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Application and analysis of marine water jet propulsion

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Abstract

Water jets are common place in vessels needing to achieve speeds of 30+ knots where conventional propeller solutions are unable to overcome the associated issues of cavitation, which in turn can lead to thrust breakdown and material failure. Any vessel designed for high speed requires a low resistance and corresponding slender hull. The propulsor needs to also be capable of accepting a high level of power and hence for a given diameter a high power density. There is a very few papers about the application of water jet propulsion of different type of ship. Water jet propulsion is widely applied in small ship as well as different kinds of big ships which are elaborately discussed in this paper. Here is also discussed the mathematical analysis of different types of water jet inlet as well as over all view of water jet propulsion from early to present as. In this analytical study, the important design variables for water jet propulsion system are established and the theoretical relationships between these variables are derived. Bottom mounted water jet has additional sinkage of stern which is consequence of waterjet hull interaction effect and this effect discussed by various mathematical parameters as well as with graphical presentation.

Key Words: *Water jet propulsion, waterjet-hull interaction, hydrofoil, T-craft, SES (surface effect ship).*

Nomenclatures:

A_j jet cross sectional area
A_P Propeller blade projected area
C_T coefficient of thrust
C_{Tcr} critical thrust coefficient
dE Energy difference between jet and ship
dE` Energy difference between jet and ship with ξ
IVR inlet velocity ratio V_i/V or V_i/V_s
m mass of water flowing per second
P_C propulsive coefficient
P_E effective horsepower
P_I energy input,
P_i pressure infront of the inlet
P_o water pressure below water line
P_T thrust horsepower
T propelling force or thrust
V free stream velocity
V_{cr} the critical velocity
V_A the speed of advance,
V_I the velocity of water at the inlet
V_J the velocity of the jet at the nozzle exit
V_S the velocity of the ship
ω the wake fraction($\frac{V_S-V_A}{V_S}$)
ν the velocity ratio(V_J/V_S)
α the velocity ratio (V_I/V_S)
η_H the hull efficiency (P_E/P_T)
η_t transmission efficiency, shp/bhp
η_P pump hydraulic efficiency
η_i propeller efficiency
η_J the efficiency of the water jet
η_{Jmax} maximum efficiency of the water jet
ρ density of water
ξ loss coefficient

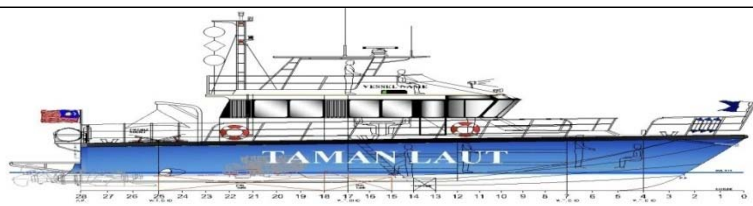
1. Introduction

Propulsion system is very important for a body which passes through a fluid like air or water. Ship is one of the best example as well as space craft, air craft, submarine etc. A moving ship experiences many kind of resistance such as frictional resistance, wind resistance, wave making resistance, eddy making resistance etc. If a ship wants to go ahead with a satisfactory speed, she must overcome these opposite forces with certain speed and this speed can be gained from the propulsion system of ship. The using propulsion systems in marine vehicles are following categories. Such as 1. Screw propellers propulsion 2. Vertical axis propeller propulsion 3. Water jet Propulsion 4. Paddle Wheels propulsion. In early time jet propulsion was simple but in modern era it is very sophisticated as well as complicated. A jet type mechanical device consists of prime mover and pump which was granted to Toogood and Hayes in1661. They described a ship having a channel through the centre in which either a plunger or centrifugal pump was installed. Water was sucked in at the bow opening of the channel, accelerated by pump and ejected at the stern as a jet at higher velocity, the reaction providing the thrust. This is one of the earliest references to a form of propulsion often proposed in later years. Benjamen Franklin made a proposal for jet propulsion of a boat in 1775. Water jet propulsion was actually applied by James Rumsey [29] in 1784. He had built an 80 foots steam propelled boat of the hydraulic jet propulsion type and made numerous private experiments with it in the Potomac river for about three years. In 1787 Rumsey held a public demonstration before several hundred people including General Gorge Washington. Between 1830 and 1860 in England alone, there were at least 35 patent applications for different means of propelling ships with water jets. A systematic account of the hydraulic jet propulsion is recorded by Pollard and Dedebout [25] in their "Theorie du Navire" Although the basic principle of these numerous propulsion Idea are the same, there are several different methods of attaining propulsive thrust from the water jet. In the 20 th century, interest in the hydraulic jet for ship propulsion has continue and during the last few decades it developed tremendously. There was considerable interest in waterjet for naval vessels. Comparatively trials were made by British Admiralty and the Swedish Government of water jet and propeller-driven ships. More conventional pumps have been used successfully in advance marine vehicles since the 1950`s. Hamilton [7] in New Zealand have pursued their own independent approach since 1954. He is the pioneer man of modern waterjet propulsion for small craft. Hamilton applied the waterjet propulsion system in small planning craft where the hull surface was skimmer. Now a day Water jet propulsion is suitable in defense purpose due to produce high speed and low noise as well as use in high speed commercial vessel such as passenger ferry, offshore vessel, patrol craft, littoral combat ship (LCS), multi roll vessel (MRV), sea truck etc.

