Proceedings of OMAE04
23rd International Conference on Offshore Mechanics and Arctic Engineering
June 20-25, 2004, Vancouver, British Columbia, Canada

OMAE2004-51081

HULL FORMS FOR ICEBREAKING TANKERS

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Keywords: Oil tankers, icebreaking, level ice, pack ice, open water

ABSTRACT

The optimum design for an icebreaking tanker will depend on the trade route and the cargo delivery requirements. For example, the hull shape of a ship that spends almost all of its time operating in heavy ice can be optimized for low speed icebreaking conditions. In contrast, a ship that spends a small portion of its time in light ice that has been previously broken and the rest of its time in open water can be optimized for different requirements. The challenge for the designer is complicated by the observation that many ship design features that enhance powering performance in ice are detrimental to open water performance.

This paper presents predictions of ship resistance in pack ice, level ice and open water for four tanker designs, which include a conventional hull with no modification for ice at all and three designs proposed for operation in Arctic ice conditions. The predictions of ship performance are based on model experiments carried out in Canada and Korea. The resistance of the four hulls in open water, two concentrations of pack ice and two level ice thicknesses are compared and discussed. Information of this sort is essential for developing the optimum ship design for a particular shipping route, given known profiles of open water, pack ice and level ice.

INTRODUCTION

Many of the modern concepts for shipping oil in ice-covered waters were pioneered by the voyage of the ‘Manhattan’ through the North West Passage in 1970 [1]. At the time it was built, ‘Manhattan’ was the most powerful tanker in the world, which made it the most suitable for conversion to icebreaking. The main engines for the ship were steam turbines, driving twin screw propellers. At the time of the conversion, the long raked bow was radical, but it has since become an accepted feature in designs for large ships operating in ice.

‘Manhattan’ was modified for operation in Arctic ice, which was considered to be a mixture of level ice, heavy pack ice, rubble ice and ridges. Almost no attention was paid to open water performance, since the limiting effect was the ability of the ship to move unassisted through heavy ice.

The most recent designs for operation in ice offer quite a different solution compared to ‘Manhattan’. The Double Acting Tankers, Tempera and Mastera [2] have a very similar deadweight to the ‘Manhattan’, but were optimized for different ice conditions. These tankers operate in the Baltic Sea, and so are less likely to break their own path through level ice, but will operate mostly in pack ice or brash ice in a broken channel. These designs have attempted to reach a more efficient compromise between open water performance and icebreaking in light to moderate ice conditions by only breaking ice in the astern direction. The normal bow of the ship has a bulb, which is usually avoided in icebreakers, but is beneficial to the open water performance. Propulsive force is provided by a single azimuthing podded propeller, which is reversed between open water and icebreaking.

These two approaches highlight the problem for a naval architect designing a ship to operate in ice. The expected ice conditions and the proportion of open water for a voyage determine the optimum solution. For example if the route was mostly open water, with a small amount of pack ice, then a hull shape optimized for open water is likely to be the optimum solution, provided it is structurally strong enough to withstand the ice forces. However, if the route has long distances of level ice or heavy pack ice cover, then providing a hull shape optimized for icebreaking will be critical to the success of the ship. The most challenging design areas are the intermediate conditions, where the trade-offs between open water and ice performance must be studied in detail.

NOMENCLATURE

B	is the vessel beam
C_o	is the ice concentration
C_p	is the pack ice concentration coefficient
f	is an arbitrary function
F_p	is the average pack ice force
Fr_p	is the pack ice Froude number
g	is the acceleration of gravity
h	is the ice thickness
n	is an exponent
V_i	is the pack ice drift velocity
ρ_i	is the density of ice

DESIGN DEVELOPMENT

This paper presents an extension of an earlier paper that presented model experiment results for two icebreaking tankers [3]. Both of these tanker designs (models IMD-493 and IMD-501) included many of the features found to be successful during the Manhattan voyage. The major difference was the restricted draft of 11.5 m compared to the Manhattan's draft of 15.4 m. The initial work on the Arctic Tanker has been extended and this paper presents results for a third hull shape (IMD-614), with increased draft from 11.5 m to 16.5 m and the resulting increase in displacement. The principal dimensions of the new hull are compared with the two earlier designs in Table 1.

