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A Combined Method to Design of the Twin-Waterjet Propulsion System for the High-Speed Craft

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Abstract This paper is presented a combined method to design of the twin-waterjet propulsion system for high-speed craft (HSC). First, a practical approach employed to obtain the main data of the geometry of waterjet system. Thrust of the system is calculated by the momentum theory. Next, RANS solver is performed with the realizable $k-\varepsilon$ turbulence model. The numerical results of the pressure distribution coefficient, thrust coefficient and the flow field inside the duct are presented and discussed.

Keywords: *twin-waterjet, practical and numerical method, pressure and thrust coefficients*

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1. Introduction

The use of conventional propellers for HSC is not practical due to the high-speed of the craft relative to the water. The high water speed results in cavitation on the propeller with a resulting loss of thrust and efficiency. Waterjet propulsion systems overcome this problem by using an intake to slow the water relative to the craft and reduce the likelihood of cavitation before delivering it to the rotor. Figure 1 show the schematic of the marine vehicle using waterjet propulsion system. Most of researches on the waterjet propulsion have been carried out by experiments for last decades [1]. Levy presented a brief description of the water-jet propulsion system as applied to hydrofoil craft, and a discussion of the salient hydrodynamic aspects of the problem of fitting the main propulsion system to the specified thrust-versus-speed requirements [2]. An example of predicted vessel performance regarding speed, power and propulsor RPM is presented which includes engine characteristics and BHP versus RPM [3]. Ghassemi & Mazinani carried out the practical method to obtain the geometry data of the waterjet system for a HSC in order to generate the required thrust [4]. A comprehensive formula based on the momentum theory studied by Allison [5]. General jet efficiency formulae are obtained based on many parameters.

The application of CFD is continuously increased by virtue of the advancement of numerical algorithms and computer hardware. Nevertheless, CFD works are mostly devoted to the intake duct and a few applications to waterjet pump were accomplished [6]. Most of them did not solve whole system of waterjet propulsion, consisting of intake duct, rotor, stator, and discharge nozzle. Recently, Park et al. [7] did waterjet performance using RANS code and analyzed the flow in the duct including full elements. A comparative study between a computation and an experiment has been conducted to predict the performance of a Pod type waterjet for an amphibious wheeled vehicle carried out by Kim et al [8]. Lam et al [9] presented time-averaged velocity and turbulence intensity at the initial plane from a ship's propeller using a computational fluid dynamics (CFD) approach. Also, CFD analysis is applied to free surface flow around a waterjet propelled ship by Hino and Ohashi [10]. A series of self-propulsion tests of a catamaran design at medium-speeds is proposed to study the influence of the hydrodynamics at medium-speeds on the waterjet propulsor [11]. In the paper two original dimensionless numerical procedures, one referred to jet units for naval applications and the other more suitable for planing boats, are presented [12]. Experiments and simulations are carried out to investigate the reactive thrust and the conversion efficiency of cylindrical nozzles, conical nozzles and optimized nozzles [13]. Tokai et al was performed to investigate the capability of a URANS flow solver for the accurate simulation of waterjet propelled ships [14].

This paper has two parts, the first part is to find the geometry of system for the special craft by the practical method and next to analyze the flow field and the performance of the waterjet propulsion system by the CFD code. The following sections are organized as follows. Practical method is described in Section 2. The governing equations of the CFD and its numerical method explained in Section 3. The numerical results are presented in Section 4, and Section 5 is given for the conclusions.

2. Practical Approach to Design the Waterjet

Before going ahead to analyze the waterjet system by CFD, it is needed to estimate the geometry and size of the twin-waterjet system by practical formulae. The main dimensions of the HSC are given in Table 1. The Craft is a single hull and prismatic wedge section hull. Displacement of the craft is 155 tones. The design speed is 40 [Kts] and its resistance is calculated 150 [kN] by Savitsky method [4]. Each unit of waterjet may be powered by one engine. Figure 2 is shown the schematic of the twin-waterjet system.

