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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF BUBBLE AUGMENTED WATERJET PROPULSION*

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Abstract: This contribution presents experimental and numerical investigations of the concept jet propulsion augmentation using bubble injection. A half-3D (D-shaped cylindrical configuration to enable optimal visualizations) divergent-convergent nozzle was designed, built, and used for extensive experiments under different air injection conditions and thrust measurement schemes. The design, optimization, and analysis were conducted using numerical simulations. The more advanced model was based on a two-way coupling between an Eulerian description of the flow field and a Lagrangian tracking of the injected bubbles using our Surface Averaged Pressure (SAP) model. The numerical results compare very favorably with nozzle experiments and both experiments and simulations validation the thrust augmentation concept. For a properly designed nozzle and air injection system, air injection produces net thrust augmentation, which increases with the rate of bubble injection. Doubling of thrust was measured for a 50% air injection rate. This beneficial effect remains at 50% after account for liquid pump additional work to overcome increased pressure by air injection.

Key words: waterjet, propulsion, bubble dynamics, multi-phase flow

Introduction

Bubble injection into a waterjet to augment thrust has received recent revived interest[1-5]. References [1,2] showed interesting results indicating that bubble injection can significantly improve the net thrust and overall self-propulsion efficiency of a water jet system. Several prior studies explored similar ideas, and some of these studies adopted the naming Water Ramjet to such a system by analogy to ramjet aerodynamic propulsion systems[4].

Analytical, numerical, and experimental evidence of the augmentation of jet thrust by bubble expansion in the jet stream, make the idea of bubble augmented thrust attractive. Unlike traditional propulsion devices which are typically limited to less than 50 knots, this propulsion concept promises thrust augmentation even at very high vehicle speeds[2].

Various prototypes have been developed and tested, e.g., Hydroduct, MARJET, and Underwater Ramjet[3,4,6]. Figure 1 shows how the concept works: fluid enters a diffuser where it is compressed (ram effect). It is then mixed with gas injected via ports at the end of the expansion area. The resulting two-phase mixture is then accelerated through a converging nozzle before exiting the propulsor nozzle. Prototypes of such systems have reported anecdotal net thrust from the injection of the bubbles under poorly controlled conditions. The performance is strongly affected by the efficiency and proper operation of bubble injection and mixing and the overall propulsion efficiency was reported typically to be less than that anticipated from the predictive models used. This may be a result of a poor mixing efficiency at the injection, possible flow chocking, or of weaknesses in the modeling[3].

Previous empirical and numerical studies of bubbly flows have modeled mixtures passing through a nozzle[3-5]. With these models, it was found that expansion of a compressed gas bubble-liquid mixture is an efficient way to generate the momentum necessary for additional thrust[1,2]. However strong approximations and simplifications in these models dictates that we develop a numerical tool which can provide a more detailed analysis of the two-phase flow, and

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which correctly includes the dynamic behavior of the injected bubbles and properly simulate water ramjet propulsion[1].

Fig.1 Concept sketch of bubble augmented jet propulsion

The approach we have developed consists of considering the bubbly mixture flow inside the nozzle from the following two perspectives:

(1) Microscopic level

Individual bubbles are tracked in a Lagrangian fashion, and their dynamics are followed by solving a “surface averaged pressure” Rayleigh-Plesset equation, where the driving pressure is obtained as an average over the bubble surface of the macroscopic solution. The bubble responds to its surrounding medium described by its mixture density, pressure, velocity, etc..

(2) Macroscopic level

Bubbles are considered collectively and the liquid bubble mixture is defined by a time and space void fraction distribution. The two-phase medium has a time and space dependent local density which is related to the local void fraction. The mixture density is provided by the microscale tracking of the bubbles, which provides bubble distribution and size, which determines the local volume fraction.

The two levels are fully coupled: the bubble dynamics are in response to the variations of the mixture flow field characteristics, and the flow field depends directly on the bubble position and size variations. This is achieved through two-way coupling between the unsteady Navier Stokes solver 3DynaFS-Vis© and the bubble dynamics and tracking code 3DynaFS-Dsm©. A quasi-steady version of the code was also developed, and was extensively used to conduct parametric studies useful for fast estimation of the overall performance of selected geometric design[3-5].