The third icebreaking hull form had less double curvature relative to the two initial designs, and was intended to provide lower resistance in heavy ice. The hull form had a spoon bow, and the appendages were reinforced shaft bossings, which were simpler to construct than the twin gondola skegs used for the two earlier designs. The hull had twin rudders. The body plan and profile for the third hull is shown in Figure 1. A picture of the stern arrangement is given in Figure 2.

A fourth hull included in this project was a conventional single screw tanker with a bulbous bow. This hull represented a tanker with a good open water form, but no modification for operation in ice. The conventional tanker used in this study (model SM173) is shown in Figures 3a, 3b and 3c.

The principle dimensions for all four hulls are given in Table 1.

As the first phase of an investigation into optimum shapes for tanker hulls in pack ice, predictions of resistance for the three Arctic tankers in two pack ice concentrations are compared to a conventional tanker, with a bulbous bow. Based on this data it will be possible to understand the trade-offs between open water resistance and resistance in broken ice.

Model experiments in ice and open water were carried out at the Institute for Ocean Technology (formerly the Institute for Marine Dynamics) on the icebreaking hulls and experiments in open water on the conventional hull were carried out at the Samsung Model Basin.

PREDICTION OF SHIP RESISTANCE IN PACK ICE

A method for analyzing the results of resistance in pack ice has been presented [4] which considers only the buoyancy and submergence forces caused by the ice on the ship's hull. This method is the same as the analysis of the pre-sawn resistance component used in level ice resistance analysis, with the addition of a concentration component. For pre-sawn ice (100% concentration) this factor has a value of 1.0.

In the analysis of level ice resistance it is assumed that there are three components, all of which scale separately. The force components are a hydrodynamic force caused by the drag of the hull, a force on the hull caused by breaking the ice and a force on the hull caused by moving the ice around the ship. This third force component can be further divided into two parts, referred to as the submergence force and the clearing force.

In the case of resistance in pack ice, provided that the flow sizes are uniformly small in relation to the ship dimensions, there is very little breaking component, and so these forces can be ignored. The hydrodynamic resistance can be estimated from the open water resistance or from the standard model scaling techniques (including a three-dimensional form factor). Resistance forces on a ship model due to pack ice are determined by subtracting the hydrodynamic resistance from the total measured resistance.

The remaining force component can be non-dimensionalized using

$$C_p = \frac{F_p}{\rho_i B h V_i^2 C_o^n}$$

Velocity can be non-dimensionalized using Pack Ice Froude Number (Fr_p,).

$$Fr_p = \frac{V}{\sqrt{ghC_o}}$$

The two coefficients are related by a function derived from the measured data.

$$C_P = f(Fr_p)$$

Experience has shown that Ln(C_p) is a linear function of Ln(Fr_p)

All the experiments in pre-sawn ice (at nominally 100% concentration) and pack ice (at a nominal concentration of 80%) that had been carried out for models IMD-493, IMD-501 and IMD-614 were analyzed using this method. Data from model experiments in pack ice and pre-sawn ice for IMD-614 is shown in Figure 4, and the resulting coefficients for all the models are given in Table 2.

In the original study [4] a value of n of 3, is recommended based on data for speeds appropriate for moored ships or FPSOs, where the only flow component was caused by a current. Analysis of the arctic tanker data, together with other ships tested in pre-sawn ice and pack ice, suggests a value of 2 collapses pack ice and presawn ice resistance onto a single line, with the smallest error band.

The conventional hull (SM173) was not tested in ice, but was tested in open water at Samsung Model Basin (SSMB). This tanker was very similar to a conventional tanker tested at IOT in a range of pack ice concentrations [5]. This data (for 100% and 90% concentrations) was reanalyzed to determine the non-dimensional coefficients in the same form as the Arctic tanker data. These results are shown in Figure 5 and included in Table 2. Predictions of resistance in pack ice for SM173 were estimated based on data from model experiments at IOT [5] re-scaled to the beam of SM173, with the hydrodynamic component calculated from a form factor calculated from the open water model experiments (using ITTC 1957 model-ship correlation line). The IOT model had a beam approximately 8% narrower than the SHI model, when scaled to the same displacement.