Table 1. Main Dimensions of HSC

Parameter	Value
Length (L)	31 [m]
Breadth (B)	8[m]
Draft (d)	1.4[m]
Dead rise angle	12 [deg.]
Displacement	155 [ton]
Speed (V_S)	40 [Knots]
Resistance (R_T)	150[kN]

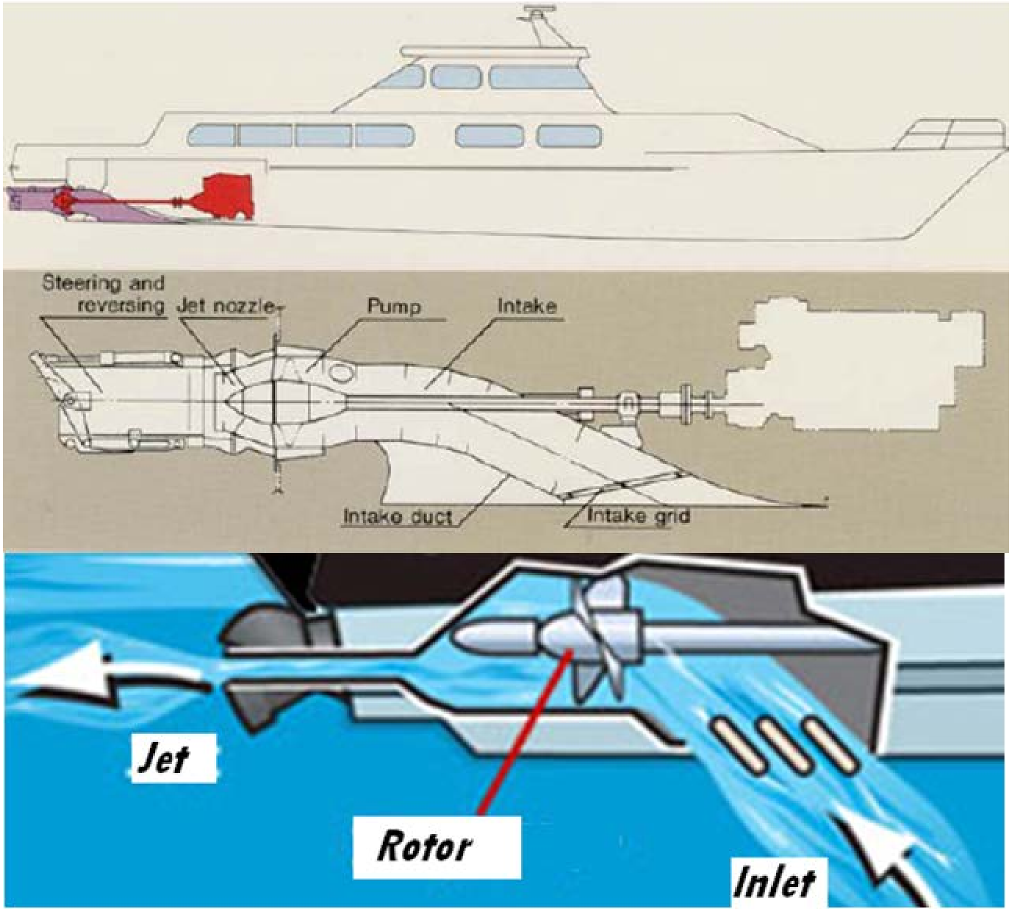

Figure 1. Schematic of the system

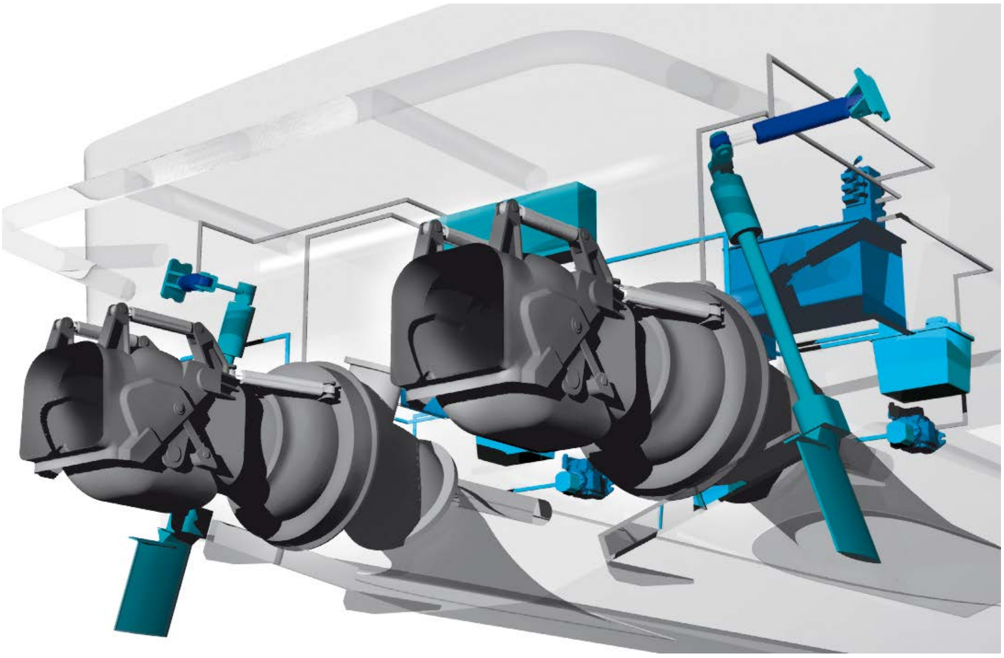

Figure 2. Schematic of the twin-waterjet system

Ghassemi & Mazizni [4] employed a practical approach and determined the optimum geometry for the planing craft. Considering all the losses in the inlet, nozzle and depth of the jet relative to water surface (h_j), the jet system can be expressed as [5]

$$\eta_j = \frac{Effective\ power}{Delivered\ power\ by\ pump} = \frac{R_T.V_S}{P_J}$$

$$\Rightarrow \eta_j = \frac{(V_j - V_A)(1-t)V_s}{0.5[V_j^2/\eta_n - \eta_i V_A^2 + gh_j]} \quad (1)$$

$$where: \begin{cases} Thrust = T = m(V_j - V_A) \\ Resistance = R_T = T(1-t) \\ Advacne\ speed = V_A = (1-w)V_s \\ P_J = 0.5m(V_j^2/\eta_n - \eta_i V_A^2 + 2gh_j) \end{cases}$$

Table 2. Main data of waterjet system

Parameter	Value
w	0.05
t	-0.02
h_j	0.9 [m]
η_R	1.0
η_n	0.99
η_i	0.80

For the craft and some data are assumed and given on the data Table 1 and Table 2, the only unknown is nozzle velocity (V_j). Therefore, maximum efficiency of the waterjet system may be obtained by derivation of the Eq. (1) in term of V_j, it can be determined as follow;

$$\frac{\partial \eta_j}{\partial V_j} = 0 \Rightarrow V_j = 28.15[m/s]. \quad (2)$$