1. Numerical model

1.1 *Governing equations*

The two-phase mixture density and viscosity can be related to the void volume fraction, α, by:

$$\rho_m = (1-\alpha)\rho_l + \alpha\rho_g \tag{1}$$

$$\mu_m = (1-\alpha)\mu_l + \alpha\mu_g \tag{2}$$

where the subscript l represents the liquid and the subscript g represents the gas bubbles.

The two-phase mixture satisfies the following general continuity and momentum equations:

$$\frac{\partial\rho_m}{\partial t} + \nabla\cdot(\rho_m \boldsymbol{u}_m) = 0 \tag{3}$$

$$\rho_m \frac{\mathrm{D}\boldsymbol{u}_m}{\mathrm{D}t} = -\nabla p_m + \nabla\cdot\left(2\mu_m\delta_{ij} - \frac{2}{3}\mu_m\nabla\cdot\boldsymbol{u}_m\right) \tag{4}$$

where, the subscript m represents the mixture medium, and δ_{ij} is the Kronecker delta.

The flow field has a variable density because the void fraction varies in space and in time. This makes the overall flow field problem similar to a compressible flow problem.

1.2 *Lagrangian bubble tracking*

Lagrangian bubble tracking is accomplished by 3DynaFS-Dsm©[7] (or a corresponding Fluent User Defined Function called Discrete Bubble Model (DBM)). It is a multi-bubble dynamics code for tracking the motion and describing the dynamics of bubble nuclei released in a flow field. The user can select a bubble dynamics model, either the incompressible Rayleigh-Plesset equation or the compressible Keller-Herring equation[8,9]. In the first option, the bubble dynamics is solved by using a modified Rayleigh-Plesset equation improved with a Surface Averaged Pressure (SAP) scheme

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho_m}\left[p_v + p_{g0}\left(\frac{R_0}{R}\right)^{3k} - P_{enc} - \frac{2\gamma}{R} - \frac{4\mu_m\dot{R}}{R}\right] + \frac{|\boldsymbol{u}_{enc} - \boldsymbol{u}_b|^2}{4} \tag{5}$$

If the second option is adopted, the effect of liquid compressibility is accounted for by using the following Keller-Herring equation.

$$\left(1-\frac{\dot{R}}{c_m}\right)R\ddot{R} + \frac{3}{2}\left(1-\frac{\dot{R}}{3c_m}\right)\dot{R}^2 = \frac{1}{\rho_m}\left(1+\frac{\dot{R}}{c_m}+\frac{R}{c_m}\frac{d}{dt}\right)\cdot \left(p_v + p_{g0}\left(\frac{R_0}{R}\right)^{3k} - P_{enc} - \frac{2\gamma}{R} - \frac{4\mu_m\dot{R}}{R}\right) + \frac{|\boldsymbol{u}_{enc} - \boldsymbol{u}_b|^2}{4} \tag{6}$$

In the above equations, R is the spherical bubble radius, dots represent time derivatives, and c_m is the sound speed in the liquid at the bubble surface. Equations (5) and (6) are commonly used and describe nonlinear bubble oscillations in an incompressible or slightly compressible liquid valid when the bubble wall speed is small compared to the sound speed in the liquid. In this paper, for all cases considered the bubble growth rate (radial bubble wall speed) is very much smaller than the water sound speed, which justifies the use of either of the above two equations. These equations also assume a balance of normal stresses at the bubble wall

$$p_l = p_v + p_g - \frac{2\gamma}{R} - 4\mu \frac{\dot{R}}{R} \tag{7}$$

where p_g is the bubble gas pressure, p_v is the liquid vapor pressure, γ is the surface tension parameter and μ is the dynamic viscosity of the liquid. Since gas diffusion is very slow, we assume that the mass of gas inside each bubble does not change and that the bubble follows a polytropic compression law

$$p_g = p_{g0} \left(\frac{R_0}{R} \right)^{3k} \tag{8}$$

where k is the polytropic gas constant, p_{g0} is the initial bubble gas pressure, and R_0 is the corresponding initial bubble radius. P_{enc} is the ambient pressure "seen" by the bubble during its travel. With the SAP model, P_{enc} and $\boldsymbol{u}_{enc}$ are the average of the pressure over the surface of the bubble.

