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DESIGN APPROACH TO OPTIMIZE WATER JET PERFORMANCE: A CASE STUDY OF COASTAL PATROL CRAFT, SRI LANKA NAVY

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ABSTRACT

Commercial water jet manufacturers publish their water jet performance curves mostly in the form of thrust/power against boat speed. The common approach is to foresee the performance of craft with candidate water jet(s), to simply plot the developed bare hull drag curve by a Naval Architect against the published power/thrust curves in graphical mode to establish the best fit. Yet this traditional approach does not uncover information on craft performance in the entire speed range or water jet model efficiency as the best choice for a particular local application. This case study incorporates approaches to seek a reduction in the craft's bare hull drag, to develop an adequate analysis that shall combine engine RPM analysis to understand the availability of full-rated engine power absorbed by propulsor/water jets. Therefore, the research employs a comprehensive mathematical-based methodology as compulsory, to evade performance glitches and to outline an accurate and fruitful design structure. Thus, the employment of universal water jet coefficients has been considered to validate the design and eliminate the flaws associated with the traditional thrust-resistance plotting technique. A naval project designed by the authors was used to demonstrate how the authors averted possible complications and optimized the design through a new calculation methodology.

KEYWORDS: traditional approach, water jet efficiency, universal water jet coefficients

1. INTRODUCTION

The boat propulsion system consists of a marine engine, gearbox, and a suitable propulsor and does not require any design of equipment as Original Equipment Manufacturer (OEM) is entrusted with the same. For marine engines and gearboxes, Naval Architect is required to confirm power transmission, power output, and RPMs meet the desired requirements. The Naval Architect to design hull, and propeller styles may be chosen, and can be suitably pitched to the engine type. Thus, equilibrium performance relations are upheld.

Figure 1 identifies the focal study elements as an engine–propulsor–hull equilibrium. This necessitates propulsor performance determination with concern on boat speed, Engine/ propulsor RPM, thrust, and torque (or power). The calculated assessments mainly focus on propulsor efficiency, engine fuel consumption, and propulsor cavitation. By this means author's aptitude was to seek, how non-dimensional (same for actual boat and model) associations could be used to conduct the above examination for a waterjet thrust (propulsor - hull interaction determination) and torque (engine - propulsor interaction determination).

Figure 1: Equilibrium performance schematic

Cavitation tunnel open water tests usually provide the velocity of advance, RPM, torque, and thrust relations of propulsor. A step forward, Propeller Theory is based on models that define non-dimensional coefficients. With distinctive and complex propeller diagrams, which contain, i.e. Advance Ratio (J), Thrust Coefficient (KT), and Torque Coefficient (KQ) curves, it is promising to estimate the propeller dimensions and efficiency. Built around the KT/KQ nomenclature as depicted in Figure 2, it offers a successful methodology that offers the benefit of (a) work with factors rather broad 3D geometry and (b) simple to calculate yet all-inclusive boat performance study. Thus, this numerically simple task leads to the successful selection of optimum parameters. Yet, unfortunately, the methodology is most validated in open-water propellers.

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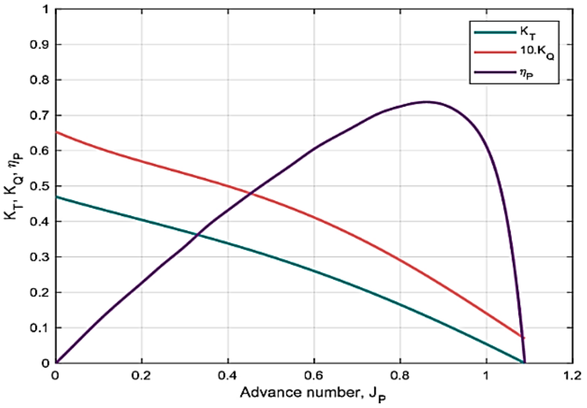
$KT = \frac{\mathrm{T}}{\rho.n^2.\mathrm{D}^4},$ Equation 01