By putting this obtained velocity in the Eq. (1), the maximum efficiency is determined 70%.

It can be checked that the optimum jet velocity ratio is $\lambda = V_j / V_i = 1.44$, and its range between 1 and 2. The required thrust by one unit (T_1), rate of the flow in the duct and head of the pump may be calculated as follows:

$$T_1 = \frac{T}{2} = \frac{R_T}{2(1-t)} = 73.5[kN] \quad (3)$$

$$\dot{m} = \frac{T_1}{\left[V_j - V_s(1-\omega)\right]} = 8.333[ton/s]$$

$$Q = \frac{\dot{m}}{\rho(=1.025)} = 8.13[m^3/s] \quad (4)$$

$$H_P = \frac{1}{2g}\left[V_j^2\eta_n - V_i^2\eta_i + 2gh_j\right] = 22.87[m]. \quad (5)$$

Selecting an axial pump and its characteristics, the following data are drawn:

$$\begin{cases} \text{Volume rate} = Q = 8.13[m^3/s] \\ \text{Head} = H_P = 22.87[m], \end{cases} \xrightarrow{Pump\ data\ selection} \begin{cases} \text{Efficiency} = \eta_P = 0.85, \\ \text{Specific speed} = N_S = 180 \\ \text{Specific diameter: } D_S = 0.70 \end{cases}$$

Shaft Rotor Speed:

$$N_S = \frac{nQ^{0.5}}{H_P^{0.75}} \Rightarrow n = \frac{N_S H_P^{0.75}}{Q^{0.5}} = 660.2[RPM]. \quad (6)$$

Total effective power:

$$EHP = R_T \times V_S = 150[kN]*40[knots]*0.5144[m/s] = 3086[kW](1\,[knots] = 0.5144\,[m/s]) \quad (7)$$

Total efficiency:

$$\eta_T = \eta_j \eta_p \eta_R = 0.71*0.85*1.0 = 0.60. \quad (8)$$

Shaft power in each jet system:

$$SHP = \frac{T_1.V_S}{\eta_T(1-t)} = 2571[kW] \approx 2600[kW] \quad (9)$$

Here, two engines (2*2600 kW) by total power (5200 kW) can be chosen for this craft.