COMPARISON OF RESULTS

Resistance in Pack Ice

Predictions of resistance in 1 metre thick pack ice are given for the four hulls in Figure 6 (95% coverage) and Figure 7 (70% coverage). The results show that the Arctic tankers have considerably lower resistance than the conventional form. The resistance in pack ice for all the Arctic tanker forms is less than half that of the conventional form. In the heavier coverage (95%) IMD-614 has the best performance throughout the speed range. In these conditions, the ice clearing force component for IMD-614 is the lowest of the three and is considerably larger than the hydrodynamic force throughout the speed range. As the ice coverage is reduced, then the hydrodynamic force becomes a higher proportion of the total. There is relatively little difference between the Arctic hulls in 70% coverage up to 6 knots, but IMD-614 has the highest values at the higher speeds. This was caused by the relatively poor open water performance of this hull, which will be discussed later. The ice resistance component for this hull is the lowest throughout the speed range.

Reducing the ice coverage from 95% to 70% lowers the resistance by between one half and one third. Clearly pack ice concentration has a very significant effect on resistance. Based on the hull forms discussed in this paper, if ice concentration was reduced to approximately 30%, then there would be virtually no penalty on resistance over the open water value.

Resistance in Level Ice

Resistance of the three Arctic tankers in ice with thickness of 1m and 2m (with a flexural strength of 500 kPa) is shown in Figure 8. This Figure shows that there is relatively little difference between the three Arctic tankers in 1m of ice, but that in the thicker ice, IMD-614 is clearly the lowest. This shows that the design objective of improving the ice resistance in heavy Arctic ice has been met. Figure 8 clearly demonstrates the advantage of a spoon bow and additional displacement in increasing the vessels ability to break ice.

Resistance in Open Water

A comparison of effective power for the four hulls in open water is shown in Figure 9. Given that IMD-614 and SM173 have very similar dimensions and displacements, this figure clearly shows the disadvantage of an extreme icebreaking hull form compared to the conventional form. At 15 knots, the effective power is approximately 80% more for the icebreaker than for the conventional hull. IMD-493 and IMD-501 both have lower effective power than SM173, but their displacement and wetted surface area are considerably smaller as can be seen in Table 1.

CONCLUSIONS

The results given in this paper show that low resistance in heavy pack ice coincides with low resistance in level ice, but that the open water resistance increases as the resistance in ice is reduced. Given the distribution of open water, pack ice and level ice, for a chosen route the different tanker designs can be compared and the optimum design, with lowest average resistance over the whole route can be determined. Varying the distribution of each type of ice that the ship encounters will affect the optimum solution. Other factors to consider will be the capital and operating costs of the ship as well as the number of round trips per year.

The next phase of this project will include a more detailed study of the optimum hull form for operation in pack ice and open water, with no level icebreaking component. In these ice conditions, it is unlikely that the extreme hull shapes required for Arctic ice breaking will be economical, but it is not clear how much distortion from a conventional hull can be tolerated while maintaining a profitable ship.

ACKNOWLEDGMENTS

The results presented in this paper were obtained as part of a collaborative research project between Samsung Heavy Industries and the National Research Council of Canada. The authors gratefully acknowledge both these organizations for their permission to publish the data.

The authors would also like to acknowledge the contributions of staff members from both organizations, without whom this project would not have been possible. In particular, the contributions of staff responsible for design, construction and testing of the models should be recognized.

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		IMD-493	IMD-501	IMD-614	SM 173
Length, wl	m	273.5	274.9	284.0	258.3
B, wl	m	43.6	43.6	42.8	46.2
T, midships	m	11.5	11.5	16.5	16.6
trim	m	0	0	0	0
Displacement	tonnes, SW	100144	102145	161935	162001
Wetted area	sq. m.	14720	14502	17689	17492

Table 1, Icebreaking Tankers, Summary of Principal Dimensions

Model	Slope	Intercept
IMD-493	-1.601	1.365
IMD-501	-1.588	1.301
IMD-614	-1.662	0.693
Tanker	-1.553	2.378

Table 2, Resistance in Pack Ice, Summary of analysis of Ln(C_p) plotted against Ln(Fr_p)