$\mathrm{KQ} = \frac{\mathrm{Q}}{\rho.n^2.\mathrm{D}^5},$ Equation 02

$\mathrm{J} = \frac{\mathrm{Va}}{\mathrm{n.D}}$ Equation 03

Where Va - forward speed of the boat or velocity of the incoming flow to the plane of rotation of the propeller, n - angular velocity of the propeller in revolutions per second, D - diameter of the propeller, ρ - density of the fluid, T - thrust force that is generated on the surface of the propeller and Q - torque of the propeller.

Figure 2: J, KT, and KQ curves (Taskar et. al, 2016)



In predicting waterjet performance, in general, the manufacturer of waterjet provides the thrust curves for a region of defined boat speeds, the traditional approach has been the graphical mapping of the boat's bare hull resistance curve on it to identify the adequacy of generated thrust to encounter the boat total resistance demand. This traditional approach hides RPM from power and shall not allow computing and analyzing important derivative performance amounts to fuel economy and boat acceleration reserves for maneuver/ combat operations which is of paramount importance for naval operations.

The research problem statement of the study is 'Non-availability of comprehensive study approach, which uncover all parameters for military applications' thereby the scope of the study is to develop a 'Design approach to optimize the performance of waterjet driven petrol craft for Naval application'. Thereby research employs a comprehensive mathematical-based methodology as compulsory, with objectives: to seek a reduction in craft bare hull drag, to promote an adequate analysis shall combine engine RPM analysis, and understand the availability of full-rated engine power absorbed by propulsor /waterjets. The significance of the research is to fill the gap, specifically in the analysis of power to RPM with a selected prime mover, fuel efficiency, boat acceleration, and treatment of key parameters of hull drag.

2. LITERATURE REVIEW

The analysis of international conference papers in the discipline of prediction of marine waterjet propulsion units has led to the categorization of 2 different methodologies which are adopted by the researchers, as noted by (Buckingham, 2004).

(i) the detailed prediction of hydrodynamic behavior and
(ii) the use of numerical modelling strategies for the integration of waterjets into propulsion system designs.

The use of computational fluid dynamics has given a major boost in recent times for the first approach. The contributed areas were to optimize specific components of the waterjet system (i.e. inlet tunnel, pump, impeller, etc.) though the main drawback noted in the literature is that the approach does not lead system designers to search the full range of design choices for different waterjets of different sizes.

Conversely, the second methodology is more useful and effective to complete the required propulsion system. It studies to assess the viability of different powering solutions and particularly to tolerate the propulsion system to be matched with the operating profile of the ship. Moreover, the significant contributions of a few authors are notable, specially' Van Terwisga (1997), MacPherson (1999), and Allison et al. (1993). Their studies have been directed towards the development of the parametric model(s), which can interpret the effect of waterjet-hull interaction on thrust and propulsive efficiency. The dependability of this approach is well-established with the availability of design information on common domains.

3. METHODOLOGY

Authors scanned the international shelf to shortlist candidate waterjet models with criteria amounts to a power-to-weight ratio, boat speed, transom detail of hull, Glass Reinforced Plastic (GRP) fabrication, and robustness for naval applications, etc., as directed by Naval Headquarters.

Authors were then obligated to commence with the information/ specification data provided by all OEMs. In a detailed study following were revealed;

a. Nozzle characteristics (transom angle, centre of effort, diameter)

b. Impeller characteristics (diameter, pitch variations, number of blades, hub construction)

c. Physical characteristics (weight, geometry, mounting detail, steering/ reversing details)

d. Rating (maximum input power and RPM)

e. Impeller Power (absorbed shaft power) vs. RPM plots, Figure 3.

f. Thrust curves (boat speed vs. thrust/power), Figure 4.

The principal boat design parameters are given in Table 1.