<u>Water jet Application</u>: Marine water jet propulsion has been used for a variety of ships. This paper highlights their applications below from early times to present times as well as their principle particulars. Latter this paper also highlight the mathematical analysis of marine waterjet propulsion

 This vessel is the SES-200. The Coast Guard of USA tested the Navy 110' SES in 1981 before it was extended to 160' (Subsequently, three 110' Bell Halter, Inc. SES's were purchased by the Coast Guard and placed into service in the newly formed SES Division out of Key West, Florida. These vessels have the same main engines as the SES-200. The SES-200 operates below the high wave drag hump speed which is in the 30+ knot range [26][24][30].	PRINCIPLE PARTICULARS Length 160 ft (48.8 m) Beam 43.0 ft (13.1m) Propulsion Water jet Displacement light 150 tons Displacement max 205 tons Design Speed 30 knots at sea state 0 but 25 knots at sea state 3 Crew 18 (2 officers, I chief petty Same officer, 15 enlisted) Main Engines Two Detroit Diesel 16V-149TI Same 1600 shp at 1900 rpm.

 It is an innovative T-Craft Demonstrator design has been developed which fully achieves the extremely demanding performance goals defined in the Office of Naval Research Broad of USA. It also known as surface effect ship (SES). This T-Craft have self-deploy over long open ocean distances, interface with Sea Base assets while at-sea, transfer cargo from vessel to vessel in medium sea states, transit at high speed to a tactical location, and ultimately cross sandbars, reefs, and mudflats to get "feet dry" on the beach to discharge its cargo. The T-Craft design progressed through two major phases of development, and included concept exploration, concept development, technology development, and design development efforts. The final design product has been reviewed by ABS and is suitable for beginning Detail Design and Construction, should the program go forward. It has also been shown to be scalable to a wide variety of missions [4].	PRINCIPLE PARTICULAR Length (overall) 80.7 m Beam (overall) 20.6 m Beam (side hull) 5.0 m Lightship displacement 1,358 tonne Tactical payload 305 tonne Full load (tactical) 1,792 tonne Full load (transit) 1,888 tonne Draft (off-cushion) 4.45 m Draft (on-cushion) 1.85 m Survival Sea State SS 8 Maximum Speed 41 knots Propulsion engine Two 22MW gas turbines Water jet Two WLD 1720+ High speed generator One 14MW Air propulsor Four 6.4 m shrouded airscrews Airscrew motor Four 4MW permanent magnetic motors,. Lift fan Four 2.1 m dia. lift fans engine Four MTU 16V4000 diesels
 The hydrofoil ship Tucumari (1968-72) was water jet propelled. This was followed by the PHM which was initiated by a join effort of NATO. Almost six ships like this built and these ships are used for US navy as well as NATO mission. The Tucumcari was effectively used during the Vietnam conflict and led to development of the missile-carrying Patrol Hydrofoil Missile ship (PHM) for NATO, first launched Nov. 9, 1974. Boeing built six PHMs, named Pegasus, Taurus, Aquila, Aries, Gemini and Hercules. The 131-foot PHM carried eight Harpoon anti ship missiles, a 75 mm rapid-fire gun, Rapid Bloom Off board Chaff System and an MK-92 fire control system [10][12].	Model number: 929 Classification: Warship Length: 40 meter Width: 8.6 meter Cruising speed: 40 knots Draft (foilborn): 2.52 meter Propulsion: Two waterjets powered by two 800 HP Mercedes-Benz diesel engines (hull born), one waterjet powered by 17000 HP GE marine gas turbine engine (foilborn) Accommodation: 21 to 24 crew
 The Jetfoil is the name Boeing 929 for a passenger-carrying waterjet-propelled hydrofoil design by Boeing. Boeing began adapting many systems used in jet airplanes for hydrofoils. Robert Bateman led development. Boeing launched its first passenger-carrying waterjet-propelled hydrofoil in April 1974. It could carry from 167 to 400 passengers. It was based on the same technology pioneered by the patrol hydrofoil Tucumcari, and used some of the same technology used in the Pegasus class military patrol hydrofoils. Currently this product line is sold to the Japanese company Kawasaki Heavy Industries [16][12].	First Launch: March 29, 1974 Model number: 929-100 Classification: Passenger Hydrofoil Length: 27.43 meter Width: 9.15 meter Cruising speed: 45 knots Draft (foilborn): 1.73 m to 1.98 m Propusion: Two Allison 501-KF turbine engines with two Rocketdyne waterjet pumps Accomodation: 4 to 8 crew, 250 to 350 passengers.

