Hydrodynamic Performance Characteristics of Open and Ducted DP/DT Thrusters

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Hydrodynamic Performance Characteristics of Open and Ducted DP/DT Thrusters

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Abstract

Existing available systematic propeller tests provide useful data base to help the designer understand the factors which influence propeller performance under various operating conditions. They also provide design diagrams, and/or charts, which will assist in selecting the most appropriate dimensions of actual propellers to a particular ship applications. Some information pertaining to stationary operation is not explicitly given by these tests. Typical examples of stationary or low speed applications includes tug boats, fishing vessels, dynamic/ tracking and heavy lift vessels. This work emphasizes the importance of parameters necessary required to assess the performance of thrusters in the stationary or low speed mode using available systematic thruster tests.

Open propellers hydrodynamic performance was first examined at low or zero advance speeds based on a number of performance criteria. These are the magnitude of both thrust (or Bollard pull) generated and torque consumed, and their derivative with respect to axial flow. In addition to thrust to power ratio or thruster effectiveness. These criteria was assessed in relation to thruster geometrical particulars (blade area, pitch, number of blades, …etc).

The above parameters were also assessed for ducted propellers and a comparison was made using the open propellers as basis. Effects of duct particulars were examined and contributions of nozzle to the overall performance were pointed out. Reasons for differences were discussed

NOMENCLATURE

A_E/A_o	expanded blade area ratio
A_o	propeller disk area
A_1	upstream capture area
A_4	downstream slipstream area
C	regression coefficient
D	propeller diameter
FOM	Figure of Merit
g	gravitational acceleration
J	advance Coefficient
K_T	thrust coefficient
K_{T0}	thrust coefficient at zero advance

K'_T	thrust coefficient derivative w. r. t. advance coefficient
K_Q	torque coefficient
K_{Q0}	torque coefficient at zero advance coefficient
K'_Q	torque coefficient derivative w. r. t. advance coeff
$\dot{m}$	mass flow rate to the propeller-nozzle system
n	thruster rotation rate
p	pressure
P	propeller pitch
Q	torque
Rn	Reynolds number
T	thrust
V_1	Upstream Axial velocity to the propeller
V_2	Axial velocity just before the propeller plane
V_3	Axial velocity just after the propeller plane
V_4	Axial velocity far downstream
x	Coordinate along the propeller axis
z	Coordinate in the vertical direction
Z	number of blades
γ	specific weight $=\rho g$
ρ	mass density
τ	Propeller thrust ratio

Introduction

Propulsion systems used for dynamic positioning or dynamic tracking DP/DT applications constitute practically of thrusters with augmentation device, and or an azimuthing capability. The augmentation device known as nozzles, shrouds, or ducts were originally introduced as guard to eliminate propeller noise and unfavorable effects on water bed. Later, it was employed for generating additional thrust particularly at low speeds. Situations requiring higher thrust include bollard pull, fishing, dynamic positioning and tracking. Propellers in nozzles may be fixed or controllable pitch. Extensive work was undertaken to introduce nozzles with enhanced and high efficiency performance. However, it is quite known that the ability of nozzles to produce additional thrust depends on the propeller itself. Hence, it was thought it would a better approach if more effort is exerted to understand the propeller action particularly at static and low speed modes. It was decided in this work to examine the performance of a homogenous group of fixed pitch open propellers and document the results to be used as a basis for comparison with other more sophisticated propulsion systems.

Propeller Nozzle system Performance at zero Advance Speed

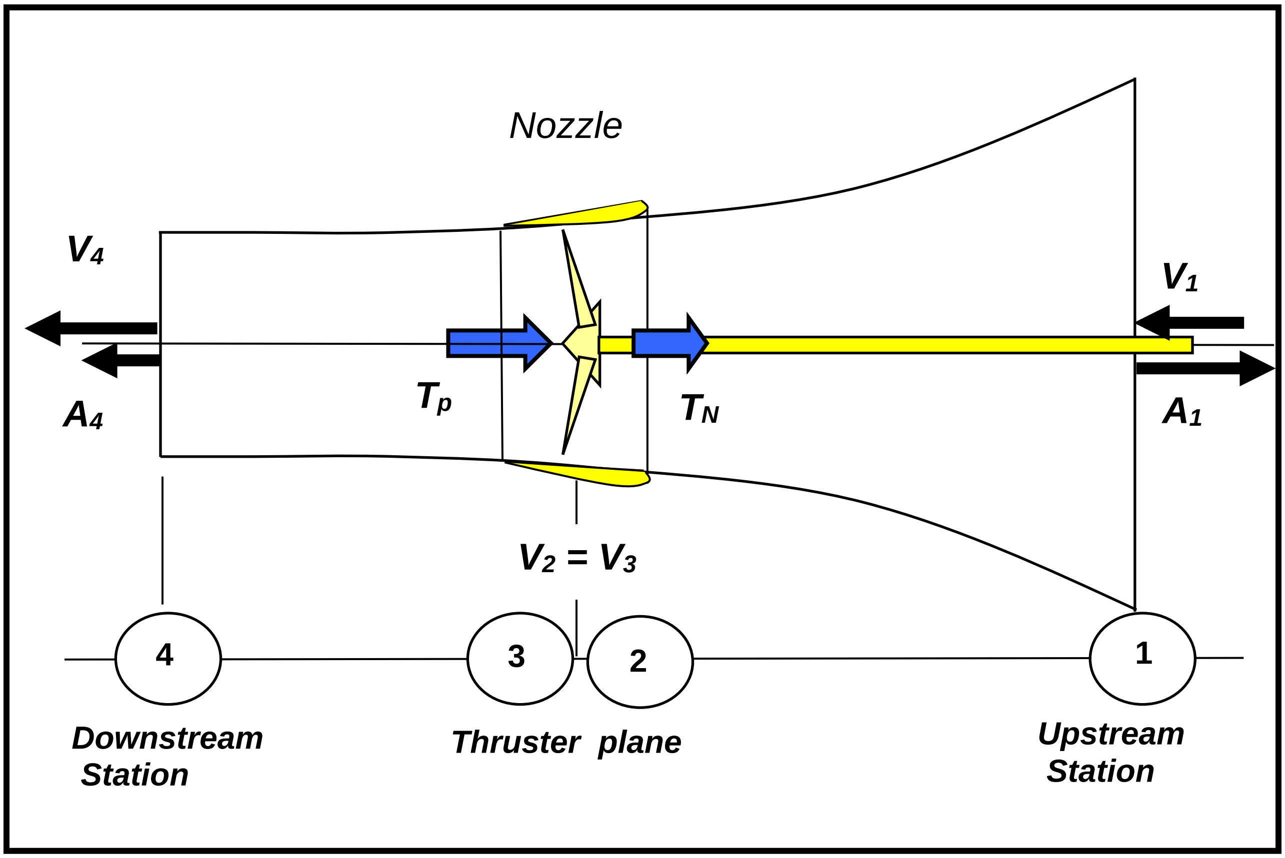


Figure (1) Control Volume enclosing propeller-nozzle system

Considering the control volume for the nozzle thruster combination shown on Figure (1), the mass flow rate through the propeller nozzle system is:

$$\dot{m} = \rho V_2 A_0 \qquad (1)$$

The total propeller thrust *T* (or Bollard Pull) can be written as:

$$T = T_P + T_N \qquad (2)$$

where T_p is the propeller thrust and T_N is the duct thrust. Equation (2) can be written in non-dimensional form as;

$$K_T = K_{T_P} + K_{T_N} \qquad (3)$$

where the non-dimensionalization factor is $\rho n^2 D^4$.