Table 1: The principal boat design parameters

Parameter	**Value**
Length overall	20 m
Beam	5 m
Hull Material	GRP
Draught	0.95 m
Full Load Displacement	Approx. 27 Ton
Maximum/Cruising speed	35/30 Knots
Hull Type	Round-bilge with hard chine
Endurance	350 Nm@ 35 kts

Length, Beam, and Depth were assumed as constant for this project (GRP mould constraints), but the authors were attentive to see how alterations in weight, Longitudinal Centre of Buoyancy (LCB), Longitudinal Centre of Gravity (LCG), deadrise angles, and trimming affected bear hull resistance. The authors' presumption on key parameters amounts to boat weight, LCG, and deadrise angles were found to be critical in this coastal petrol craft design. Since the non-availability of precise weights, parametric estimates with educated deduction arrived at the weight estimation of 27 Tons. LCG and LCB were finalized with planning characteristics (Figure 4). Large AFT/stern deadrise angle avoided improving performance (Figure 4). Further, trim by AFT condition was promoting planning conditions to swiftly transfer boat weight to hydrodynamic forces (Figure 5).

However, the authors were cognizant of the fact that an LCG too far forward or too far aft would both have adverse effects. If the LCG is too far forward, the craft would have more power to plane than the same hull shape designed with zero trim or a bit by the stern. However, if the LCG is too far aft, a dynamic instability called "proposing" would occur, which is primarily caused by concentrating too much weight in the stern. So, a good middle ground has to be reached between keeping weight aft for good planning and keeping it far enough forward to prevent proposing. Careful analysis was conducted by studying a similar craft and calculating the resistance against the LCG change to reach an adequate balance. The benchmark of these studies was to reach an equilibrium trim angle between 3^o to 5^o for the whole speed range as indicated in Figure 5.

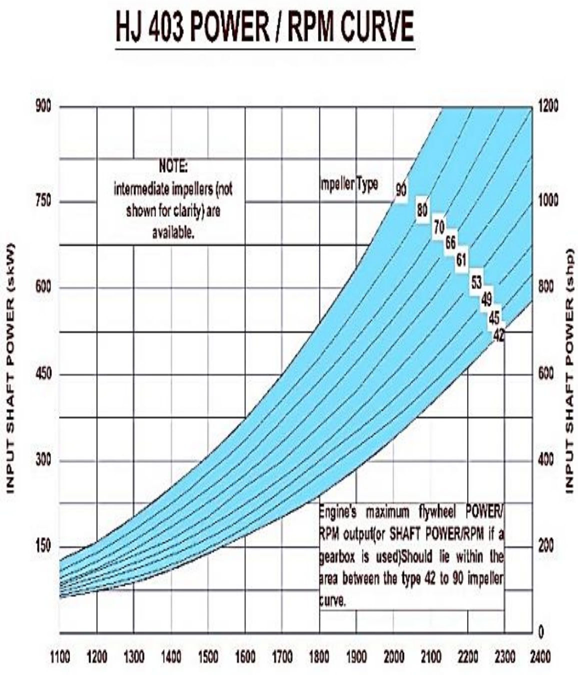
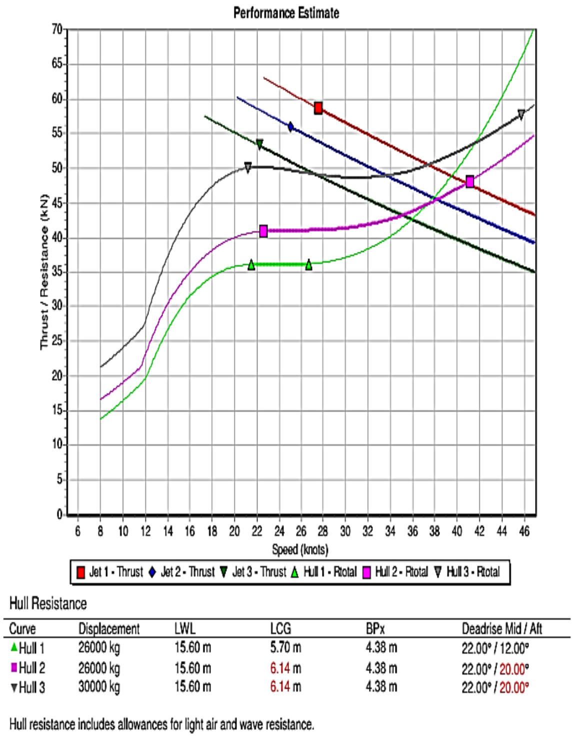