 This one great beauty of aluminum water jet propelled ship which having speed up to 40 knots at 90% MCR with length overall 107 meters. This high-speed vehicle-passenger ferry "Alakai", built for Hawaii Superferry, has recommenced its daily service between Maui and Oahu. It`s maximum dead weight 800 tonnes with 866 passengers and 282 cars. The vessel performed very well in the extreme operating conditions upto sea state 6 [32].	PRINCIPAL PARTICULARS Length overall: 106.5 metres Beam moulded: 23.8 metres Hull depth moulded: 9.4 metres Maximum deadweight: 800 tonnes Passengers: 866, Vehicles: 282 cars or 28 trucks 65 cars, Main engines: 4 xMTU 20V 8,000 M71 4 x 8200kW, Gearboxes: 4 x ZF 53000-2 Water jets: KaMeWa 125 S11 Operational speed: 40 knots @ 90% MCR Classification: Germanischer Lloyd
 "Cat No.1", a 52 metre high speed passenger catamaran, has made an impressive debut in the German Bight for AG Reederei Norden-Frisia. Seakeeping was extremely important to Norden Frisia and was the prime consideration in the vessel's design to ensure a smooth operation in its North Sea conditions where it will experience significant wave heights of up to 2.5 metres and Beaufort Force 7 winds. In addition to Austal's well proven rounded-bilge and bulbous-bow semiswath hull form, a unique feature of the aluminum catamaran is its middle bow hull form which only comes into effect in seas greater than 2.0 metres [32].	PRINCIPLE PARTICULARS Length Overall . . . . 52.4 metres Length Waterline . . . . . . 45.4 metres Beam (Moulded) . . . . 13.0 metres Hull Draft . . . . 1.5 metres Passengers. . . . . 432 nos Propulsion:Main Engine 4 x MTU 16V 2320kW@2000rpm Gearboxes ....…….. 4 x Reintjes VLJ 930 Waterjets.................. 4 x KaMeWa 71 S11 Service Speed……… 40 knots (100% MCR) Classification……….. Germanischer Lloyd.
 This amazing new AIR RIDER have been launched early February 2013. Sporting twin V12 MAN diesels with DOEN water jets and a top speed over 30 knots, this hull re-define performance. Built as a Bangladesh Coast Guard Patrol Vessel and built by Dockyard & Engineering Works, Naryangonj Ltd. This ship is constructed under the author supervision as well as consultancy service. The hull material is aluminum 5083, 6082 and electrode filler material is 5363. Same vessel almost 10 nos built in Malaysia and the designer was Global Marine Design Pty Ltd [33].	PRINCIPLE PARTICULARS Overall Length 20.11 m Waterline Length 16.55 m Beam 5.20 m Draft @ Working Displ. 1.00 m Working Displacement 35 T Light Displacement 31 T Deck height above Waterline 1.80 m Bow Freeboard at rest 2.04 m , Fuel Capacity 6,000 L Engine/s 2 x MAN V12 D2862 LE463 2 x DOEN DJ220 Waterjet Total Installed Power 2 x 1,030 kW 2 x 1,400 HP @ 2100 RPM , Cruise Speed 28 + Knots

