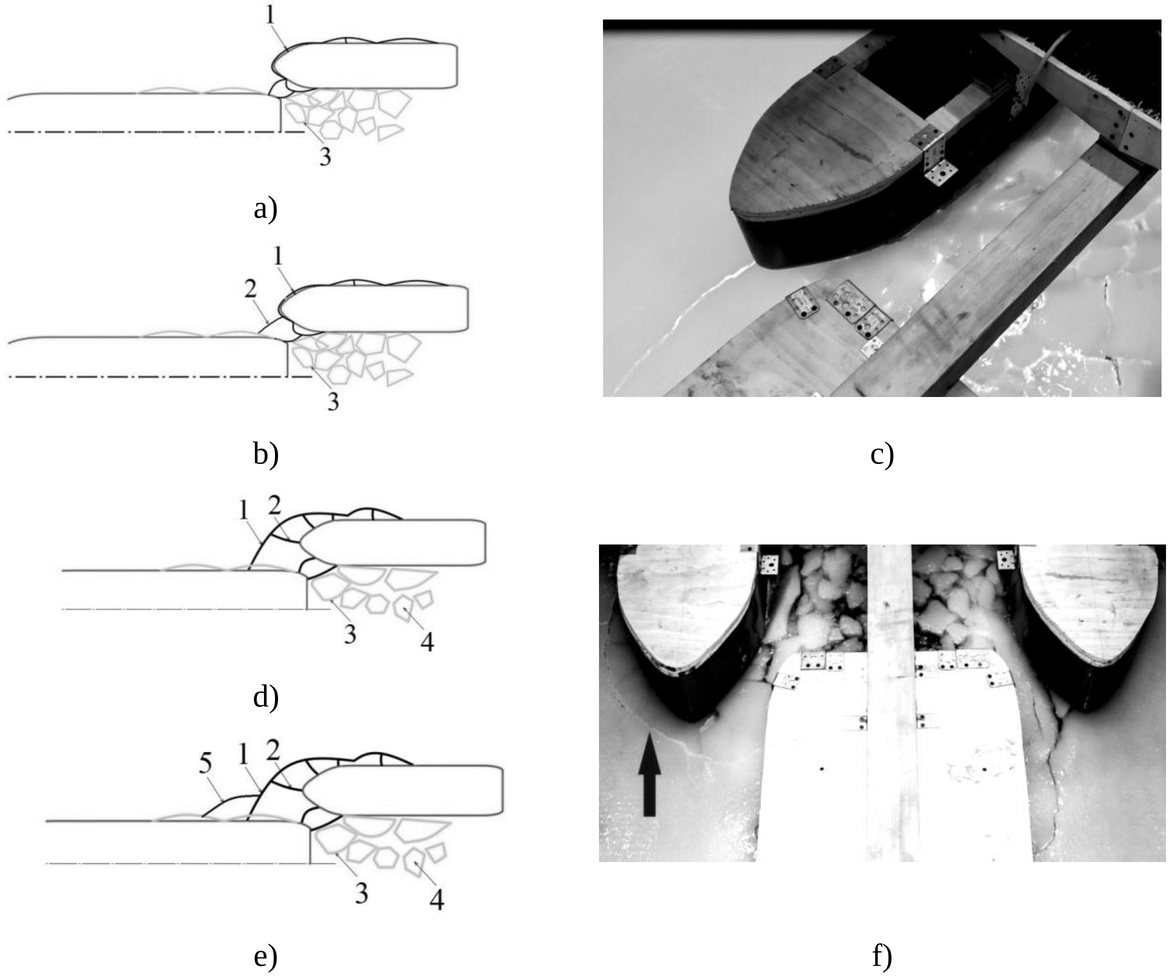


Fig. 4 – Mechanism of ice breaking by icebreaker wing hulls:

a) at 5.0 knots and higher; b) at 3.0 to 5.0 knots; c) cracking pattern at 3.0 to 5.0 knots; d) at 1.0 to 3.0 knots; e) at 1.0 knots; f) cracking pattern under 3.0 knots.

The pattern of ice breaking by wing hulls largely depends on the model speed.