Figure 3: HJ 403 standard impeller power vs. RPM curves (C. W. F. Hamilton & Co. NZ 2019)

Figure 4 depicts a considerable resistance rise near 20 knots (planning of craft), with a wide flat region of the same hull resistance up to 32 knots. Naval application with extreme manoeuvres as the primary design objective is required to operate the boat above the drag "hollow". The initial analysis revealed that the boat parameter improvement is a necessity. Further, the traditional approach does not allow the visibility of the acceleration reserve and efficiency of this operation. Thus, the authors opted for a complete system analysis with "universal waterjet coefficients" for the steady-state performance with boat acceleration study, as promoted in their studies (MacPherson, 1999). Thereby, possible modifications were evaluated in hull form in line with performance enhancement. This numerical model provided the characteristics that amount to (a) Parametric - simple and clear define parameters, (b) Universal - applicability to all waterjets, and (c) Computational easiness - easily employed in computer codes.



Hull Resistance

Curve	Displacement	LWL	LCG	BPx	Deadrise Mid / Aft
▲Hull 1	26000 kg	15.60 m	5.70 m	4.38 m	22.00° / 12.00°
■Hull 2	26000 kg	15.60 m	6.14 m	4.38 m	22.00° / 20.00°
▼Hull 3	30000 kg	15.60 m	6.14 m	4.38 m	22.00° / 20.00°

Hull resistance includes allowances for light air and wave resistance.

Figure 4: HJ 403 Waterjet thrust and hull drag curves (C. W. F. Hamilton & Co. NZ 2019)

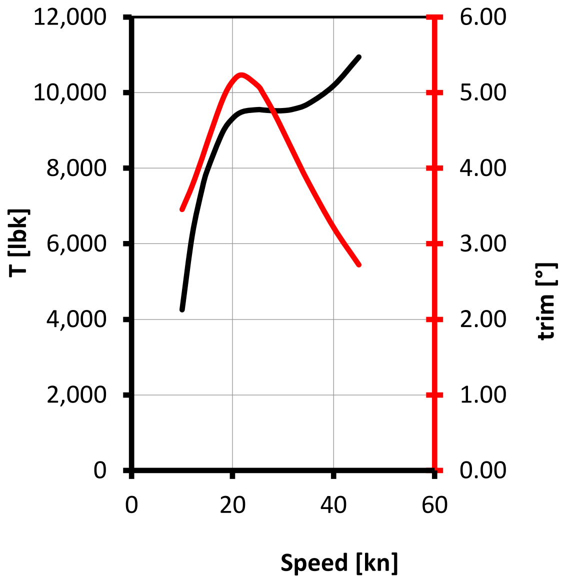


Figure 5: Boat trim conditions

4. RESULTS AND DISCUSSION

Three coefficients were utilized by authors to transform the above-mentioned commonly available waterjet information provided by respective manufacturers into a non-dimensional exemplification of the traditional plots.