The thrust force as obtained from momentum principle will be :

$$T = \dot{m}(V_4) = \rho A V_2 V_4 \qquad (4)$$

Pressure difference across the propeller plane is:

$$\Delta p = \frac{T}{A_0} = p_3 - p_2 \qquad (5)$$

Writing the Energy Equations (or Bernoulli's equation in this case) between the upstream stations (1) and the station just before the thruster plane (2), we get:

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} \qquad (6)$$

Here the elevation terms z_1 and z_2 are equal, hence:

$$\frac{p_2}{\gamma} = \frac{p_1}{\gamma} + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) \qquad (7)$$

Again the Bernoulli's equation is applied between the downstream station (4) and the station just after the thruster plane (3), yields:

$$\frac{p_3}{\gamma} = \frac{p_4}{\gamma} + \left(\frac{V_4^2}{2g} - \frac{V_3^2}{2g}\right)$$

(8)

Using equations (5) and (6) the pressure difference across the propeller plane is:

$$\frac{\Delta p}{\gamma}=\frac{p_4}{\gamma}+\left(\frac{V_4^2}{2g}-\frac{V_3^2}{2g}\right)-\frac{p_1}{\gamma}-\left(\frac{V_1^2}{2g}-\frac{V_2^2}{2g}\right) \qquad (9)$$

The up and downstream stations are taken far enough for the pressure to completely recover ; hence $p_1=p_4$, hence;

$$\Delta p=\frac{\rho}{2}\left(V_4^2-V_1^2\right) \qquad (10)$$

,and by definition V_1 is zero in the bollard condition; hence

$$\Delta p=\frac{\rho}{2}V_4^2 \qquad (11)$$

Substituting equation (11) into equation (5); the thrust expression is found as:

$$T=\frac{\rho}{2}V_4^2A_0 \qquad (12)$$

Equating the two expressions for thrust as per momentum and energy equations we get:

$$T=\frac{\rho}{2}V_4^2A_0=\rho A_0V_2V_4 \qquad (13)$$

Which yields

$$V_4=2V_2 \qquad (14)$$

Using the relation arrived at in equation (14) and substitute in equation (4)

$$T_p=\rho A\frac{V_4^2}{2}$$

(15)

The corresponding energy and pressure variations along the propeller axis are depicted on Fig. (2)

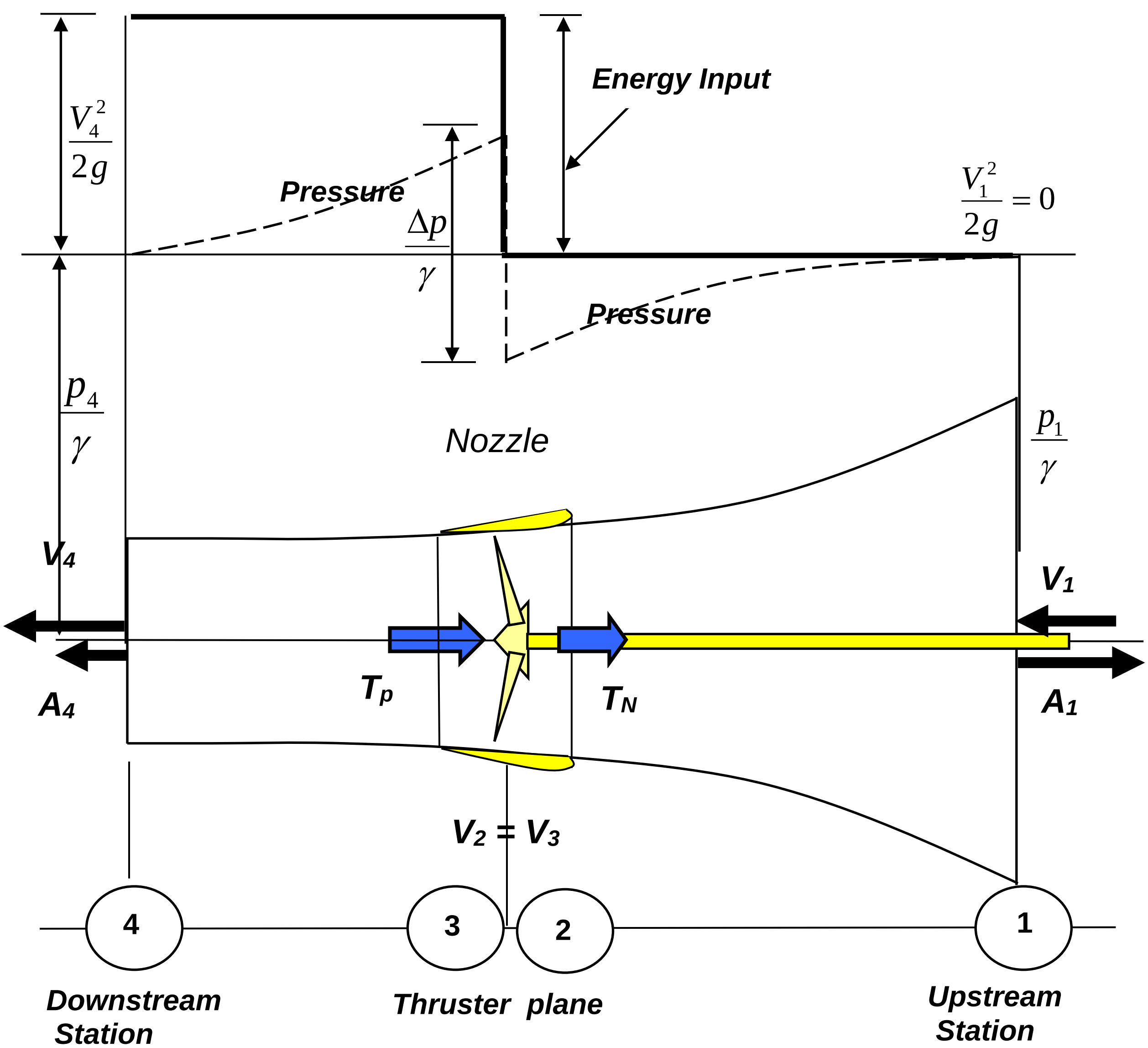


Figure (2) Energy variation along the thruster axis

Now, assume the propeller contributes ion to the total thrust through the ratio:

$$\tau = \frac{T_p}{T} \qquad (16)$$

Substituting from the definition in (16) into equation (15)

$$T_p = \tau T = \rho A \frac{V_4^2}{2} \qquad (17)$$

Using the coefficient K_T to represent the nondimensional total thrust

$$K_T = \frac{T}{\rho n^2 D^4} \qquad (18)$$

And substituting (18) into (17)

$$\tau \rho n^2 D^4 K_T = \rho \frac{\pi D^2}{4} \frac{V_4^2}{2} \qquad (19)$$

an expression for the induced velocity V_4 can be arrived at as

$$\frac{V_4}{nD} = \sqrt{\frac{8\tau K_T}{\pi}} \qquad (20)$$

Again using the ratio "τ" to solve for the induced velocity V_2

$$\tau = \frac{T_p}{T} = \frac{\rho A \frac{V_4^2}{2}}{\rho A V_2 V_4} = \frac{V_4}{2V_2} \qquad (21)$$