The bubble trajectory is obtained from the bubble motion equation[10]

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{u}_b}{\mathrm{d}t} = {} & F_D(\boldsymbol{u}-\boldsymbol{u}_b) + \frac{\rho_m}{\rho_b}\frac{3\dot{R}}{2R}(\boldsymbol{u}-\boldsymbol{u}_b) + \frac{\rho_m}{\rho_b}\boldsymbol{u}_b\frac{\partial \boldsymbol{u}}{\partial x} + \\ & \frac{1}{2}\frac{\rho_m}{\rho_b}\left(\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} - \frac{\mathrm{d}\boldsymbol{u}_b}{\mathrm{d}t}\right) + \frac{(\rho_b - \rho_m)}{\rho_b} g + \\ & \frac{K\nu^{1/2}\rho_m d_{ij}}{\rho_b R (d_{lk} d_{kl})^{1/4}}(\boldsymbol{u}-\boldsymbol{u}_b) \end{aligned} \tag{9}$$

The first term in Eq.(9) accounts for the drag force effect on the bubble trajectory. The drag coefficient FD is determined empirically as used in our previous studies[11-13]. The second and third term in Eq.(9) account for the effect of change in added mass on the bubble trajectory. The fourth term accounts for the effect of pressure gradient, and the fifth term accounts for the effect of gravity. The last term in Eq.(9) is the Saffman lift force due to shear. The coefficient K is 2.594, ν is the kinematic viscosity, and d_{ij} is the deformation tensor.

1.3 *0-D and 1-D modelling*

To study conditions where the flow can be considered one-dimensional with cross section averaged quantities, the governing equations for unsteady 1-D flow through a nozzle of varying cross-section, $A(x)$, can be written as

$$\begin{gathered} \frac{\partial \rho_m}{\partial t} + \frac{1}{A}\frac{\partial \rho_m u_m A}{\partial x} = 0, \\ \frac{\partial \rho_m u_m}{\partial t} + \frac{1}{A}\frac{\partial \rho_m u_m A u_m}{\partial x} + \frac{\partial p}{\partial x} = 0 \end{gathered} \tag{10}$$

where ρ_m, u_m, p are the mixture density, velocity and pressure, all dependent on x and t.

A one dimensional code, 1-D BAP, was developed for this study[3]. The liquid was assumed to be incompressible so that all compressibility effects of the mixture arose from the disperse gas phase only. The void fraction, α, is determined by the volume occupied by the bubbles per unit mixture volume, additionally, it is assumed that other than at the injection locations, no bubbles are created or destroyed. If we are interested in the steady solutions, the time derivatives terms in Eq.(10) can be ignored. In addition, if we assume that the bubbles remain spherical, the local bubble dynamics in the nozzle is governed by either of the two Eqs.(5) or (6) or by assuming that the bubbles are readily in static equilibrium with the local pressure. This quasi-steady approximation can be written by removing all dynamics components from the Rayleigh-Plesset equation. This method is further described in Ref.[5].

In addition to the 1-D model, an analytical 0-D model to predict thrust enhancement due to bubble injection was developed[5] starting from the mixture continuity and momentum equations in the expanding-contacting nozzle. The model takes into account the areas of the inlet section, the outlet section and the injection section. It also accounts for the pressure and velocity jumps at the injection location.

1.4 *3-D unsteady fully coupled modeling*

The 3-D coupling between the mixture flow field and the bubble dynamics and tracking is realized by coupling the viscous Eulerian code, 3DynaFS_Vis©, with the Lagrangian multi-bubble dynamics code 3DynaFS_Dsm©. The unsteady two-way interaction can be described as follows. The dynamics of the

Fig.2 Sketch of the test setup for the bubble augmented jet propulsion experiment

bubbles in the flow field are determined by the local densities, velocities, pressures, and pressure gradients of the mixture medium as described in Eqs.(5) to (9). The mixture flow field is influenced by the presence of the bubbles. The local void fraction, and accordingly the local mixture density, is modified by the migration and size change of the bubbles, i.e., the bubble population and size. The flow field is adjusted according to the modified mixture density distribution in such a way that the continuity and momentum are conserved through Eqs.(3) and (4).

The two-way interaction described above is very strong as the void fraction can change significantly (from near zero in the water inlet to as high as 70% at the nozzle exit) in Bubble Augmented jet Propulsion (BAP) applications. Void fractions based on the α-cell (cells where the local α's are computed) concept were introduced in the 3-D space to compute the void fraction[3].