4.1. Speed-Thrust-Power coefficients

Figure 4 depicted the thrust curve that was collapsed by authors into two coefficients, called C_P (power coefficient) and C_T, (thrust coefficient) are marked in Figure 6. Since thrust is developed in a waterjet due to the change in the momentum of the water that accelerates through a tunnel, the Thrust could be defined as follows.

$$Thrust = \rho . V_{jet} . A_n . (V_{jet} - V_S) \qquad \text{Equation 04}$$

Since the velocity of the waterjet stream can be defined in terms of ship speed using a coefficient, an equation could be developed to obtain C_T. For a given ship speed, the power of the craft is given by the following equations.

$$Power = Thrust \, . V_S \qquad \text{Equation 05-I}$$

$$Power = \rho . V_{jet} . A_n . (V_{jet} - V_S) . V_S \qquad \text{Equation 05-II}$$

Using the same process for C_T a coefficient for the power of the craft, Cp could be developed.

$$Cp = \frac{P}{\rho . A_n . {V_S}^3} \qquad \text{Equation 06}$$

$$Ct = \frac{T}{\rho . A_n . {V_S}^2} \qquad \text{Equation 07}$$

Where, P = shaft power, T = thrust, ρ = mass density of water, A_n = nozzle discharge area, V_s = ship velocity, and V_{jet} = Waterjet stream velocity.

Large numbers for C_T and C_P indicate high thrust with low speed, the waterjet's equivalence of the "bollard pull" area. Proposed waterjet manufacturer's charts and geometric data were used to calculate the coefficients as follows to identify the suitability of operation relating to Figure 6. Since the operating range of CPC (35 knots) lies in the region of small X and Y values, waterjet selection could be justified.

Table 2: Water Jet Parameters and Coefficients

Parameter	Value
Nozzle area (A_n)	0.126 m^2
Impeller diameter (D_i)	0.400 m
Speed (V_s)	35 kts (18.00 m/s)
Power (P)	1,500 kW
Thrust (T)	45,000 N
C_T	1.077
C_P	1.99

Further, coefficients were employed to determine one of the most critical parameters jet efficiency, η_{JET}, which equals C_T/C_P (and also TVs/P). Figure 7 provides the plot of η_{JET} vs. C_P. Thus, the arrival of a clearly defined efficiency peak is a possibility. The operating region of the CPC is at an efficiency of 0.56, almost reaching the peak efficiency as per Figure 7.