Substituting equation (20) into (21) , hence

$$\tau = \frac{V_4}{2V_2} = \frac{nD\sqrt{\frac{8\tau K_T}{\pi}}}{2V_2}$$

Which yields

$$\frac{V_2}{nD} = \frac{1}{2\tau}\sqrt{\frac{8\tau K_T}{\pi}} \qquad (22)$$

The induced velocity in the plane of the propeller disk, V_2, is considered as the sum of the ‘nozzle-induced velocity’, V_{2N}, and the ‘propeller-induced velocity’, V_{2p}:

$$V_2 = V_{2p} + V_{2N} \qquad (23)$$

and the ratio between the two components is assumed as:

$$\frac{V_{2N}}{V_{2p}} = \frac{1-\tau}{\tau} \qquad (24)$$

The terms in equation (23) is normalized by (nD) and the sum is equated to (22)

$$\frac{V_2}{nD} = \frac{V_{2N}}{nD} + \frac{V_{2P}}{nD} = \frac{1}{2\tau}\sqrt{\frac{8\tau K_T}{\pi}} \qquad (25)$$

Solving equations (24) and (25) to get the separate contributions as:

$$\frac{V_{2P}}{nD} = \frac{1}{2}\sqrt{\frac{8\tau K_T}{\pi}} \qquad (26)$$

$$\frac{V_{2N}}{nD} = \frac{1-\tau}{2\tau}\sqrt{\frac{8\tau K_T}{\pi}} \qquad (27)$$

The propeller induced velocity ratio V_{2p}/V_4 will remain (in theory) constant regardless the "τ" value. This also applies to the product (V_2V_4) as shown in equation (28)

$$\frac{T}{\rho A} = V_2 V_4 \qquad (28)$$

The velocity variation along the propeller axis are shown on Fig. 3

Figures (4) and (5) show the effect of splitting the total required thrust between the propeller and the nozzle on the induced velocities at the propeller and downstream stations.