Inlet diameter:

$$Q = V_i \times A_i \Rightarrow D_i = 0.78\,[m] \quad (10)$$

Nozzle diameter:

$$D_j = \sqrt{\frac{V_i}{V_j} D_i^2} \Rightarrow D_j = 0.63 \quad (11)$$

Rotor diameter:

$$D_{Rotor} = \frac{D_S \times Q^{0.5}}{H_P^{0.25}} = \frac{0.7 \times 8.13^{0.5}}{(22.87)^{0.25}} = 0.91\,[m] \quad (12)$$

Table 3 presents the all main dimensions of waterjet system, pump data, power and efficiency. Based on the employed similar system, the numbers of rotor and stator blades are selected 4 and 9, respectively. It should be explained that those data are calculated via practical formulae. Next, 3D model can be made in Rhino software. The rotor blade geometry is made by data section of the blade. The rotor is modeled by propcad software open software [15].

Table 3. Main dimensions of waterjet system, pump data, power and efficiency

Inlet diameter:	$D_i = 0.78[m]$	Jet Efficiency:	$\eta_j = 0.70$
Nozzle diameter:	$D_j = 0.63[m]$	Head of pump (H_P):	22.87 [m]
Rotor diameter:	$D_{Rotor} = 0.91[m]$	Pump efficiency:	$\eta_P = 0.85$
Rotor blade number:	Z_{Rotor}=4	Specific speed:	N_S=180
Rotor speed:	$n = 660\ [rpm]$	Specific diameter:	D_S=0.70
Stator blade number:	Z_{Stator}= 9	Total effective power:	3086 [kW]
Flow rate on duct:	$8.13\,[m^3/s]$	Total Efficiency:	$\eta_T = 0.60$
Height of nozzle:	$h_j = 0.9\,[m]$	Shaft power:	2*2600 [kW]

3. CFD Solver

The flow field in the whole system (duct, rotor, stator and shaft) is simulated employing commercial CFD code and the obtained flow velocity compared with experimental studies. The CFD simulation is based on the Reynolds Averaged Navier Stokes (RANS) equations solver using a finite-volume method. The flow field domain (solution domain) is subdivided into finite number of control volumes. The conservation equations are then applied to each control volume. In actual implementation the integral equation of conservation equation is converted into linearized algebraic difference form for the discrete dependent variable and applied to the computational node positioned at the centroid of each control volume.

Based on the results of three turbulence models (*k-ε* standard, *k-ω SST* and RSM) to the Kort-nozzle propeller [16], for the present waterjet system the standard $k-\varepsilon$ model which is a semi-empirical model based on equations for turbulent kinetic energy (k) and its dissipation rate (ε), is then used. The transport equations are

$$\bar{U}_i \frac{\partial k}{\partial x_i} = -\overline{u_i' u_j'} \frac{\partial \bar{U}}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_i}\left[\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right] \tag{13}$$

$$\frac{\bar{U}_i \dfrac{\partial \varepsilon}{\partial x_i} = -C_{\varepsilon 1}\dfrac{\varepsilon}{k}\overline{u_i' u_j'}\partial \bar{U}}{\partial x_j - C_{\varepsilon 2}\dfrac{\varepsilon^2}{k} + \dfrac{\partial}{\partial x_i}\left[\dfrac{\nu_t}{\sigma_k}\dfrac{\partial k}{\partial x_i}\right]} \tag{14}$$

where:

$C_{\mu=0.09}, \sigma_k = 1.0,\ C\xi_1 = 1.44,\ C\xi_2 = 1.92$

σ_k = turbulent Prantle number for $k(1.0)$

σ_ε = turbulent Prantle number for $\varepsilon(1.3)$.

These are the constants for the standard $k-\varepsilon$ model. The eddy or turbulent viscosity, ν_t is computed by combining k and ε as follows

$$\nu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{15}$$

where C_μ =constant (=0.09).

4. Numerical Results

Because the rotor of the system has helical twisted form, the grid generation of the system is very complicated due to rotor. We considered the whole systems as a compact unit. The flow field computational domain is discretized into finite control volumes as shown in Figure 3. Unstructured grid has been used for domain discretization in the intake of the duct (bottom of the craft). Using graded mesh sizes, a total number of finite volume cells (approximately 3 million) have been generated.

Figure 4 is shown the surface body and their surface mesh generation. Figure 5 shows pressure distribution coefficient on the rotor at three radius r/R=0.6, 0.75 and 0.9 and advance coefficient J=1.7. Here, advance velocity coefficient, pressure distribution coefficient and thrust coefficient are defined as

$$J = \frac{V_A}{nD_{Rotor}}, \quad C_P = \frac{P}{0.50\rho V_A^2}$$
$$K_t = \frac{T}{\rho n^2 D^4} = \frac{\dot{m}(V_j - V_A)}{\rho n^2 D^4}. \tag{16}$$

Thrust coefficient against advance coefficient is shown in Figure 6. As shown, with increasing the advance coefficient the thrust coefficient is diminished. Flow velocity vector in the duct is shown in Figure 7. Some reverse flow may be seen in the inlet of the duct. Mean axial velocity at three advance coefficients J=0.77, 1.2 and 1.7 are given in the Figure 8. When the speed increased the flow velocity is increased and there is jump velocity in the center due to the shaft of rotor. Some lower speed can be given in the lower *-0.4<r/R<+0.4* due to the hub of the rotor.