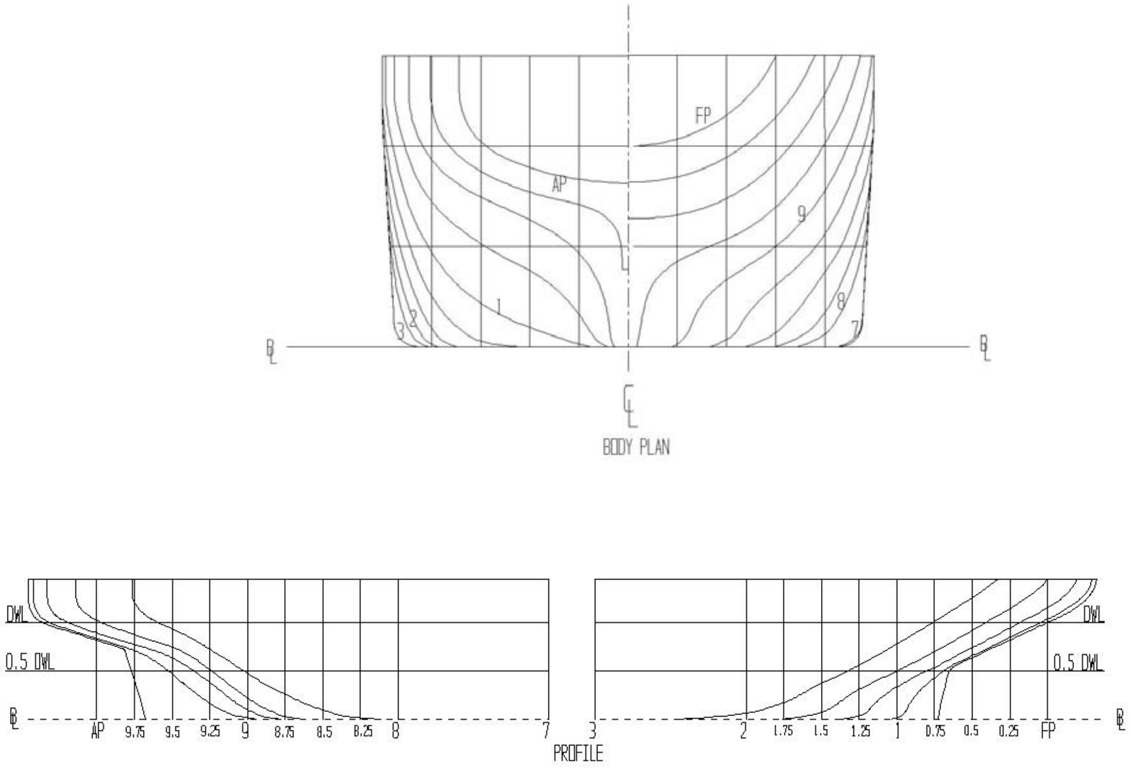

Figure 1, IMD-614, Bodyplan and Profile

Figure 2, IMD-614, Stern Arrangement

Figure 3a, SM173, Bow profile

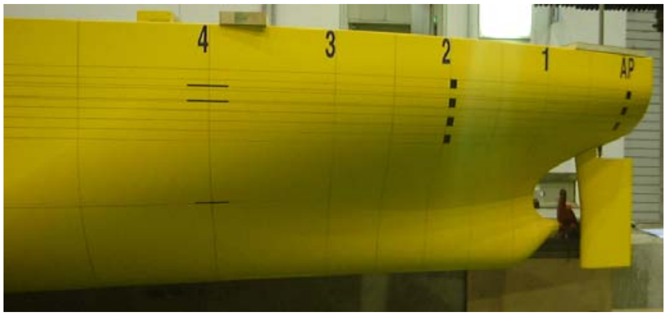

Figure 3b, SM173, Stern profile

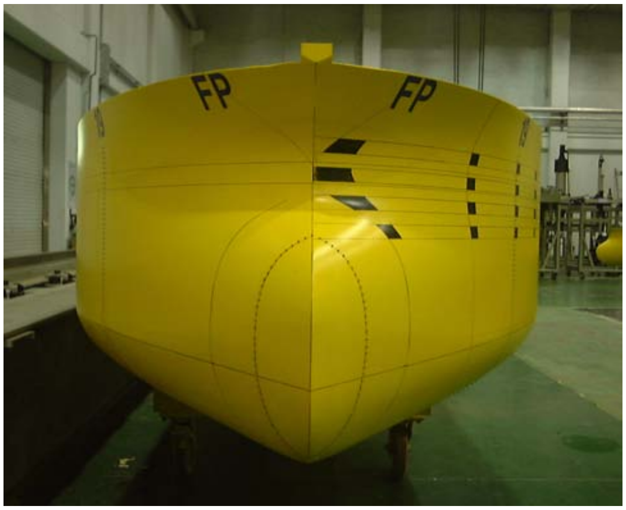

Figure 3c, SM173, Bow view