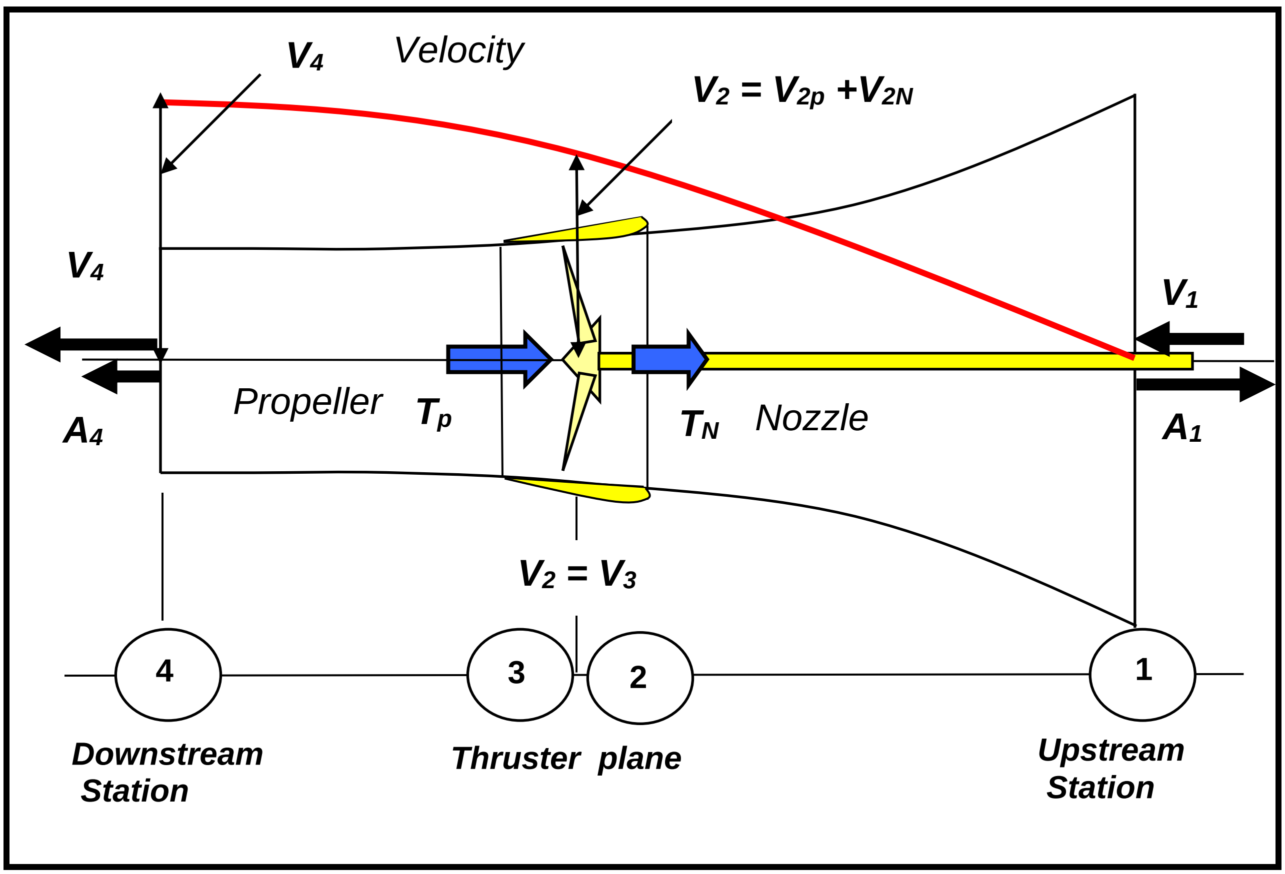


Figure (3) Velocity Variation along the thruster at zero advance speed

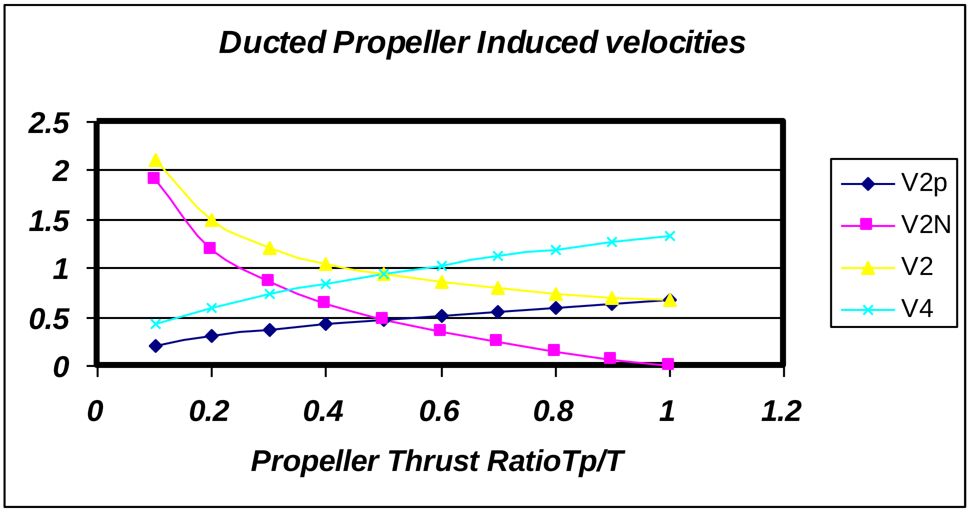


Figure (4) Induced velocity variations with propeller thrust ratio Tp/T at zero advance for the Ka 4.70 propeller- nozzle system

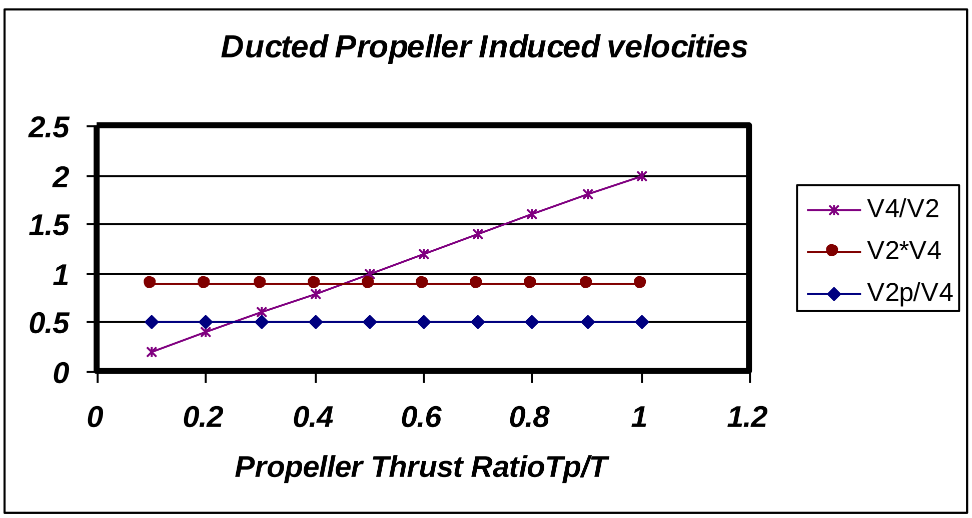


Figure (5) Induced velocity ratios variations with propeller thrust ratio Tp/T at zero advance for the Ka 4.70 propeller- nozzle system

The thruster nozzle system "Efficiency" or effectiveness at static condition can be derived from a Figure of merit (FOM) given by:

$$FOM = \frac{(K_{T0})^{1.5}}{\pi^{1.5} K_{Q0}} \tag{29}$$

This is an important factor in the selection of thruster devices for vessels to be used for ocean exploration, tugs, fishing ships, and dynamic positioning applications. It reflects the thrust – power relationship at zero forward speed.

K_{T0}, and K_{Q0} in equation (29) are thrust, and torque coefficients at static conditions defined as:

$$K_{T0} = \frac{T_0}{\rho n^2 D^4} \tag{30}$$

$$K_{Q0} = \frac{Q_0}{\rho n^2 D^5} \tag{31}$$

This efficiency coefficient can be used as a direct measure for the effectiveness of propulsion devices at the static condition (zero forward speed), if systems with the same diameter and power are considered.

Thrust and torque coefficients are obtained from open water tests on model propellers in water tunnels and presented in graph form. They are usually functions of number of blades, pitch diameter ratio, Reynolds number, cavitation number, and advance coefficient.

In addition to the figure of merit given in equation (29), a number of other criteria is usually devised to assess the performance of thrusters at zero or low speeds. These are : thrust and torque coefficients at zero speed as given in equations (30) and (31) , and their derivatives with respect to advance coefficients at zero advance. These derivatives are defined as:

$$K'_T = \left.\frac{dK_T}{dJ}\right|_{J=0} \quad (32)$$

$$K'_Q = \left.\frac{dK_Q}{dJ}\right|_{J=0} \quad (33)$$

where J is the advance coefficient defined as:

$$J = \frac{V}{nD} \quad (34)$$

These parameters can be picked up using performance open water data or graphs resulting from model testing.

In order to examine the functional dependence of these parameters on thrusters system geometry; particularly pitch diameter ratio, number of blades, blade area ratio, type of nozzle, use is made of the existing systematic data on propeller models.
Several key systematic series exist, developed for fixed pitch, controllable pitch propellers, ducted propellers, etc.

In this work, a ducted, fixed pitch type thruster is selected for examining their performance particularly at static condition. Earlier work Ref (1) was carried out by the authors on the same propeller but in the unducted configuration. The results will be used here as basis to illustrate the effect of the duct on the overall performance.
Reference here will be directed towards Wageningen B-screw series (Ref 2, 3, and 4) as it is considered the most extensive and widely used propeller series. The Wageningen case selected is a 0.7 blade area ratio, 4 bladed propeller in a 19A nozzle.

The regression expressions reported by Oosterveld and van Oossanen (Ref. 6), also reproduced in (Ref. 7) for Wageningen and other Series are used to calculate the thrust, torque, derivatives, and the associated figure of merits at static mode,. The regression equations for open propellers are given in equations (35) and (36) at a Reynolds number of 2×10^6 .

$$K_T = \sum_{n=1}^{n=39} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \quad (35)$$

$$K_Q = \sum_{n=1}^{n=47} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \quad (36)$$

Regression polynomials have been also developed to express K_T, K_{TN} and K_Q as functions of *P/D and J* .for ducted propellers. The form of the polynomials are given in equations (37), (38), and (39)

$$K_T = \sum_{x,y=0}^{6} A_{x,y} (P/D)^x (J)^y \quad (37)$$

$$K_Q = \sum_{x,y=0}^{6} B_{x,y} (P/D)^x (J)^y \quad (38)$$

$$K_{TN} = \sum_{x,y=0}^{6} C_{x,y} (P/D)^x (J)^y \quad (39)$$

where the coefficients *A*, *B* and *C* are given in Ref . (7) for the 19A and 37 duct profiles with the Ka 4–70 propeller.

Open Propeller Performance

Before examining the performance characteristics of ducted propellers in static conditions, results pertaining to open propellers will be reported here for the sake of comparison and reference basis. The open propeller case as mentioned earlier will be a B4.70 thruster. The performance parameters will reported for a range of P/D ratio of 0.6 to 1.4.