1.5 *Thrust definitions*

We use two definitions for the thrust based on the application type. For ramjet type propulsion, where both inlet and outlet conditions are results of the engineering solution, the thrust of the nozzle can be computed by integrating the pressure and the momentum flux over the surface of a control volume that contains both the inlet and outlet of the nozzle.

$$T_R = \iint_A \left(p + \rho_m u_m^2 \right) \rho_m \mathrm{d}A \tag{11}$$

where u_m is the axial component of the mixture velocity.

For waterjet type applications, where the inlet conditions are provided by the available pump, the exit water jet momentum flux is the relevant quantity and the thrust of the nozzle can be defined as the integral only the momentum flux over the exit surface of the nozzle.

$$T_W = \iint_{A_o} \rho_m u_m^2 \mathrm{d}A \tag{12}$$

where A_o is the exit surface area of the nozzle.

Under the 1-D assumption, the expression for the thrust of the ramjet can be expanded as follows

$$T_R = \left(p_o A_o - p_i A_i \right) + \left(\rho_{m,o} A_o u_{m,o}{}^2 - \rho_{m,i} A_i u_{m,i}{}^2 \right) \tag{13}$$

where the subscripts i and o represent the inlet and the outlet of the ramjet respectively. The component of the thrust described in the first parenthesis in Eq.(13) is the contribution from the pressure variation between the inlet and the outlet. The terms in the second parenthesis represent the thrust due to the momentum change between the inlet and the outlet.

The thrust for a waterjet with the 1-D assumption can be simply written as

$$T_W = \rho_{m,o} A_o u_{m,o}{}^2 \tag{14}$$

We can define two normalized thrust augmentation, the first one, ξ, is defined as the net thrust increase with bubble injection normalized by the thrust without bubble injection as follows (the $_*$ indicates $_W$ or $_R$)

$$\xi = \frac{T_{*,\alpha} - T_{*,0}}{T_{*,0}} \tag{15}$$

in which $T_{*,\alpha}$ and $T_{*,0}$ are thrusts with and without bubble injection, and can be applied to either ramjet or water jet thrust.

The second one, ξ_m, is defined as the net thrust increase with bubble injection normalized by the inlet momentum flux as follows

$$\xi_m = \frac{T_{*,\alpha} - T_{*,0}}{T_{m-\text{inlet}}} \tag{16}$$

where $T_{m-\text{inlet}}$ is inlet momentum flux.

2. Experimental study

2.1 *Set-up*

The test setup used in this study is shown in Fig.2. The tests were conducted in Dynaflow's 72 ft wind-wave tank. The flow was driven by two 15 HP pumps (Goulds Model 3656), each of which is capable of producing a maximum flow rate of 550 gpm at a pressure head of 25 psi. The two pumps can work in parallel to boost the flow rate and a bypass line is used to adjust the flow rate. The nozzle test section is placed in a tank below the free surface. The wind wave tank is used as a very large water reservoir, so that the possible accumulation of air bubbles generated from the testing is minimized. A flow adaptor is used to convert the flow from a circular cross section to a matching cross section with the shape of the test section geometry. A flow straightening section is inserted between the flow adaptor and the nozzle inlet.

2.2 *Pressure and velocity measurements*

Variable reluctance type pressure transducer arrays are arranged in the nozzle walls to measure the pressures at different locations along the test section. Pressure signals are sent to the data acquisition system for data logging.

Various methods were used for velocity measurement depending on the experimental conditions:

(1) A planar PIV system was used to characterize the flow field without air injection or in the region before air injection.

(2) An optical bubble tracking method was used for velocity measurement for flows with low void fraction air injections when individual bubbles could be tracked to characterize the flow field.

(3) For flows with high void fraction which posed difficulties for optical method, Pitot tubes and Kiel probes were used for velocity measurement. Void fraction effects are corrected for using the following formula[14]

$$V_L = \frac{1}{\sqrt{\left(1 - \frac{\alpha^2}{2}\right)}} \sqrt{\frac{2\Delta P}{\rho_L}} \tag{17}$$

2.3 Void fraction measurements

The void fraction was measured or estimated using several methods:

(1) A nominal void fraction was obtained by dividing the air flow rate by the liquid flow rate.

(2) A photographic method was used to measure the void fraction with image analysis. This was applicable only to low void fraction media where the bubbles did not overlap too much in the images.

(3) The attenuation of laser light through the bubbly medium due to light scattering on the bubble surfaces.

(4) An acoustic method that utilizes DYNAFLOW's Acoustic bubble Spectrometer® (ABS) was used to measure bubble size distribution and integrate it to obtain the void fraction[15-17].