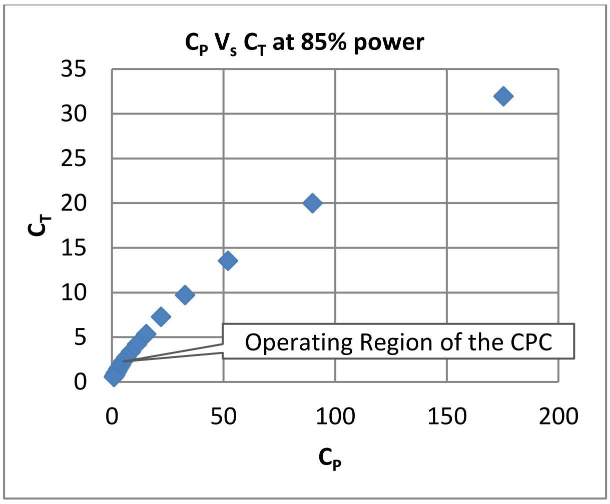


Figure 6: C_T vs C_P plot

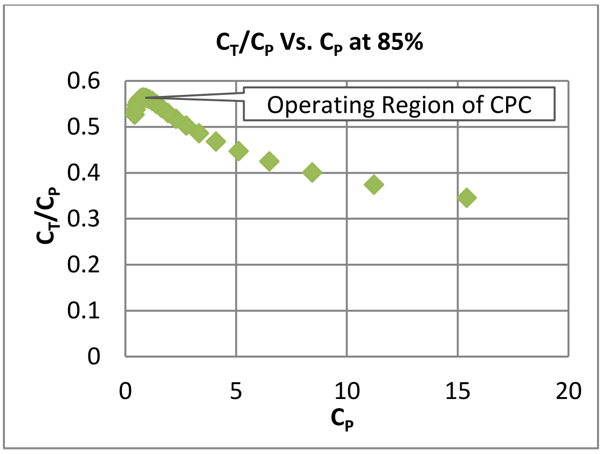


Figure 7: C_P/C_T (η_{JET}) vs C_T plot

One research outcome of employing "universal waterjet coefficients" was the ability to identify the operational location of maximum jet efficiency. Now it is probable to select the best-performing waterjet with the greatest efficiency. A "maximum efficiency" track was the plot in Figure 8. The authors' design is closer to the maximum possible waterjet efficiency. Thus, the selected waterjet with peak efficiency at a higher speed was the requirement. This outcome promotes an adequate analysis that shall combine engine RPM analysis, an objective of the study.

4.2. Power-RPM coefficient

The authors studied the applicability to employ coefficient KQ (for a conventional propeller) to be suited for the water jet approach, instead of torque employing power, the formula would be:

$$K_Q = \frac{P}{2\pi\rho n^3 D_i^5} \qquad \text{Equation 08}$$

Where, P = shaft power, ρ = mass density of water, n = shaft speed, Di = impeller diameter

The torque coefficient KQ is a function of a particular standard impeller and is a fixed number for a separate impeller. Thus, Figure 3 represent the KQ calculation with data. This approach is useful as this stage shaft power, diameter, and velocity of advance are known. For impeller type 90 on the Power-RPM curve (Figure 3). Power (P) = 765 (85% Power), RPM (n) = 2150 rpm. Thus, KQ = 0.258. With the calculated KQ value, as marked in Figure 2 (with a KQ/J^3) on the optimal efficiency line to find the RPM envelope. Figure 9 depicts the availability of full-rated engine power absorbed by propulsor /waterjets.

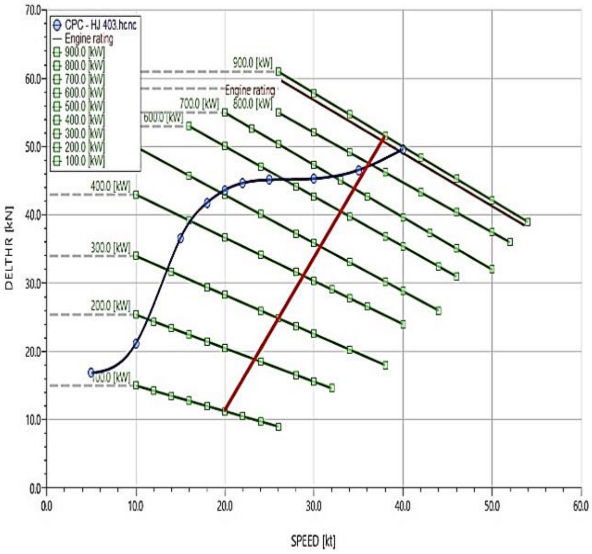


Figure 8: HJ 403 Waterjet thrust and hull drag curves upon parameter improvement

4.3. The power-RPM curve

The matching of the marine engine with the selected waterjet with respect to the entire operation envelope is required to determine swift operation. This study demonstrates the achievement of the ‘Hitting the Corner’ criterion and provides a glimpse of the superiority of the design in terms of manoeuvrability. Figure 10 depicts the’ prediction of vessel acceleration comparison values.