Figure (6) shows thrust, torque and FOM coefficients variations with pitch/diameter ratio at zero advance. Thrust and torque derivatives with respect to advance coefficient variations with pitch/diameter ratio at zero advance are given in Figure (7). Maximum effectives or figure of merit occurs at low pitch diameter ratio. It falls down as the pitch diameter ratio gets higher. The open propeller Finally, the induced velocity at the rotor plane due to the propeller action variations with pitch/diameter ratio at zero advance are displayed in Figure (8).

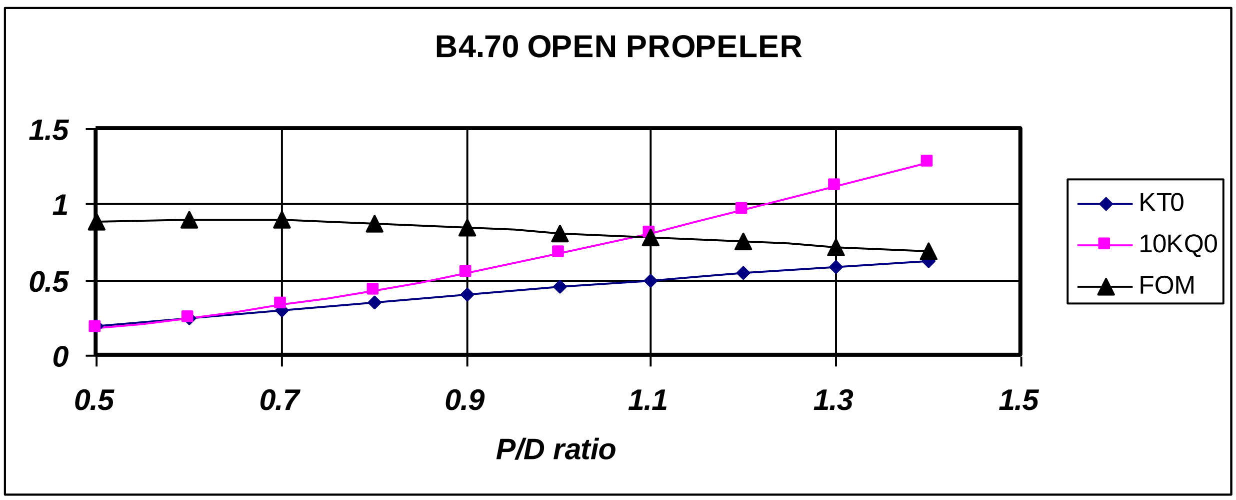


Figure (6) Thrust ,Torque and FOM variations with pitch/diameter ratio at zero advance for the B4.70 open propeller

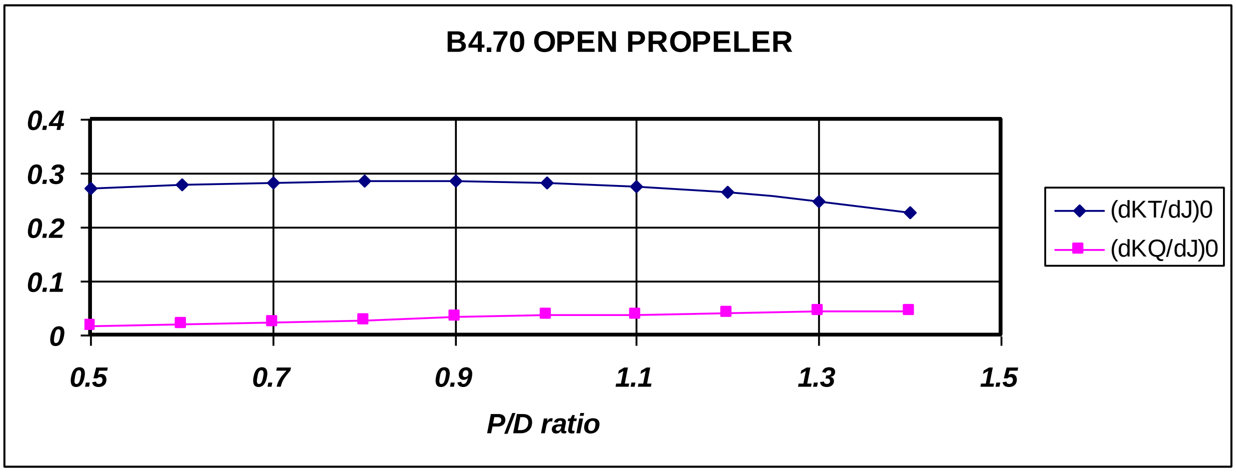


Figure (7) Thrust and Torque derivatives with respect to advance coefficient variations with pitch/diameter ratio at zero advance for the B4.70 open propeller

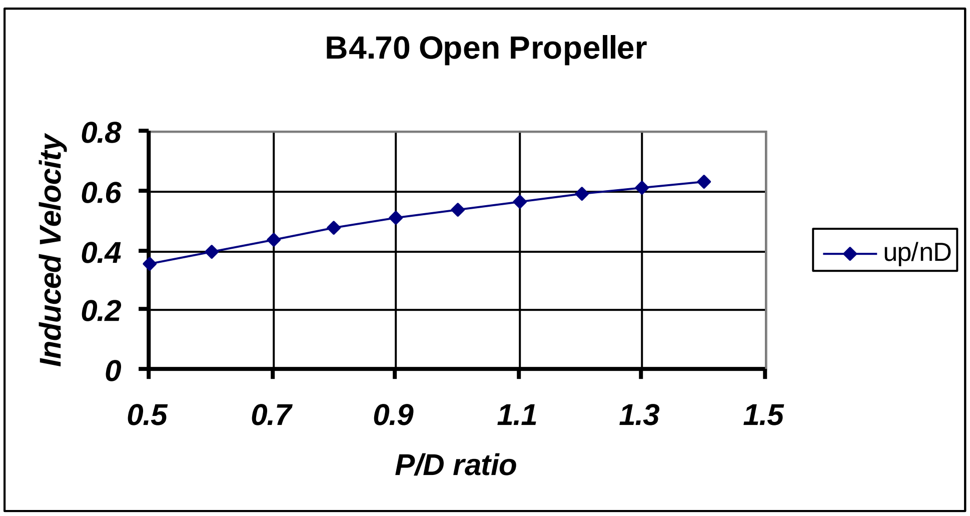


Figure (8) Induced velocity at the propeller plane variations with pitch/diameter ratio at zero advance for the B4.70 open propeller

Ducted Propeller Performance

The same 4.70 propeller as fitted with 19A nozzle was examined over the same range of pitch diameter ratio. Figure (9) shows propeller thrust, nozzle thrust, torque and FOM variations with pitch/diameter ratio at zero advance. The maximum effectiveness at bollard conditions occurs at pitch diameter ratio of 1.0 which is a little higher the open propeller case. The torque coefficient is, of course, not split into components since the propeller itself absorbs all of the torque of the engine. Figure (10) displays derivatives of thrust and torque with respect to advance coefficient variations with pitch/diameter ratio at zero advance. The induced velocity components due to both propeller and nozzle actions at the propeller plane variations with pitch/diameter ratio at zero advance are given in Figure (11).