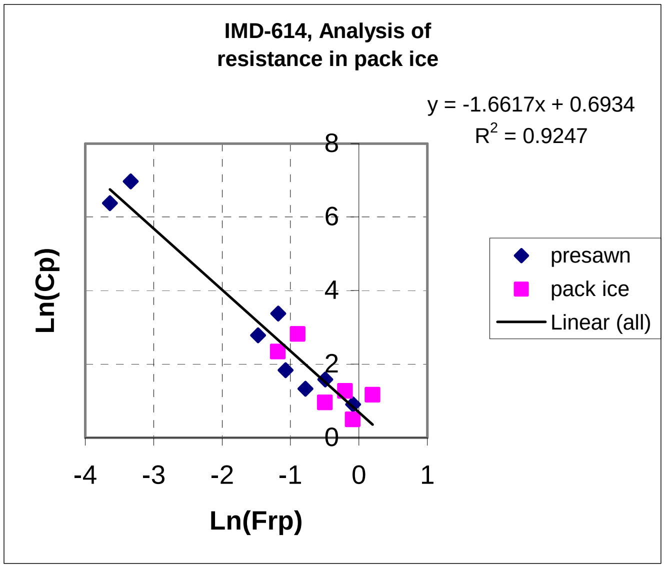

Figure 4, Analysis of Resistance in Pack Ice, IMD-614, Arctic Tanker

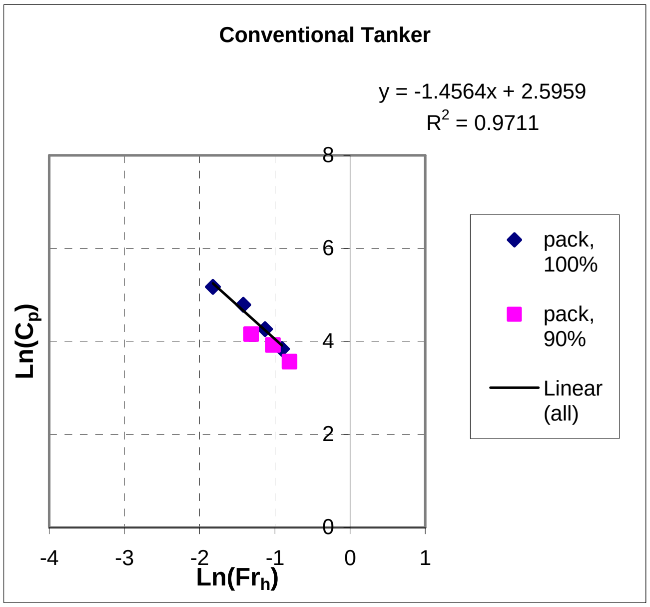

Figure 5, Analysis of Resistance in Pack Ice, Conventional Tanker

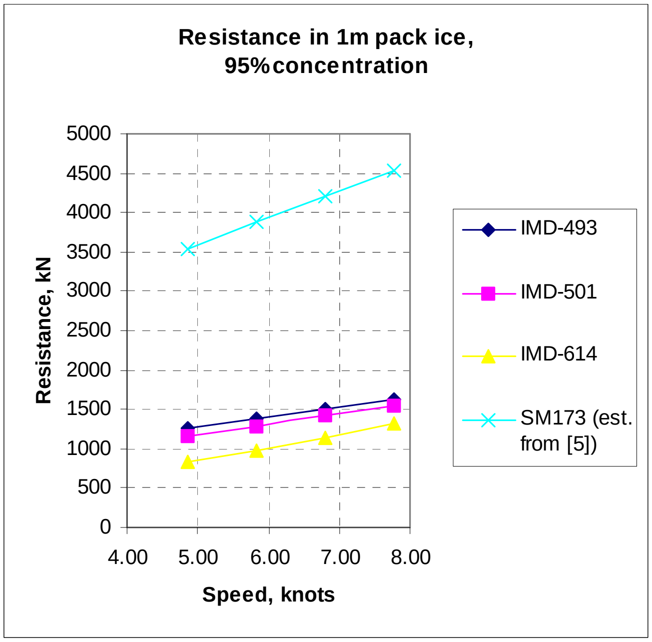