- At model speed higher than 0.36 m/s (5.0 knots full-scale) the wing hulls are breaking ice by bending (Fig. 4b). The angles of roll and trim are small. Ice failure mechanism is according to high-speed icebreaker operation in continuous level ice described in (Dobrodeev & Sazonov, 2018). The velocity of ice pieces is significantly reduced and the ice jacket is observed over the entire bottom of the model hull. A certain peculiarity of the multi-hull icebreaker is that the number of ice sectors on the inner side of wing hulls is less than on the outer side, while their size is respectively larger at all speeds under considerations.
- At slower speeds the size of ice sectors insignificantly grows and main cracks start to develop before the stem of wing hulls. These cracks go to the channel edges formed in

wake of the leading hull (Fig. 4b and 4c). Cracking at speeds under 5.0 knots can be explained by the lateral force from the wing hull on the channel edge. This force is caused by non-uniform ice breaking by icebreaker hulls and larger angles of roll and trim as compared with higher speeds. The force on ice sheet edge is generated with changes in the icebreaker trim and roll, and large fragments of ice are broken off.

– At speeds under 3.0 knots the pattern of icebreaker interaction with ice has significantly larger size of ice sectors. The observed effect is similar to the icebreaking pattern at a speed close to limiting ice-going capacity (Fig.4d and 4e). In this case the ice failure mechanism contributes to persistent breaking off large pieces of ice into channel behind the leading hull, which is a different scenario from those considered above. At slower speeds it can also be noted that half of the wing hull breadth is cleared of ice jacket. It happens because the bow breaks off ice fragments and part of ice pieces surface from under the bottom in way of midship section.

In general, from the analysis of experimental data it is seen that the channel behind icebreaker is filled with brash ice measuring 2 to 15 m across with practically no larger ice fragments. Consolidation of ice in the channel is about 8/10 – 9/10. No buildup of ice fragments between the strernpost of the leading hull and stems of the wing hulls were observed.

RESULTS OF MODEL TESTS IN ICE BASIN

The width of ice channel in wake of the trimaran icebreaker according to experimental investigations is 67 m.

The measurements of icebreaker’s ice resistance are shown in Fig. 5. For comparison this figure also indicates the ice resistance of a hypothetical icebreaker, which is able to produce the ice channel of the same width as the icebreaker under study.

Figure 5 – Comparison of trimaran icebreaker’s ice resistance with that of a hypothetical icebreaker able to produce 67 m wide channel.

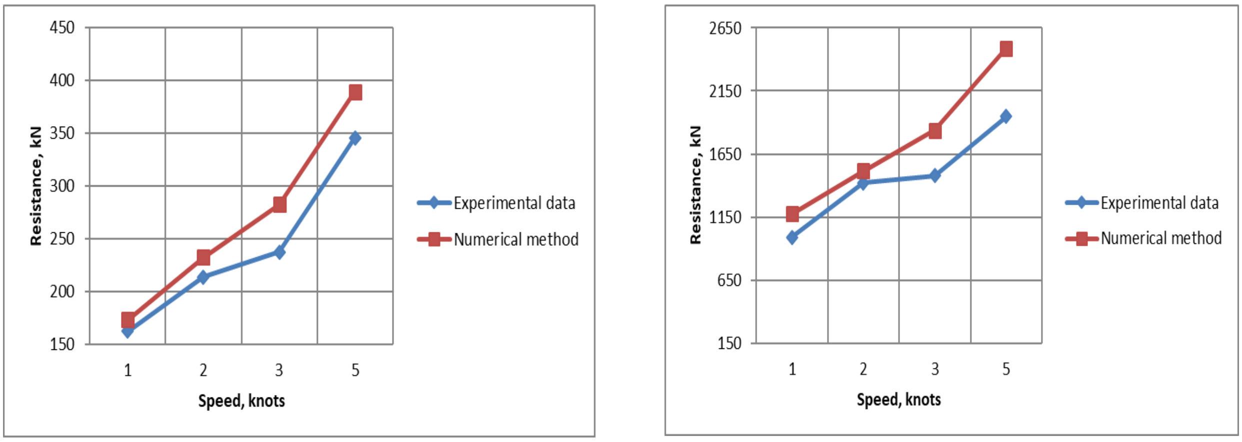
Numerically, the trimaran ice resistance can be represented as a summation of the middle and wing hull resistance.