(5) Conductivity probes were used to measure conductivity and convert this to void fraction information. This method can be applied to a wide range of void fraction, but appears more accurate for the higher void fractions.

Fig.3 Experiment setup for exit momentum force measurement using a load cell

2.4 Thrust measurements

Additionally, a force load setup, as shown in Fig.3, was used to efficiently measure real time the exit momentum force directly using a force measurement plate. The plate had a dimension of 0.305 × 0.152 m and was placed in front of the BAP nozzle exit at a prescribed distance. Flow of the mixture coming out from the BAP impinged on the plate and the force applied on the plate was measured by a load cell (PCB Load and Torque Model 1102-115-03A with full scale of 200 lbf.). In order to capture as much as possible of the exit momentum with the force measurement plate, enclosure plates (side, top, bottom, and front plates) were used together with the force measurement plate such that the diverted flow could only exit from one direction which from the side was in a direction perpe- ndicular to the force load plate.

The air source for air injections was provided by a 5 hp air compressor (Compbell Hausfeld DP5810-Q) which has a rating of 25.4 CFM at 90 PSI.

Fig.4 Cut-through plane dimensions of original nozzle design with an expansion exit

Fig.5(a) CAD rendered drawing of the 3-D nozzle with an expansion without the side plate

Fig.5(b) CAD drawing of the complete nozzle with a flow adaptor and a flow straightener sections

Fig.6 Area changes of the half-circle cross section along the nozzle for different parametrically examined throat areas

Fig.7 The change of thrust normalized with inlet momentum flux with nominal void fraction at injection. The different colors correspond to the colors of the examined profiles shown in Fig.6

2.5 Propulsor/nozzle geometry design

In the study reported here, the nozzle was fully made of transparent Plexiglas to enable visualization. The geometry was half of a fully 3-D cylindrical axisymmetric divergent convergent nozzle with a vertical cut through a center plane. This set up represents the flow of the full 3-D nozzle and enables good flow visualization of the bubbles away from the cylindrical wall through the flat transparent plate in the symmetry plane. The initial design featured an expansion exit as well, as shown in Fig.4 in the cut-through plane as previously reported[3,4]. Figure 5 shows CAD drawings of the half 3-D nozzle with the expansion exit.

1D-BAP was used to evaluate the effects of the throat on the performance of the nozzle with an expansion exit. Figure 6 shows, for a parametric study, variations of the cross section outline along the nozzle for different throat geometries. Notice that the only varying parameter in these profiles is the diameter of the throat.

Figure 7 shows the predicted normalized thrusts for different nominal void fractions at injection for the different geometry profiles. The color of the thrust curve corresponds to the color of the nozzle geometry in Fig.6 The thrust is normalized by the inlet momentum flux defined as

$$\bar{T}_R = \frac{T_R}{\rho_l A_{\text{in}} V_{\text{in}}^2} \tag{18}$$

As indicated in Fig.7, the expansion exit actually causes a thrust decrease with bubble injection, this prompted the modification of the base nozzle design to a nozzle without the expansion exit section. Figure 8 shows the dimensions of the half 3-D nozzle, which has the same dimensions as those shown in Fig.4 without the expansion exit.

Fig.8 Dimensions of the half 3-D nozzle selected for testing

Fig.9 CAD drawing of the air injector positioned in the outer boundary of the nozzle. On the left is the injector assembly and on the right is an exploded view of the air chamber and porous membrane

2.6 *Air injection scheme*

In order to achieve as uniform bubble injection as possible, a porous medium air injector covering the outer half circular boundary of the nozzle was used. Figure 9 shows a CAD drawing of the outer air injector. A half circular air chamber was covered by a flexible porous plate that was curved to match the nozzle wall profile and was used as the nozzle boundary wall. Compressed air was forced through the porous plate to inject bubble streams in the propulsor flow. As shown on the right picture of Fig.9, the air chamber was partitioned into six separate small chambers and each chamber had its own air supply line such that more uniform air injection could be achieved by adjusting the pressured applied to each chamber and compensate for differences in porous plate properties and hydrostatic head.

Fig.10 Experimental setup for characterizing the bubbles generated from the porous plate

The flexible porous plate was 1/8 inch thick and has pores of 7 μm diameter. To characterize the bubble sizes generated from the flexible porous plate, an experiment as sketched in Fig.10, was used to measure the bubble size distribution obtained under different pressure and flow conditions. A 1 inch square porous plate was glued at one end of square Plexiglas tube and compressed air was applied to the other end of the tube and forced through the porous plate to generate bubbles.