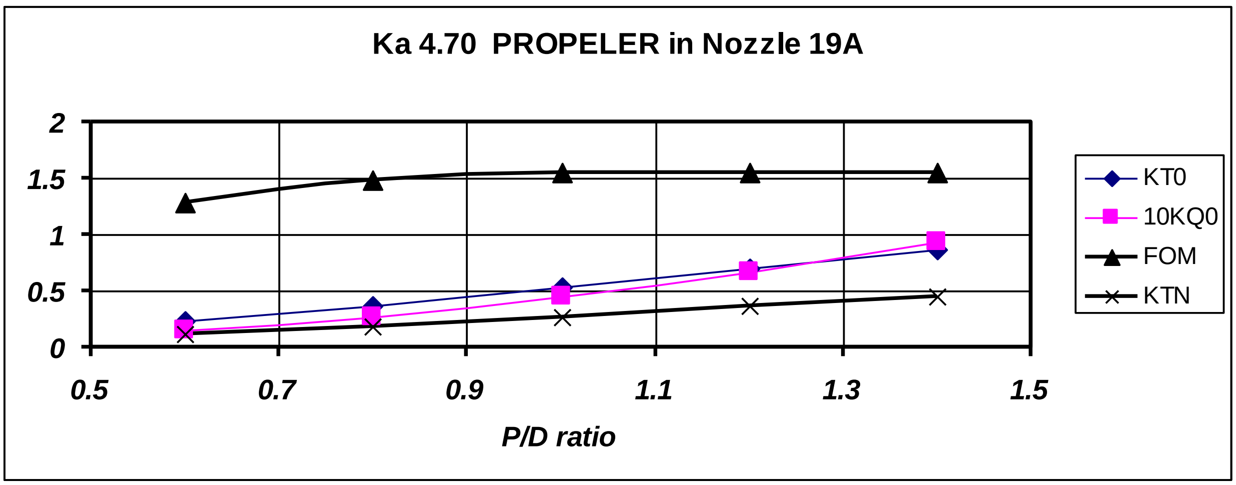


Figure (9) Thrust ,Torque and FOM variations with pitch/diameter ratio at zero advance for the Ka 4.70 propeller in a 19A nozzle

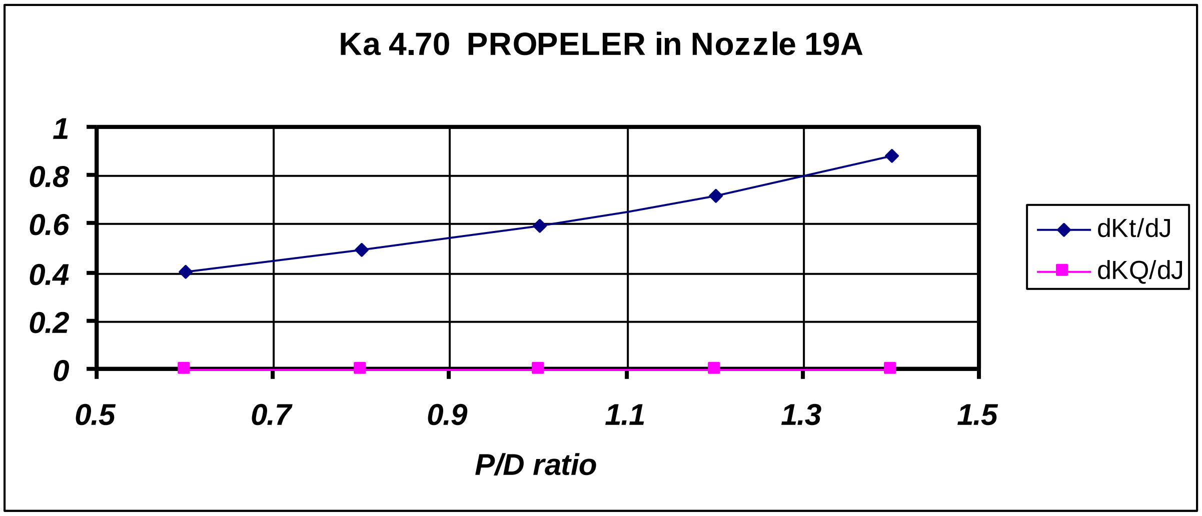


Figure (10) Thrust and Torque derivatives with respect to advance coefficient variations with pitch/diameter ratio at zero advance for Ka 4.70 propeller in a 19A nozzle

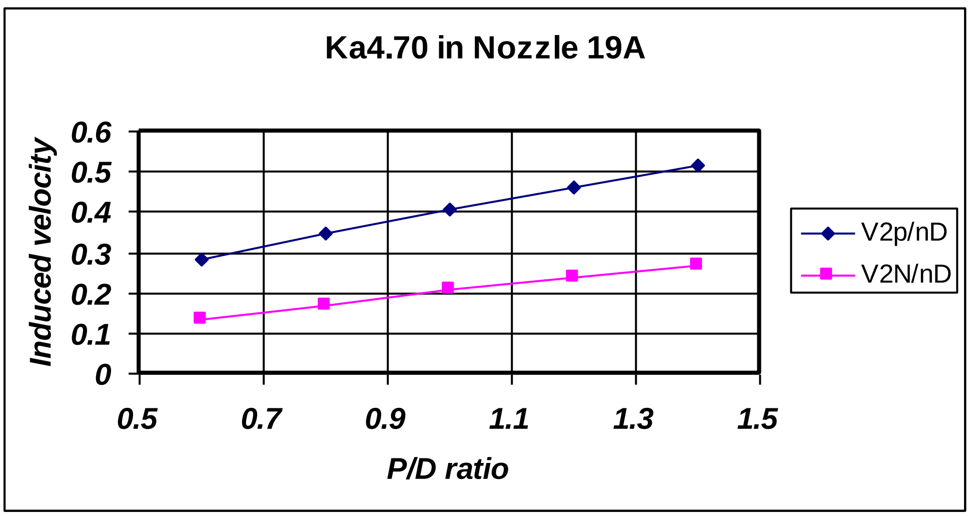


Figure (11) Induced velocity at the propeller plane variations with pitch/diameter ratio at zero advance for the Ka 4.70 propeller in a 19A nozzle

Comparison of ducted propeller system with open propeller

Having presented the main performance parameters of both open and ducted propellers, it would be useful to discuss the main differences between the two propulsion systems. Figure (12) shows thrust of a ducted propeller as compared to same propeller with no duct at different pitch/diameter ratios at zero forward speed. The results are displayed in ahead and astern modes. The ducted propeller systems in the ahead mode generates higher thrust the same propeller in the open mode for the whole pitch diameter ratio. The thrust increase ratio is higher at larger pitch diameter ratio indicating nozzle effectiveness at high pitch diameter ratios. About 40% increase in thrust value at P/D of 1.4 was reported for the case under consideration. The nozzle/propeller system performs very poorly in astern direction. Probably this is because the tested case is designed for ahead operations. The values in Figure (12) indicate that the ducted propeller develops only approximately 60% of the ahead thrust while operating in reverse. It is known that open propeller develops in reverse a thrust of 70% to 80% of the thrust ahead. Nozzle geometry optimization may be required to improve reverse thrust performance.