 The 127 metre long, 31.6 metre wide trimaran built in aluminum and powered by two gas turbine and two diesel engines to reach sustainable speeds in excess of 40 knots. The ship is designed to allow a crew of fewer than 40 sailors to fully operate, maintain ad defend it. The flexibility, speed, endurance, volume, seakeeping, payload capacity, and maneuvering characteristics of the trimaran, coupled with modular mission packages and other modifications to address military-specific requirements, provide an optimal solution for the US Navy's Littoral Combat Ship (LCS) requirements[31].	PRINCIPAL DIMENSIONS Length overall 127.1 metres Beam overall 31.4 metres Hull draft (maximum) 4.5 metres Payload and capacities: Complement, Core Crew 40, Mission crew 36 Maximum mission load 210 tonnes Mission packages ASW, SUW, MIW Main engines 2 x GE LM2500 2 x MTU 20V Waterjets 4 x Wartsila steerable PERFORMANCE Speed 40 knots, Range 3,500 nm Operational limitation Survival in Sea State 8 WEAPONS AND SENSORS Standard 1 x 57 mm gun, 4 x .50 calibre guns 1 x SAM launcher, 3 x weapons modules
 The vessel is a 290m, 6500t Dwt high speed Pentamaran Ro-Pax vessel designed for SeaBridge International Inc. The vessel is powered by a Diesel Electric Propulsion plant in combination with waterjets. A rendering of the vessel is shown in Figure of The SeaBridge approach uses the sea to complement existing land-based travel on selected routes to attract freight movements away from overcrowded highways, for at least part of the journey from shipper to receiver. By using the sea as a bridge, SeaBridge intends to transport more goods, with less environmental impact, at lower cost, and in a shorter time frame than any comparable transportation alternative available today [9].	PRINCIPLE PARTICULARS LOA 300.00 m LWL 290.00 m Beam Moulded 45.00 m Beam Central Hull WL 20.70 m Design Displacement 30000.0 t Scantling Displacement 34000.0 t Main Engines 8 x MAN 48/60B 18V Waterjets 8 x LIPS/Kamewa Speed at 90% MCR 41.5 knots

Mathematical analysis of water jet: In early of waterjet era, mathematical treatment had started with elementary momentum theory and this theory could not compete with propeller propulsion efficiency with pumps of realistic size. But in present time sophisticated treatment evolve which show that waterjet has a secondary effect and this effect influence on efficiency of waterjet. The simple momentum theory will be discussed here as well as few complicated theory. Let consider a ship, taking water in bow and pump out at nozzle which situated at stern of ship. The bow intake and nozzle connected by a duct and the duct made a tunnel between them. This duct is installed along the centre line of ship and all nozzle water passes through it. When water impulse on water through nozzle then thrust is produced and ship goes to ahead. Since intake at bow, no intake losses occur and the intake velocity of water and ship velocity will be equal to each other [1], [18].

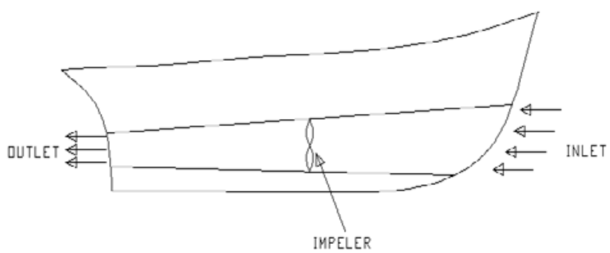


Figure1 shows duct system which passes water from intake to nozzle.

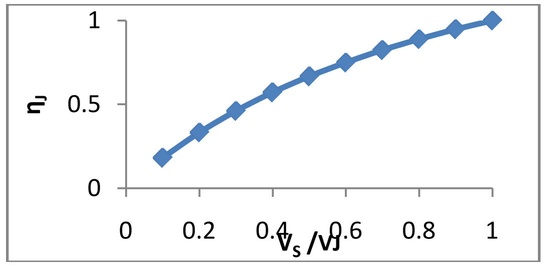


Figure2: Variation of jet efficiency (η_J) and velocity ratio ($\mu=V_S/V_J$) denoted by ship speed to jet speed.