B.P Ionov method can be used for calculation of the first term (Ionov, 2001), the second term is more difficult to describe numerically because of physical specifics of ice/hull interaction. Based on model test observations, the author suggests a method for calculating the ice resistance of wing hulls. According to this technique the ice resistance of wing hull for speeds under 5 knots is made up of two terms. The first term is the resistance of hull's inner side, which is assumed for calculation as the resistance in broken ice. The component of outer side is calculated as the ship resistance in continuous level ice and obtained by B.P Ionov method. For speeds above 5.0 knots, according to observations, the ice resistance of each of the 3 hulls are calculated by one method (Ionov, 2001).

An improved formula of V.A. Zuev is used for estimation of the broken ice component (Zuev, 1986):

$$R_I = 0{,}63 \cdot \frac{\rho_I g B h_I^2}{(B_c/B)^{3/4}} \cdot \left(0{,}13\frac{B}{h_I} + 1{,}3Fn_h + 0{,}5Fn_h^2\right) \cdot \qquad (1)$$

where B is equal to the wing hull half breadth, м; $B_к = \frac{B}{2}$; α_0 – design waterline entrance angle, rad; tanφ – angle of stem to design waterline, rad.



a) b)

Figure 6 – Comparison of icebreaker's ice resistance obtained in the experiment and by new calculation technique

General analytic expression for the ice resistance and its components at the icebreaker motion in continuous level ice is as follows (Ionov, 2001):

$$R_Л^* = 2k_i \frac{\sigma_И h^2}{b}\left[\alpha_1(\beta)B + f_Д \alpha_2(\beta)BL\right] + 0{,}3k_2\rho_0 ghBL\left(\frac{(tg\alpha_0)^2}{tg\alpha_0 + \frac{B}{L}}\right)\left[\alpha_1(\beta)\sin\alpha_0 + f_Д\alpha_2(\beta)(1+\cos\alpha_0)\right] +$$

$$0{,}5k_3\rho_Л ghB^2 Fr_B\left(1 + \frac{1}{\cos\alpha_0}\right)\left[\frac{(tg\alpha_0)^2}{2tg\alpha_0 - \frac{B}{L}} + f_Д\right] + k_4 f_Д \rho_0 ghBL_{Ц.В} \qquad (2)$$

The formula for calculation of the wing hull ice resistance is:

$$R_{Side} = \frac{R_{Л}^{*}/2 + R_1}{k} \qquad (3)$$

where k – empirical coefficient obtained from experimental investigation and assumed as 1.8 - 2.

Fig. 6a presents the resistance of wing hull obtained in model tests and calculated according to the technique suggested in the work. Fig. 6b compares the total resistance of icebreaker obtained in the experiment and according to the new calculation technique.

POWERPLANT OF TRIMARAN ICEBBREAKER

As a part of trimaran icebreaker concept development, her powerplant and propulsion/rudder system has been worked out in detail. The middle hull should be equipped with a propulsion motor to transmit the torque to a four-bladed propeller of ice class. The wing hulls are planned to have azimuth thrusters of ice class. This arrangement will enhance the icebreaker maneuverability. Based on calculations using RS methods (K.B. Khlystova, A.V. Andryushin, 2018) it is concluded that the propulsion system meets requirements of icebreakers. The total strength of blade root section is much higher than that of the conventional propeller (2-2.5 times). Strength margin is from 16 to 20 and higher.

A preliminary qualimetric analysis of the icebreaker with two options of powerplant was carried out. The first type was using heavy fuel oil (HFO), while the second type was operating on liquefied natural gas (LNG). The criteria of assessment was as follows: energy efficiency criterion; survivability criterion; fuel consumption criterion of icebreaker powerplant per meter across ice channel and endurance criterion.