Ducted propellers absorbs less torque than open propeller in both ahead and astern operations as shown in Figure (13). The torque difference between astern and ahead is not quiet significant.

Ducted propellers thrust sensitivity to variations in forward speeds at zero advance is displayed on Figure (14) over a range of pitch diameter ratios. Ahead and reverse operations modes are displayed on the same graph. The results indicate that the ducted system is more sensitive to forward speed than open propeller. This sensitivity gets higher as the pitch diameter ratio increases. Same trend was observed for the reveres operation but to a less degree.

Ducted propellers torque sensitivity to variations in forward speeds at zero advance is almost negligible particularly in the ahead operations. This is not the case as in the reverse mode. This is displayed on Figure (15).

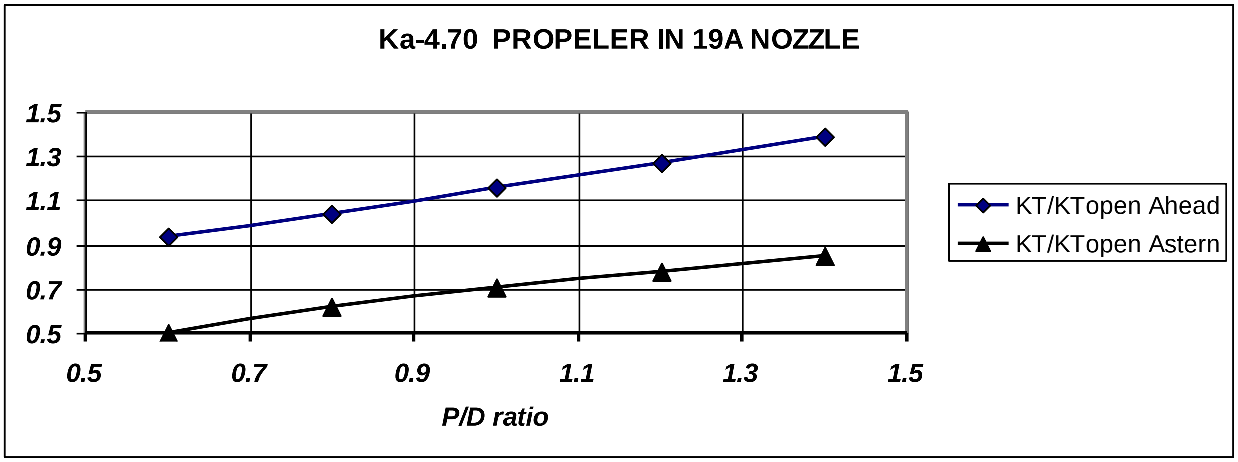


Figure (12) Thrust of ducted propeller as compared to open propellers values variations with pitch/diameter ratio at zero advance in ahead and astern modes

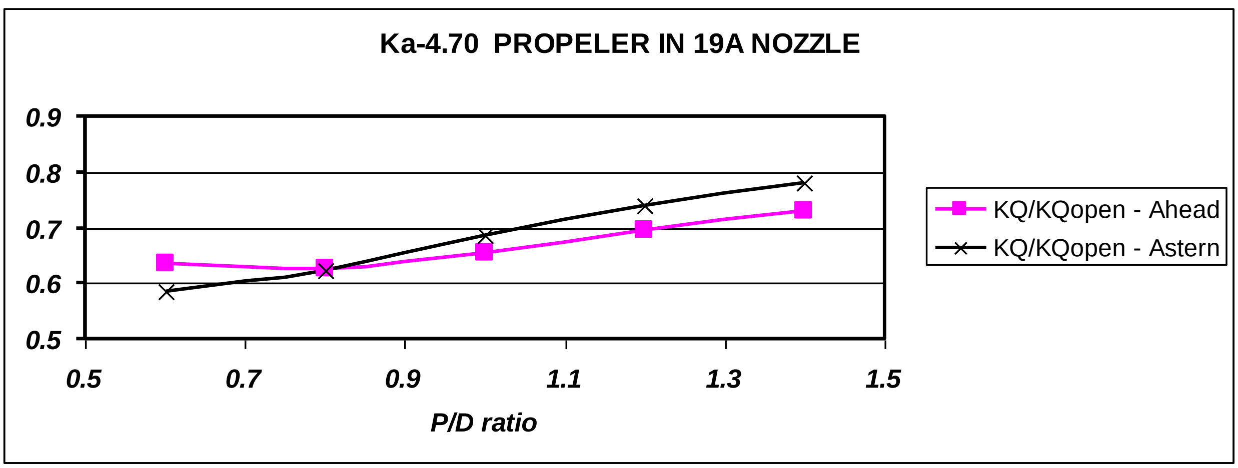


Figure (13) Torque of ducted propeller as compared to open propellers values variations with pitch/diameter ratio at zero advance in ahead and astern modes

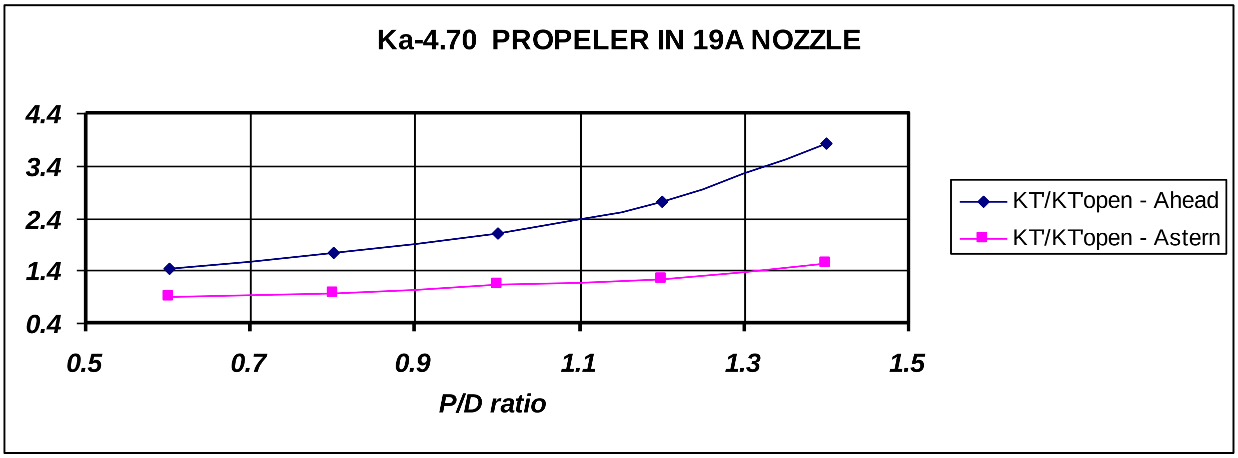


Figure (14) Thrust derivative of ducted propeller as compared to open propellers values variations with pitch/diameter ratio at zero advance in ahead and astern modes