Now the mass of water discharge per unit time through nozzle, m =ρAV_J… (1), Change in velocity = (V_J-V_s), The thrust developed by water jetT= ρAV_s (V_J-V_s) …… (2) Useful work done by waterjet on the ship= thrust*speed of the ship =TVs= ρAV_s (V_J-V_s) V_s …… (3) The waterjet cannot impulse totally on water due to ship velocity. Because of this, a lost velocity occur and which equal to (V_J-V_s). So the lost kinetic energy of jet = $\frac{1}{2}$m $(V_J-V_s)^2$ = $\frac{1}{2}$ρA V_S $(V_J-V_s)^2$ ……..(4) Energy delivered by the jet=$\frac{1}{2}$ m $V_J{}^2$. Let us consider the intake velocity of water at bow V_I. Then energy delivered by the pump E = $\frac{1}{2}$ m $V_J{}^2$ - $\frac{1}{2}$ m$V_I{}^2$… (5). Where $\frac{1}{2}$ m$V_I{}^2$ is the inlet kinetic energy of water. Or, E $=\frac{1}{2}\rho AV_JV_J{}^2-\frac{1}{2}\rho AV_JV_I{}^2=\frac{1}{2}\rho AV_J(V_J{}^2-V_I{}^2)$……(6) So the efficiency of jet, $\eta_J=\frac{\text{Energy output or useful workdone}}{\text{Energy Input by the pump}}$

$\eta_J=\frac{\rho AV_J(V_J-V_s)V_s}{\frac{1}{2}\rho AV_J(V_J{}^2-V_I{}^2)}=\frac{2(V_J-V_s)V_s}{(V_J{}^2-V_I{}^2)}=\frac{2(V_J-V_s)V_s}{(V_J+V_I)(V_J-V_I)}=\frac{2V_s}{V_J+V_I}\ \frac{V_J-V_s}{V_J-V_I}$…… (7). Let consider the fluid is ideal, therefore $V_s=V_I$

Now the equation (7) become $\eta_J=\frac{2V_s}{V_J+V_I}$….. (8) Now introduce a new term μ is ratio of ship speed and jet velocity. Therefore $\mu=\frac{Vs}{V_J}$. So the efficiency becomes $\eta_J=\frac{2\mu}{1+\mu}$.. (9) Based on equation (9) a graphical view is shown in figure 2. When the forward of the ship or bow need to install something (like a bow thruster), then there is no opportunity to ducting. Therefore the ships have to intake water from another portion of underwater of hull. Let consider the inlets are now in starboard and port of ship in below water level. Now additional kinetic energy is needed to intake water. In this case water in rest condition and ship speed is Vs. If we consider the ship speed zero and water speed Vs with respect to ship then the value of efficiency do not vary. Now the additional intake kinetic energy will be equal to $\frac{1}{2}$m$V_s{}^2$. So the efficiency $\eta_J=\frac{Usefull\ workdone}{Use\ full\ work+Lost\ kinetic\ enerjetgy\ of\ jet+Additional\ kinetic\ energy}=\frac{\rho AV_J(V_J-V_s)V_s}{\rho AV_J(V_J-V_s)V_s+\frac{1}{2}\rho AV_J(V_J-Vs)^2+\frac{1}{2}\rho AV_JV_s{}^2}$

$\eta_J=\frac{2(V_J-V_s)V_s}{V_J{}^2}$.. (10). Let the two ratio $\frac{V_J}{V_s}=\nu$ and $\frac{V_I}{V_s}=\propto$, Then the equation become $\eta_J=\frac{2}{\nu+\propto}\ \frac{\nu-1}{\nu-\propto}=\frac{2(\nu-1)}{\nu^2-\propto^2}$…. (11)

To obtain maximum jet efficiency, equation (11) have to differentiate with respect to ν and it becomes $\frac{d\,\eta_J}{d\nu}=\frac{2}{\nu^2-\propto^2}-\frac{2(\nu-1)2\nu}{(\nu^2-\propto^2)^2}$ …. (12). For maximum value of η_j, $\frac{d\,\eta_j}{d\nu}$ equal to must be zero. Hence the equation (12) after simplification becomes ν^2-2ν+ $\propto^2$=0, So we get $\nu=1\mp\sqrt{1-\propto^2}$, Since ν is the ratio of $\frac{V_J}{Vs}$ and V_J is always greater than V_s. So ν must be always greater than unity. Taking positive value of above equation for critical velocity and it becomes $\nu_{cr}=1+\sqrt{1-\propto^2}$……. (13). From equation (2) we know Or T = ρAν$V_s{}^2(\nu-1)$ after substituting the value of V_J. But thrust coefficient is defined as follows $C_T=\frac{T}{\frac{1}{2}\rho AV_s{}^2}$…… *(14)* $=\frac{\rho A\nu V_s{}^2(\nu-1)}{\frac{1}{2}\rho AV_s{}^2}$ *Or* $C_T=2\nu(\nu-1)$………(15)

It is known as critical thrust coefficient. If the value of ν equal to unity then the critical thrust coefficient is zero. It is possible when jet velocity and ship velocity equal to each other. These characteristics are drawn in figure3 using equation (15).