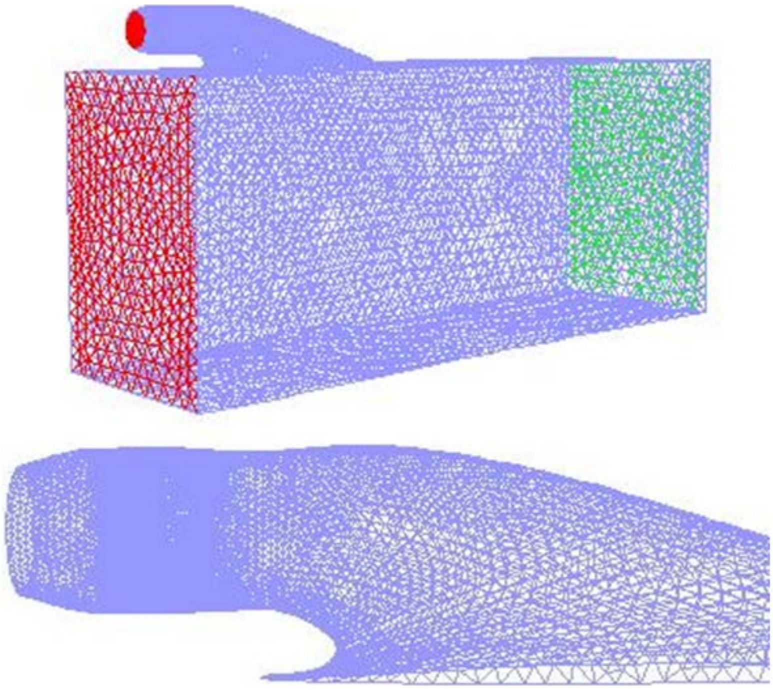

Figure 3. Computational domain mesh

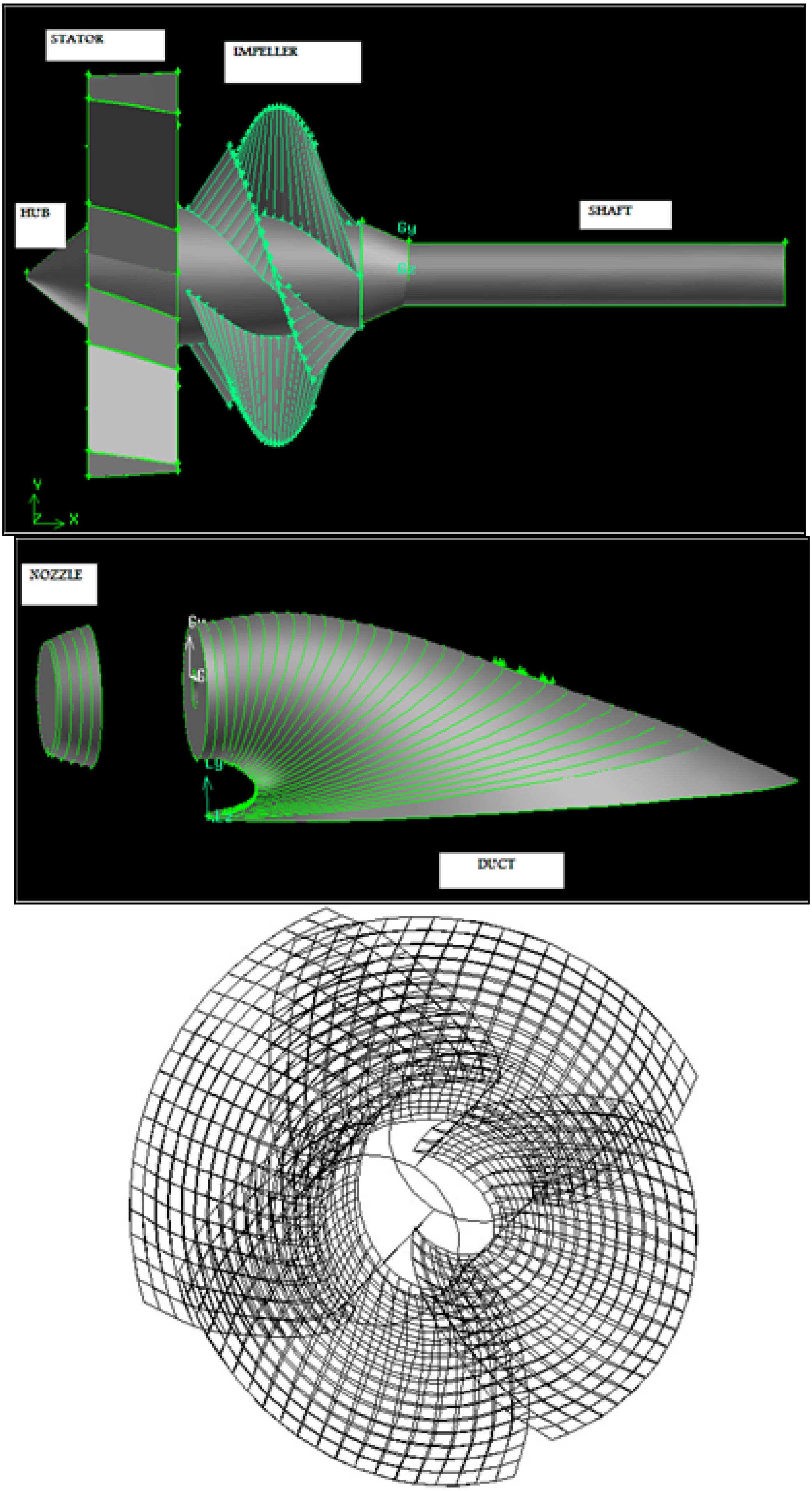

Figure 4. View showing rotor, duct and stator

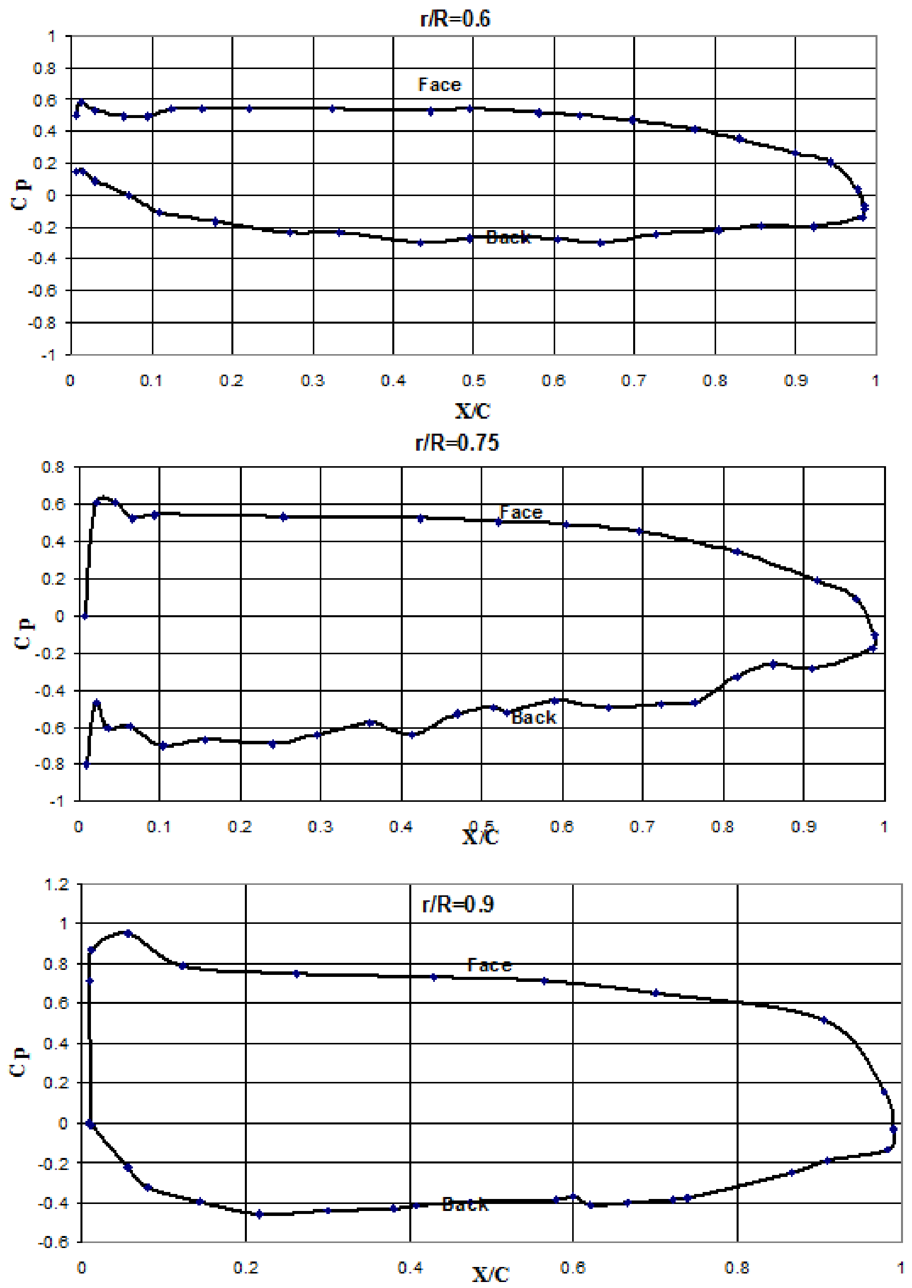

Figure 5. Pressure distribution on rotor blade at J=1.7

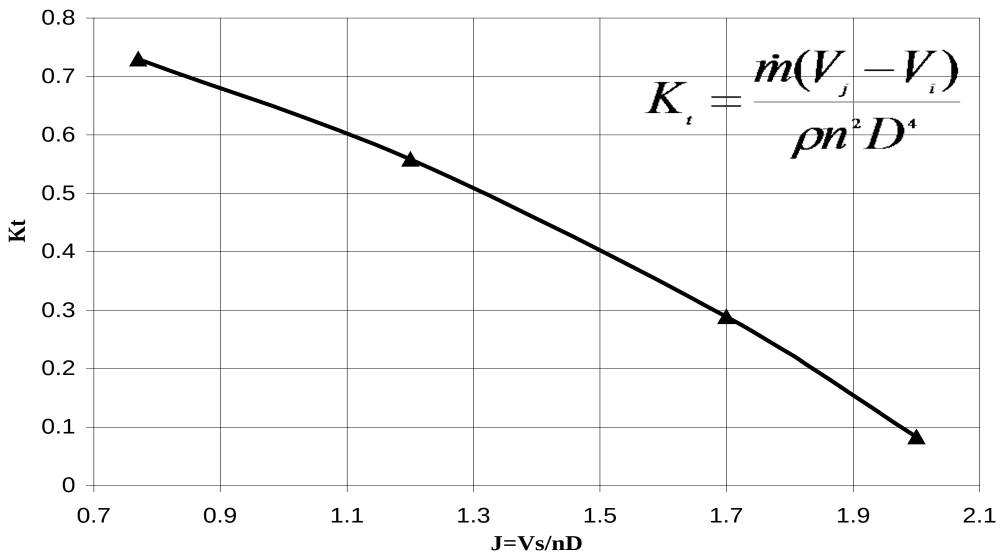

Figure 6. Thrust coefficient at various speeds