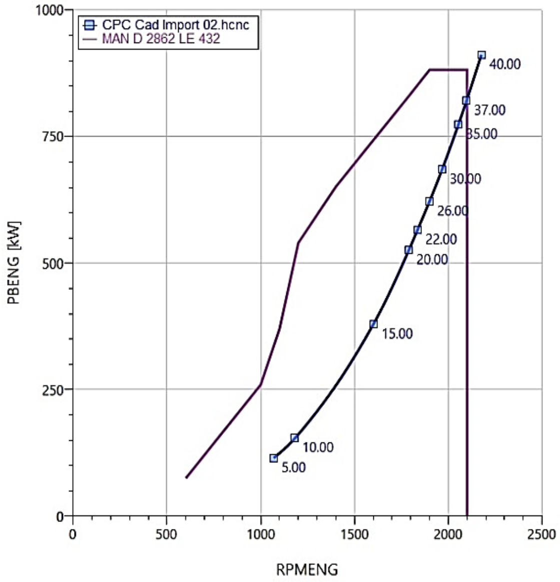


Figure 9: Power vs. RPM Curves

4.4. Vessel acceleration

The universal waterjet coefficients simplified the various powering situations with computer simulations. The boat acceleration analysis was conducted and depicted in Figure 10. The acceleration analysis with a similar waterjet model from another manufacturer was plotted to examine the variance in time-to-speed for both choices. The waterjet selected by the authors took approximately 20 seconds while the other unit reached the same speed in 22 seconds, to reach 30 knots. To reach the design speed of 35 knots, the selected waterjet unit took only 32 seconds, while the other unit spent 62 seconds. This information is critical since the time to reach the maximum speed is of vital importance to a patrol boat. Hence, this approach of assessing the waterjet performance using 'universal waterjet coefficients' is justified.

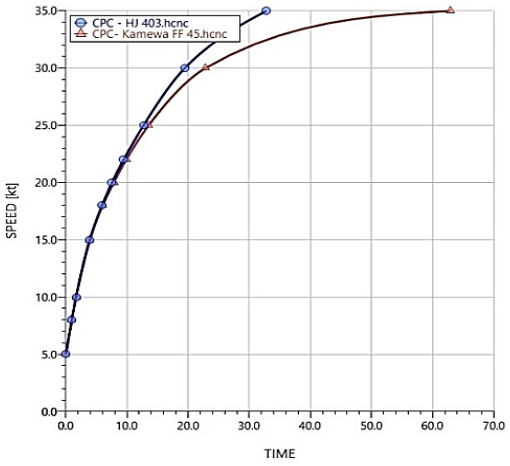


Figure 10: Vessel acceleration comparison

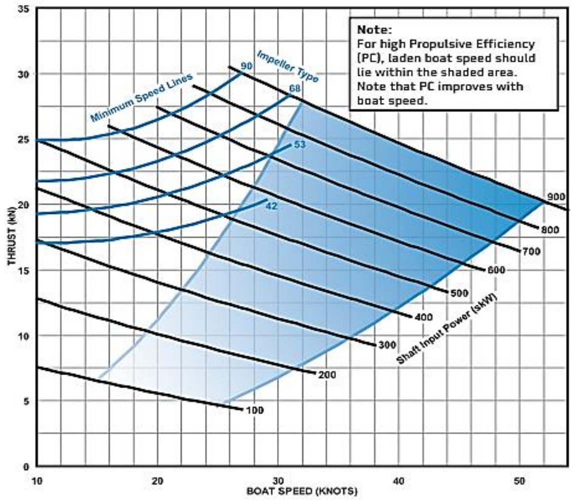


Figure 11: Cavitation study (C. W. F. Hamilton & Co. NZ 2019)

The cavitation regime is depicted in Figure 11 and found that the design areas are well clear of the cavitation region.

5. CONCLUSION

Even though most waterjets look suitable for an any application, however are usually optimized by the manufacturer for a particular application, based on the speed. The selection of appropriate type of waterjet is the responsibility of the boat building yard and Naval Architects. The actual example of naval petrol craft design discussed during the study demonstrates the reason that naval architects need to have dependable techniques to assess waterjet performance. Traditional methods are beneficial to ensure that a particular waterjet will meet some performance requirements, yet the approach is usually inadequate for many virtual assessments of waterjet performance on efficiency, acceleration, entire RPM envelop operation, and so forth. The study demonstrated how to employ universal waterjet coefficients as a methodology, which guides and points the way to the accurate propulsor choice. As the outcome of the study, the correct operation point/match of the hull, propulsor, and engine was found.

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