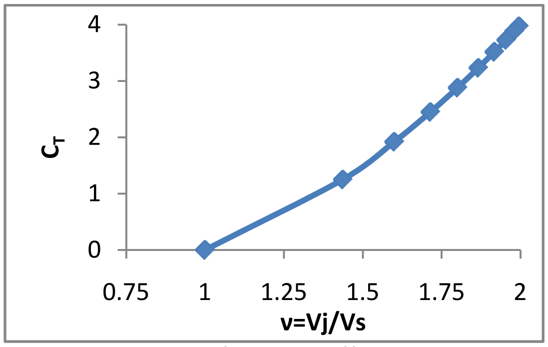


Figure3: Variation of thrust coefficient (C_T) with velocity ratio (ν).

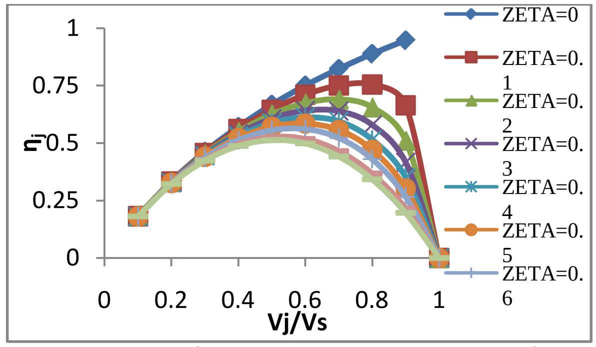


Figure4: Variation of efficiency (η_j) with the ratio of jet velocity to ship velocity (Vj/Vs) at different values of zeta (ξ).

<u>Loss consideration</u>: In case of ideal fluid resistance and drag force of ship and nozzle was not considered. But in real case ship must experience resistance and drug forces which create a loss in efficiency [1]. Let the loss coefficient is ξ. Then the loss term become $(\frac{1}{2}\rho AV_J V_s^2)\xi$. Now the loss energy term will be added with energy difference term dE. So dE`= $\frac{1}{2}\rho AV_J(V_J^2 - V_s^2) + (\frac{1}{2}\rho AV_J V_s^2)\xi$……(16)=$\frac{1}{2}\rho AV_J[V_J^2 - V_s^2(1-\xi)]$. So the jet efficiency $\eta_J = \frac{\text{Useful workdone}}{\text{Energy delivered by pump(dE`)}} = \frac{\rho AV_J(V_J - V_s)V_s}{\frac{1}{2}\rho AV_J[V_J^2 - V_s^2(1-\xi)]} = \frac{2\mu(1-\mu)}{1-\mu^{2(1-\xi)}}$…..(17). Based on the equation (17) following figure 4 can be drawn.

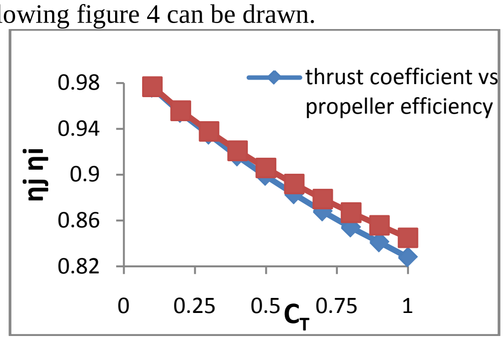
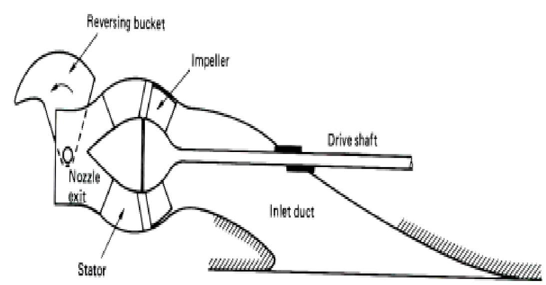


Figure 5: comparison propeller efficiency (η_i) and jet efficiency (η_j) with thrust coefficient(c_T).



Figur6 shows waterjet propulsion system with suction inlet and nozzle

Jet efficiency can be expressed in terms of thrust coefficient $\eta_j = \frac{4}{3+\sqrt{1+2C_T}}$............ (18) Where $C_T = \frac{T}{\frac{1}{2}\rho A_J Vs^2}$

For propeller the efficiency is $\eta_i = \frac{2}{1+\sqrt{1+C_T}}$……… (19) Where $C_T = \frac{T}{\frac{1}{2}\rho A_P Vs^2}$.