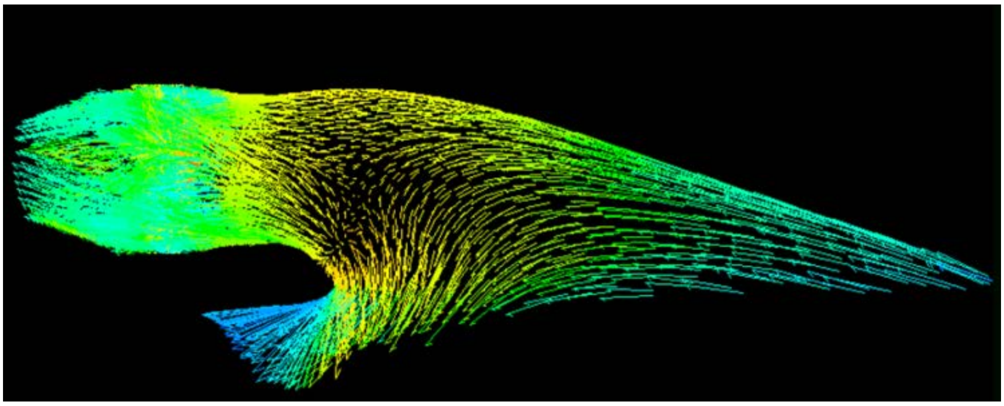

Figure 7. Flow velocity vector on the duct at J=1.7

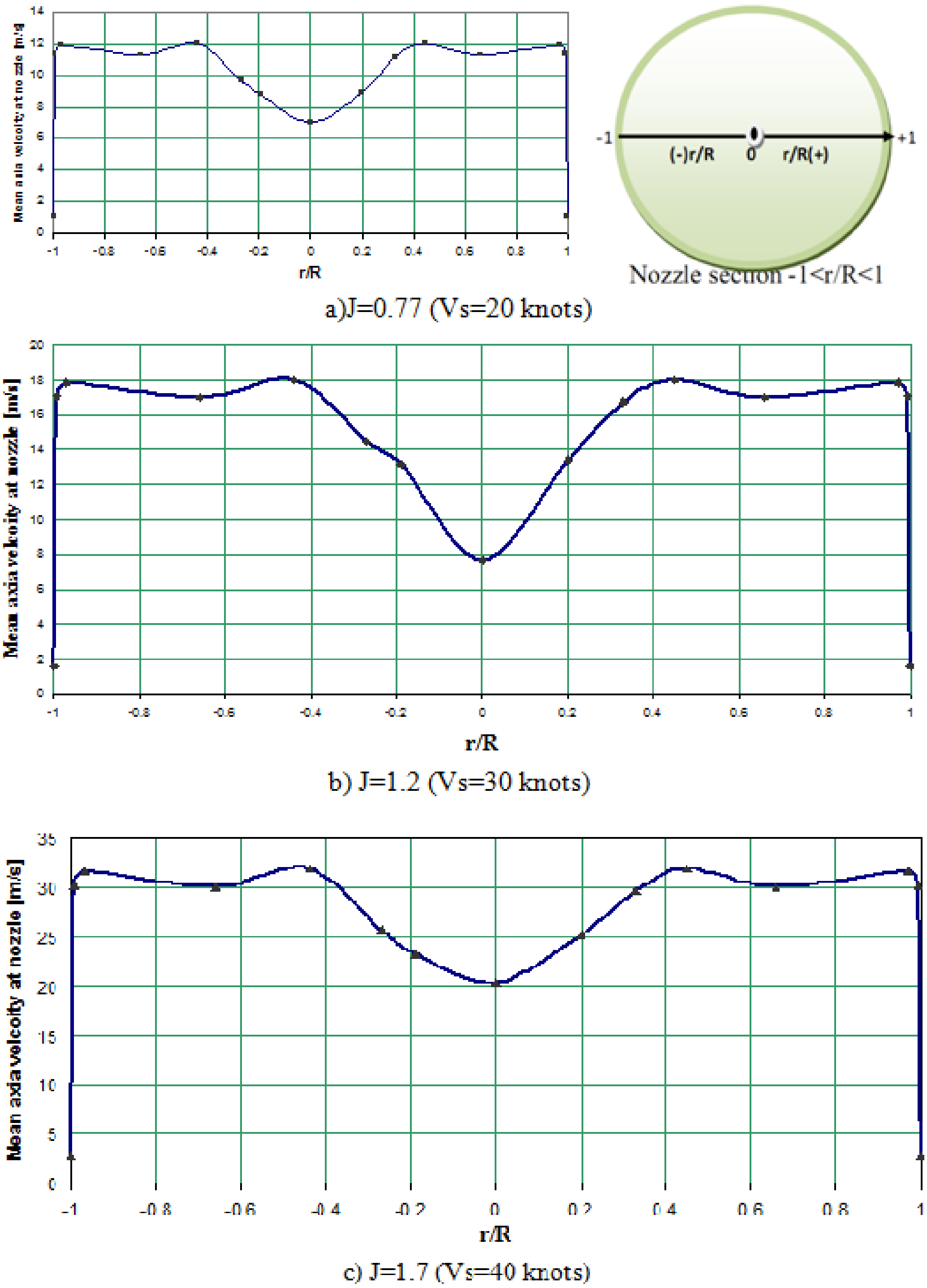

Figure 8. Axial velocity at nozzle at different velocities

5. Conclusions

A combine practical approach and numerical method are employed to design the waterjet propulsion system for the marine vehicle. Based on the results, the following conclusions can be drawn:

1. Main data of the waterjet determined by the practical method to generate the required thrust. Important value of nozzle velocity is obtained 1.44 times the intake velocity (almost equal to vehicle's speed) that is reasonable.
2. Pressure distribution coefficients on the rotor and thrust coefficients at different advance coefficients are obtained.
3. When the craft's speed is 40 knots (or 20.575 m/s), the average velocity at the jet is around 29 m/s (from Figure 8-c) and practical solution is obtained 28.15 m/s by Eq. (2). So, relative error is less than 3%.

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