The qualimetric method of analysis make it possible to assess and compare the quality of one or several objects. The analysis employs an additive model of the vector criterion aggregation:

$$Q_A = \sum_{n=1}^{N} (\alpha_n \cdot q_n) \qquad (4)$$

where n – number of quality indicator, α – importance of quality indicator, q – numerical value of quality.

Based on the numerical analysis it is decided to use LNG powerplant. This plant meets all modern requirements of International Maritime Organization (IMO) prescribed in the respective sections of MARPOL Annex VI Tier II and Tier III. It is noted for fuel economy and installation efficiency, survivability and reliability.

Model test series have determined the required power requirements in various operation modes.

The installation consists of six diesel generators arranged separately in three hulls. Diesel generators produce electric power fed into Integrated Electric Power System (IEPS) of the vessel. IEPS distributes the electric power to users. By application of IEPS we increase the survivability of installation, it enables load distribution between diesel generators in various modes of operation. It allows us to enhance the economic efficiency of the powerplant based on optimum service mode of the diesel engine.

Fig. 7 shows a general view of the engine room deck for the heavy fuel (HFO) version of the powerplant with main diesel generators (3) and IEPS equipment (6). Some of the equipment is shown schematically – boilers (2) with service pumps, tank tanks (5), ballast tanks (1), ice boxes (4).

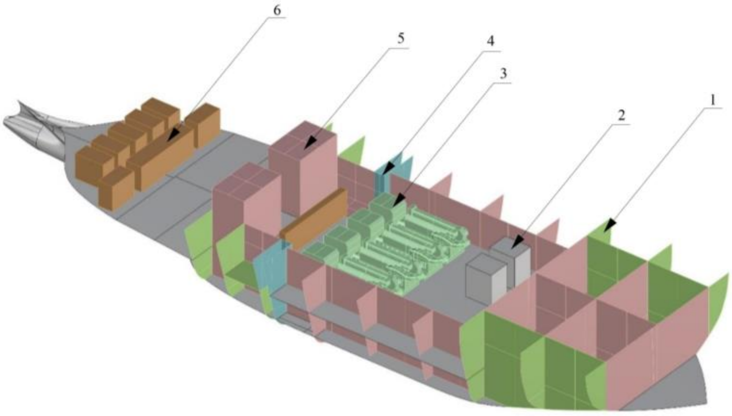


Figure 7 – ER general view

High energy efficiency of the installation is achieved by means of diesel generator waste heat recovery including heat of exhaust gases from diesel generator, heat of diesel generator cooling water, low-temperature lube oil heat of diesel generator and low-temperature heat from surfaces of diesel generator.

For quantified assessment of these resources, the analysis of energy balance for two installations is carried out in the work. One installation is operating on HFO another is on LNG. Also, the calculations were done for each waste heat recovery option. Analysis has shown the following possibilities of diesel generator waste heat recovery for each of the two installations:

- use of waste heat turbo-generator for additional electric power;

- replacement of diesel engine driven accessories by equipment driven by additional electric power;

- use of Stirling engine for waste heat recovery from turbo-generator steam;

- fresh water from distilling plants by waste heat recovery of diesel generator cooling water;

- use of waste heat from diesel generator surfaces for heating the icebreaker spaces.

CONCLUSION

A detailed study of the innovative trimaran icebreaker and her powerplant was carried out during Master thesis elaboration. Model tests in ice basin have demonstrated that such icebreaker has less ice resistance as compared with a hypothetical icebreaker able to make an ice channel of equal width in ice cover 1.5 m. Experiments indicated that the pattern of trimaran icebreaker interaction with ice depends on three main factors: mutual arrangement of wing hulls with respect to the middle hull, the icebreaker hullform and speed.

Based on the series of model experiments a mathematical method for calculating the ice resistance of a multi-hull icebreaker is suggested, which enables assessment of the ice-going capacity and required power early in the design process. Versions of classical and advanced powerplant has been developed for trimaran icebreaker. In the first case the powerplant operates on heavy diesel fuel and in the second case on liquefied natural gas. Deep recovery of diesel generator waste heat is developed for each type of installation, and the required equipment is chosen and specified.

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