Fig.11 Variation of bubble generation with different air injection rate

Figure 11 shows bubbles generated at different air flow rate, both the number of bubbles and the bubble sizes increase with increased air flow rate. The mean bubble radius was 860 μm, 1 100 μm, and 1 300 μm for air flow rates at 1 l/min, 2 l/min, and 3 l/min respectively in absence of shear or liquid flow.

Figure 12 shows a picture of bubbles generated from the outer air injector. Most of the bubbles were concentrated on the outer boundary, and the bubble concentration was significantly lower in the central region. In order to achieve a more uniform distribution, an inner air injection scheme, as show in Fig.13, was also designed to fit in the nozzle. The inner air injection consisted of a flat injector and a half circular injector with a total of three air injection faces, one on the flat injector and two on both sides of the circular injector.

Fig.12 Air injection from the outer air injector in the half 3-D BAP nozzle.

Fig.13 A sketch of the inner air injector

Fig.14 The simulation domain of the nozzle used to study the effects of the inner injector on the flow field of the nozzle

To study how the flow field in the nozzle was affected by the inner injector, we conducted preliminary liquid only CFD simulations. Figure 14 shows the simulation domain of the nozzle with the inner injector. A vertical symmetry plane was used to speed up the computation (Fig.15). Figure 16 shows comparisons of the pressure and velocity distributions with and without the inner air injector when the inlet velocity was 4.67 m/s (300 gpm). As shown in the figures, the effects of the inner injector on the flow field are not significant from both the pressures and the velocities. The differences of thrust in this case with and without the inner air injector were 0.3 N and 1.9 N for waterjet and ramjet thrusts respectively.

Fig.15 Close up of the inner injector grid

Fig.16 Comparison of the pressure distributions and velocity distributions along the nozzle with and without the inner injector

Fig.17 A snapshot of the 3-D nozzle set up with air injection

To achieve better control over the injected bubbles distribution, the inner air injector also has independent air chambers such that air supply to each air chamber can be adjusted to achieve overall uniform bubble injection. Combined with the outer air injector, a more uniform bubble injection can be achieved compared to using just a single air injector. Figure 17 shows a picture of the 3-D nozzle set up in the tank. As shown in the picture, multiple air hoses are connected to the chambers of the air injectors to control the air supply independently.

3. Numerical study

3.1 *Nozzle geometry optimization*

To study the effects of nozzle geometry on the thrust augmentation, a series of numerical studies were conducted to provide guidance for nozzle geometry optimization.

Fig.18 Variation of the normalized thrust augmentation (Eq.(16)) with normalized nozzle exit area at 2.4 m/s

Figure 18 shows the variation of the normalized ramjet thrust augmentation, ξ_m (Eq.(16)), with the normalized nozzle outlet area, C for inlet velocity 2.4 m/s. C is defined as the ratio of the exit area to the inlet area,

$$C = \frac{A_{\text{exit}}}{A_{\text{inlet}}} \tag{19}$$

As indicated in the figure, both 0-D BAP (a simplified analytic approach[4,5]) and 1-D BAP results show that in order to obtain a positive thrust augmentation gain, i.e., $\xi_m > 0$, the exit area has to be large enough such that C is greater than about 0.6. Figure 18 also shows that there is an optimal C value for different bubble injection void fractions, which is around 1.0. Notice that the base design shown in Fig.8 before has a C value of 0.27 that is well below the minimum C value for positive net thrust increase. This is consistent with the measurements[3].

Additionally, Fig.18 indicates that for a given nozzle inlet area, the net thrust increase is determined only by the exit area and is not controlled by the nozzle length and the cross sections variation in between. Therefore the easiest optimization to our experimental base nozzle was to cut short the exit contraction section such that C became close to the optimal value for thrust augmentation. Figure 19 shows the corresponding variation of ξ as defined in Eq.(15) with C. ξ indicates that there is a region with $0.75 < C < 1.0$, where the bubble injection is detrimental.