Figure 6, Resistance in Pack Ice, 95% coverage

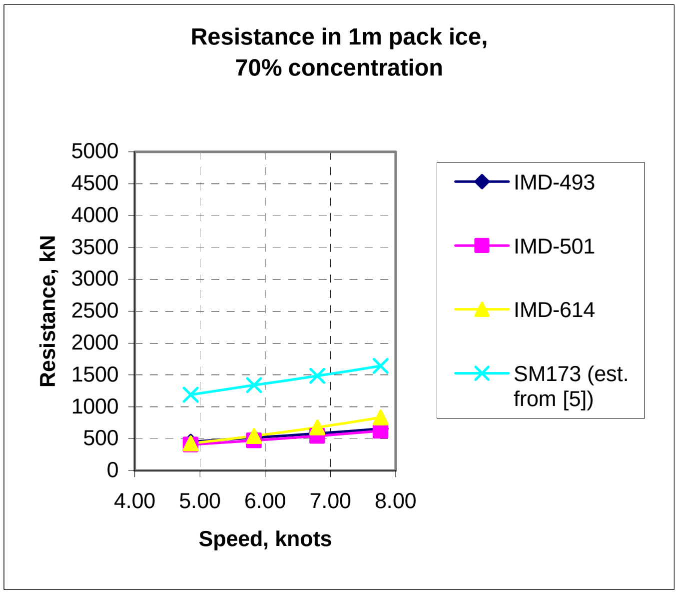

Figure 7, Resistance in Pack Ice, 70% coverage

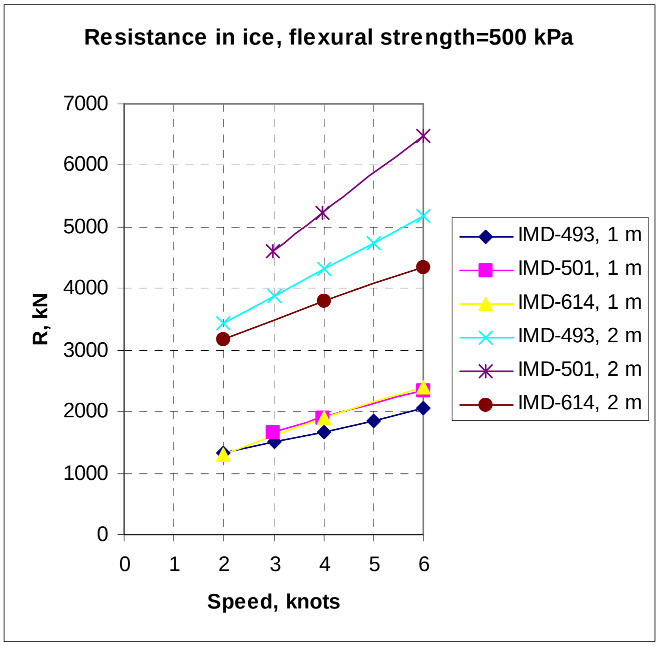

Figure 8, Level Ice Resistance

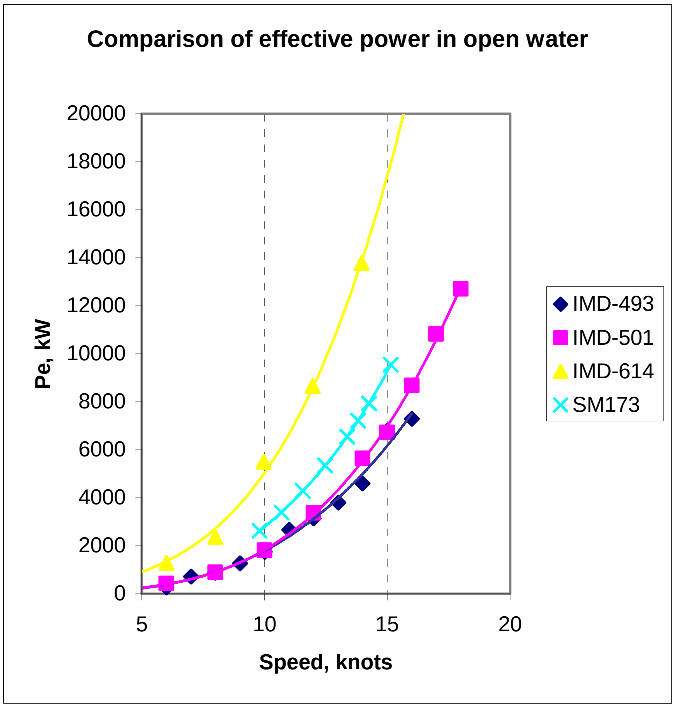

Figure 9, Effective Power in Open Water