But the overall propulsive coefficient $PC = \eta_J * \eta_P * \eta_r * \eta_t * \eta_H$. In case of water jet, relative rotative efficiency η_r equal to unity. Therefore the propulsive co efficient become $PC = \eta_J * \eta_P * \eta_t * \eta_H$ .... (20)

<u>Water jet-hull interaction effect</u>: Hydrodynamic characteristics of bottom mounted transom suction waterjet is very complicated. When a ship moving, a continuous flow flowing through duct from inlet to nozzle according to figure6. Water is sucked at inlet opening and exhale at nozzle with very high speed. With respect to water suck speed, inlet flow pattern will be changed according to figure7 and this will discussed latter in this section. Applying Bernoulli`s equation between inlet and outlet points, it becomes $\frac{P_i}{\rho g} + h_i + \frac{V_s^2}{2g} = \frac{P_o}{\rho g} + h_o + \frac{V_j^2}{2g}$… (22). The pressure P_o is atmospheric pressure plus water pressure below the water line. The magnitude of P_o and water depth h_o are small with respect to inlet pressure P_i and inlet depth h_i respectively. Now ignoring these P_o & h_o, equation (22) becomes $\frac{P_i}{\rho g} + h_i + \frac{V_s^2}{2g} = \frac{V_j^2}{2g}$. Or, $V_j = \sqrt{(V_s^2 + P_i + \rho g h_i)}$ …. (23). Here P_i is the static pressure infront of the inlet and $\rho g h_i$ is static pressure at inlet. When ship start to move forwar from rest, then the boundary layer at inlet will be accelareted. This acceleration is produced by absorbing presssure energy and the absorption reduce the static pressure at inlet because the total energy is constant (from Bernoulli`s Equation). Due to the reduction of static pressure, jet velocity should be decreased according to equation (23). But at time of operation the jet velocity remains same. Now a question arise in mind that how is it possible? During moving condition, ship stern sinkage is bigger than rest ship sinkage and result of them increasing stern draft[2]. Because of increasing this draft and ship movement, the static pressure in front of the inlet (P_i) is reduced. Due to reduction of this pressure ship is sink further and static pressure ($\rho g h_i$) increase which keep jet velocity V_j remains same.

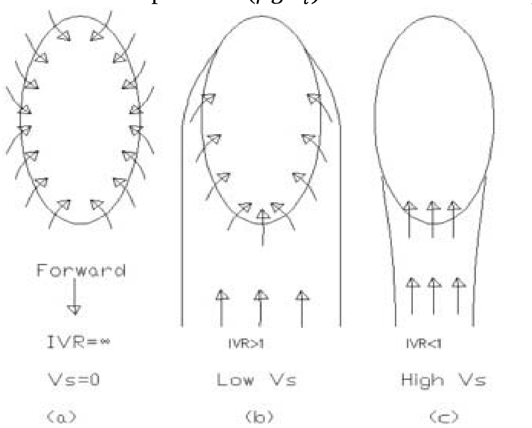


Figure7 shows inlet flow pattern at different speed.

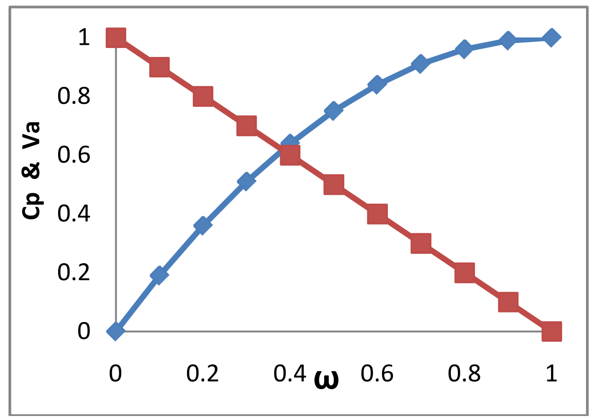


Figure8 shows the pressure coefficient (C_p) and speed of advance (V_a) with wake fraction (ω).