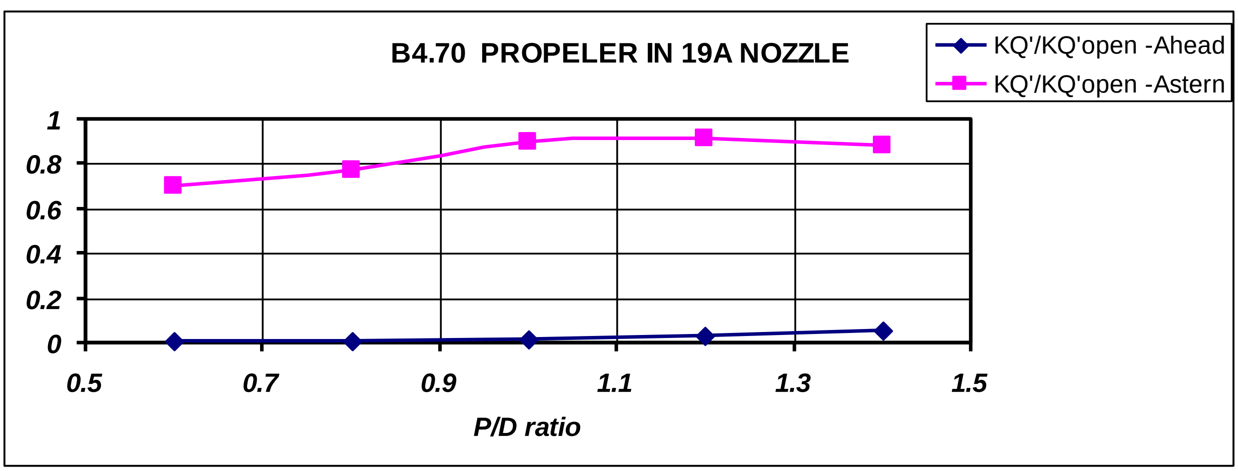
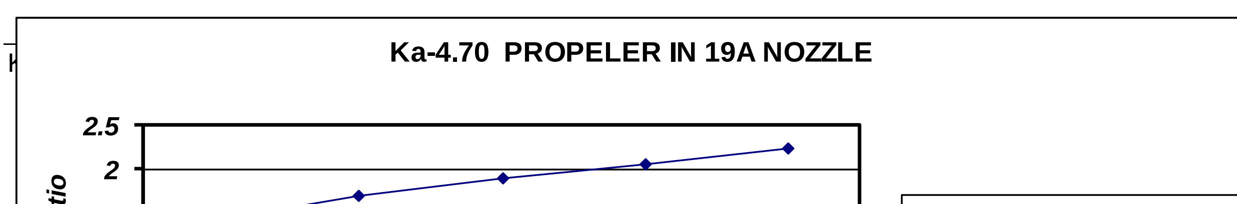


Figure (15) Torque derivative of ducted propeller as compared to open propellers values variations with pitch/diameter ratio at zero advance in ahead and astern modes



A comparison between figure of merits of a ducted propeller system as compared to open propeller is given in Figure (16). The comparison is shown for a range of pitch diameter ratio as well as ahead and stern operation. The figure indicated the affectivity of ducted system particularly at the ahead operation.

Figure (17) shows the nozzle contribution to the total system thrust at different pitch diameter ratios. The contribution is about 50% at the bollard pull or zero advance coefficient, condition, while the system is developing forward thrust. The contribution does not exceed 30% in the reverse mode. This finding is only for this nozzle type. Other nozzle performs better when designed for such applications.

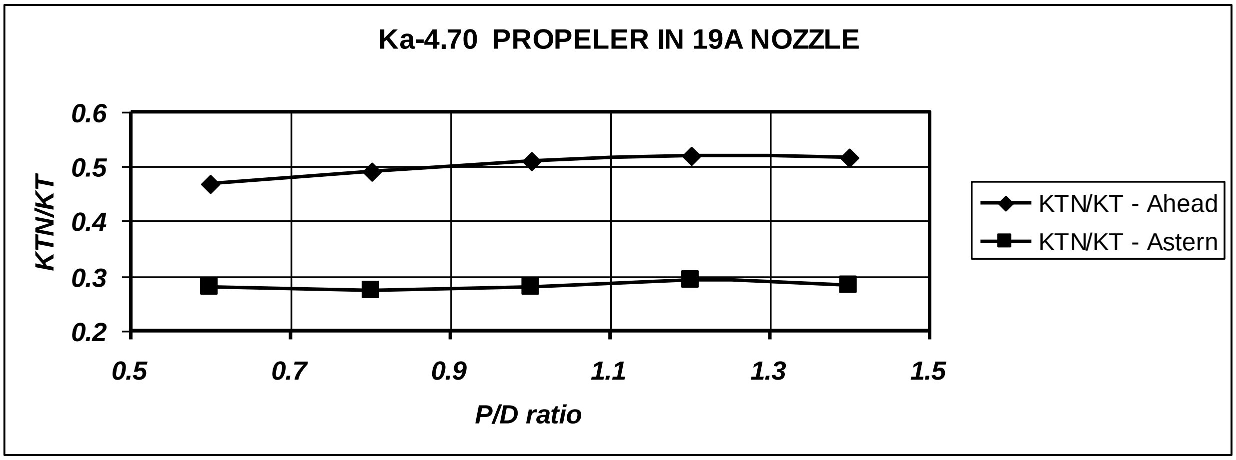


Figure (17) Nozzle Thrust ducted propeller as compared to open propellers values variations with pitch/diameter ratio at zero advance in ahead and astern modes

Conclusions and remarks

A number of conclusions and remarks are derived from the work carried out in this study. These are:

1. In comparison with an open- propeller the accelerating nozzle offers a very effective means of improving higher efficiency of a propulsion system at heavier loads. The nozzle itself produces a positive thrust. The nozzle propeller offers about 25% to 30% more total thrust than an open propeller at zero ship speed (bollard condition).
2. Open propeller, exhibits highest pulling efficiency at its lowest pitch diameter ratio. This implies a large diameter or low pitch. The highest merit coefficient is quite below the theoretical upper limit.
3. The bollard pull efficiency of a nozzle propeller is significantly higher than open propellers. However this efficiency drops down at low pitch diameter ratio

4. The nozzle propeller figure of merit curve excluding the low P/D region exhibits almost constant value regardless the pitch diameter value selection. This feature permits smaller diameter thruster and hence compactness and better space utilization. More useful comparison aspects between open, ducted , controllable pitch and contra rotating propellers can be found in Ref. (8)
5. The torque was found out to be insensitive to the sailing / current speed.
6. More detailed calculations for nozzles flow fields will defiantly help explaining some hydrodynamic aspects such as trailing vortices elimination at blade tips, amount of circulation about nozzles. This will results in designing and testing of new high efficiency nozzle-propeller integrated systems. Highlights on CFD on nozzles can be found in Ref. (9).

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