Fig.19 Variation of the normalized thrust augmentation with normalized nozzle exit area at 2.4 m/s

Fig.20 Variation of net thrust increase with nominal void fraction for different lengths of the half 3-D nozzle, and a nominal inlet velocity of 2.4 m/s

Fig.21 Variation of net thrust increase with nominal void fraction for different lengths of the half 3-D nozzle and a nominal inlet velocity of 3.57 m/s

Figure 20 and Fig.21 show 1-D BAP simulations of the net thrust increase if the nozzle contraction section was shortened differently from the base nozzle for nominal inlet flows of 2.4 m/s and 3.57 m/s. The resulting total BAP length is measured from the nozzle inlet. As shown in the figures, the best nozzle length for maximum net thrust increase falls between nozzle length of 0.9 m and 1.02 m, which correspond to C values of 1.46 and 0.78. Therefore, for the optimized nozzle used in this study, the converging section of the nozzle was cut down to 0.3153 m which gives a C value of 1.0 and a nozzle length of 0.9775 m. Figure 22 shows the dimension of the modified nozzle with a shortened converging section.

Fig.22 Dimensions of the modified half 3-D nozzle cut short from the base nozzle for optimal thrust augmentation

3.2 *Numerical thrust predictions*

Both 1-D and 3-D two-way coupled numerical simulations were conducted to evaluate the performance of the selected half 3-D nozzle geometry.

Fig.23 Pressure contours (a) and axial velocity contours (b) from 3-D computations at a nominal inlet velocity of 3.11 m/s without air injection

Figure 23 shows the pressures and flow velocities along the axial direction for a nominal inlet flow velocity of 3.11 m/s (200 gpm) without air injection. The pressure contours indicate that the pressure varies significantly along the axial direction but is quite uniform vertically. The velocity contours show that there are re-circulating zones near the air injection area.

Fig.24 Bubble size distribution for the bubble injection used in the 3-D two-way coupling simulation

In order to estimate the nozzle performance, 3DYNAFS© 3D two–way coupled simulations were conducted for different bubble injection rates at nominal inlet flow velocity of 3.11 m/s. Figure 24 shows the selected size distribution of the bubbles injected at a base line void fraction of 4.43%. Bubble distributions for higher void fractions have similar distribution shapes but the number of bubbles is multiplied by the ratio of the needed void fraction to the base line void fraction, the bubbles are injected into the flow through the inner and outer injectors.

Fig.25 Exit velocity profile from 3DynaFS_Vis© predictions for different void fractions of bubble injection at a nominal inlet velocity of 3.11 m/s.

Figure 25 shows the exit velocity profile for different void fractions. As the curves show, the profiles have similar shapes but the velocity magnitudes increase significantly with increased bubble injection. The average pressure and velocity distributions along the nozzle are shown in Fig.26 and Fig.27, and, as expected, higher bubble injection rates cause higher pressure increases at the inlet, and significantly higher exit velocity enhancements.

Fig.26 3DynaFS_Vis© results showing average pressure distributions along the nozzle for different nominal void fractions at a nominal inlet velocity of 3.11 m/s

Fig.27 3DynaFS_Vis© results showing average velocity variations along the nozzle for different nominal void fractions at a nominal inlet velocity of 3.11 m/s

Fig.28 Comparison of the normalized thrust augmentation computed from the 1-D and 3-D models for different nominal void fractions at a nominal inlet velocity of 3.11 m/s (needs to be reconciled with later comparison)

Figure 28 shows the predicted normalized net thrust increase, ξ_m, as a function of the void fraction obtained by the 0-D, 1-D-BAP, as well as the 3-D simulations. All simulations show positive net thrust for the 3-D nozzle. 0-D and 1-D results match closely. The predictions from the 1-D and 3-D codes match pretty well at low void fractions and start to deviate at void fractions higher than 20%, 3DynaFS_Vis© predicts higher thrust increase than what 1-D BAP predicts, the difference is due to the fact that 1-D BAP does not fully consider bubble dynamics as 3DynaFS_Vis© does. These effects become stronger as the void fraction increases.

4. Results

4.1 *Effects of air injection on inlet flow*

To examine the effects of air injection on the inlet flow condition, the fluctuations of the inlet flow rate with and without air injection were examined systematically with the pump and valve settings being maintained the same. Figure 29 shows the inlet flow rate fluctuations (defined as the ratio of the flow rates, $(Q_{\max} - Q_{\min})/Q_{ave}$, where $Q_{\max}$, $Q_{\min}$, and Q_{ave} are the measured maximum, minimum, and average flow rates) with and without air injection at different flow conditions, the fluctuations were less than 4% in any test conditions, and air injection did not have any noticeable effects on the inlet flow rate. Therefore, no flow rate adjustment was performed in the thrust measurement tests and the inlet velocity profile was assumed to be the same for the same flow rate regardless of air injection condition.