waterjet-inlet interaction effect discussed by Svenssons [26] and it is about lifting force at the stern of ship and this lifting force is produced in the vicinity of waterjet inlet. Svensson introduce a pressure coefficient C_p and which is equal to $\frac{P_s-\rho g h_i}{\frac{1}{2}\rho {V_s}^2}$. Therefore it can be written as $C_p = \frac{P_s-\rho g h_i}{\frac{1}{2}\rho {V_s}^2}$…. (24) Where P_s is static pressure in front of the inlet h_i is depth of inlet. This pressure coefficient is related by another relation[27] $C_p = 1-(\frac{V_a}{V})^2$… (25) Where V_a is the speed of advance. V is the free stream velocity. But the free stream velocity can be replaced by ship speed V_s and the equation (25) becomes $C_p = 1-(\frac{V_a}{V_s})^2$… (26) V_a and V_s are related by another relation that $V_a = (1-\omega)V_s$ ….(27)Where ω is the wake fraction. Now substitute the value of V_a in equation (26) and it becomes $C_p = 1-(1-\omega)^2$ Or, $C_p = \omega(2-\omega)$…….(28). On the basis of equation (27) and (28) the above figure can be drawn and which intersect at value of ω of 0.38. Let consider the ship is not in underway or in bollard pull test then the inlet velocity flow pattern will be like a patch of skins of figure7a. In this condition inlet velocity ratio (IVR) is infinite and capture area maximum. If the ship start to move forward with very low ship speed or with IVR of greater than unity, then the stream line will be like figure7b. In this state the capture area is less than from previous condition but flow entering amount has no variation which is proven from equation of continuity. If ship speed further increase or with IVR less than unity, the capture area will be decreased further without no changing of flow entering amount. But at low IVR condition, the stern of ship sink further due to pressure variation in the vicinity of inlet which is already been discussed earlier in this section.

<u>Results and Discussions</u>: Figure 2 based on equation (5) and shows variation of jet efficiency (η_J) with velocity ratio (V_S/V_J). With increasing velocity ratio, the jet efficiency increases. The increasing rate not linear but slightly decrease with increasing of velocity ratio. That means for lower velocity ratio or at higher velocity of jet, the efficiency is high. Therefore marine water jet propulsion is appropriate for higher velocity. Figure 3 based on equation (15) and it shows that the variation of critical velocity with respect to velocity ratio ν. For unity value of ν, the critical thrust coefficient is zero. Due to equal velocity of jet and ship or unity value of υ, thrust coefficient C_T is zero which is proven from equation (15) as well as from figure3. Figure4 based on equation (17) and shows the variation of velocity ratio and jet efficiency with loss consideration. When the loss coefficient zeta is increase successively, the efficiency decreases successively. At zeta equal to zero the efficiency is maximum and same as figure2 which is for ideal condition. Since the loss coefficient decrease efficiency and the loss associated with duct, the inlet duct system should design in such a way that loss should be minimized. Therefore this formulae help to designer to design water jet system in efficient way. Figure5 based on equation (18) and (19) and it shows the variation of thrust coefficient with propeller and jet efficiency. The efficiencies are decrease with increasing thrust coefficient but not equally. At very lower value of C_T or higher value of V_S the efficiencies are equal. But at higher velocity of ship, propeller blade break down can be happened which is avoidable in case of waterjet propulsion. Due to these reasons waterjet propulsion is suitable over the propeller propulsion at higher speed and jet propulsion system generally installed in high speed craft. Figure8 is drawn on the basis of equation (27) and (28) with unity ship velocity. The pressure coefficient C_P and speed of advance V_a is drawn with wake fraction ω and these curve intersect at point ω=0.38 that is at this value of wake fraction 0.38, pressure coefficient C_P and speed of advance V_a have same values. Higher value of C_P decrease efficiency[1] but lower value reduces ship speed. Another relation speed of advance V_a increases efficiency but the efficiency also depended on others values. This wake fraction with pressure coefficient and speed of advance gives particular type of stream line or inlet flow pattern. This flow pattern involve with lifting coefficient at vicinity of waterjet inlet[1] and with other hydrodynamic characteristics which help designer to design appropriate position and size of waterjet inlet.

Conclusion: In this paper clearly discussed the beauty application of waterjet propulsion in case of small vessel as well as big type of ship with high service speed. From above discussions it is clear that waterjet propulsion can be drive passenger ferry to cruise ship, fire fighting vessel to offshore vessel, vehicle carrier to yacht, pleasure craft etc and these discussions will raise importance of waterjet propulsion to the rest of the world. Mathematical operations are mentioned for all type of inlets which are give different view among them. Waterjet-hull interaction effect has shown with pressure coefficient, wake fraction, speed of advance as well as graphical characteristics of them which help to designer to design inlet size, inlet position etc. Waterjet-hull interaction effect also discussed with Bernoulli's equation and mathematically established the relations among jet velocity, hydrostatic pressure, sinkage, trim etc based on equation (22), (23) & (24).

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