Fig.29 Air injection had no noticeable effects on inlet flow rate fluctuations. The dimensionless fluctuation is defined as the ratio $(Q_{\max} - Q_{\min})/Q_{ave}$

4.2 *Performance of force measurement plate*

As expected, the placement of the force measurement plate has noticeable effects on the force measured. Figure 30 shows the force measured by the load cell under different void fractions and inlet flow rate conditions when the force measurement plate was placed at three different standoff distances from the nozzle exit. It is clear from the tests that at the largest tested standoff distance of 5.338 inch, the force measurement plate captures the most of the exit momentum force. Therefore all the force measurement results reported afterward were obtained with the force measurement plate position at that 5.338 inch distance from the nozzle exit.

Fig.30 Load cell force measurement versus void-fraction for different water flow rates and different stand-off distances of the measurement plate from the exit

Fig.31 Fraction of the total exit momentum force captured by the force measurement plate at different exit mixture flow rate (with and without air injection)

The efficiency of the force measurement plate in capturing the exit momentum force was also examined at different inlet flow rare and air injection conditions. Figure 31 shows the variation of ratio of the force captured by the force measurement plate, $F/\rho_l Q_l V_l$, with the exit mixture flow rate, $Q_l/(1-\alpha)$, in which, Q_l is the liquid flow rate and V_l is the liquid velocity at the exit which is assumed to be the same as the mixture velocity. As shown in the figure, the fraction of the exit momentum force decreases when the exit mixture flow rate increases and reaches to a plateau. A fourth order polynomial curve fitting given by the following,

$$y = -7.45\ 10^{-9}\ Q_m^{\ 3} + 1.14\ 10^{-5} Q_m^{\ 2} - 5.82\ 10^{-3} Q_m + 1.66 \tag{20}$$

captures the trend pretty well, in which Q_m is the exit mixture flow rate and y is the corresponding capture efficiency of the exit momentum force of the force measurement plate. When compared with the numerical simulations, the measured thrust force, T_*, was corrected by the capture efficiency, y, from the force directly measured by the load cell as follows

$$T_* = \frac{F}{y} \tag{21}$$

4.3 *Effects of air injection on net thrust*

From the 0-D BAP theory, the normalized thrust increase can be expressed as follows

$$\frac{T_\alpha - T_0}{T_0} = \frac{\rho_l (1-\alpha) A_0 u^2_{L,\text{outlet},\alpha} - \rho_l A_i u^2_{L,\text{inlet},0}}{\rho_l A_i u^2_{L,\text{outlet},0}} \tag{22}$$

Since for the nozzle geometry under consideration, $A_o = A_i$, $u^2_{L,\text{outlet},0} = u^2_{L,\text{inlet},0} = u^2_{L,\text{inlet},\alpha}$, therefore

$$\frac{T_\alpha - T_0}{T_0} = (1-\alpha)\left(\frac{u^2_{L,\text{outlet},\alpha}}{u^2_{L,\text{inlet},\alpha}}\right) - 1 \tag{23}$$

From the mixture continuity equation, we know that

$$\rho_l (1-\alpha) u_{L,\text{outlet},\alpha} = \rho_l u_{L,\text{inlet},\alpha} \tag{24}$$

Therefore,

$$\frac{T_{p,\alpha} - T_{p,0}}{T_{p,0}} = \frac{1-\alpha}{(1-\alpha)^2} - 1 = \frac{\alpha}{1-\alpha} \tag{25}$$

Extensive experiments were conducted to study the effects of air injection on the nozzle thrust. In addition to the direct force measurements using the load cell, pressure and velocity measurements were also conducted at the nozzle inlet and exit. Figure 32 shows the test matrix of void fraction and inlet liquid flow rate in the experimental study, void fraction ranged from 0 up to 50% and the inlet velocity range from 3.1 m/s (200 GPM) to 9.3 m/s (600 GPM).

Figure 33 shows the variations of the normalized net thrust increase with void fraction, obtained from both numerical simulations and experiments. The numerical and experimental results agree very well with each other and follow the theoretic prediction of $\alpha(1-\alpha)$, which proves that the nozzle become more efficient in net thrust increase with increased void fraction.

The thrust in Fig.33 is the waterjet thrust. In the discussion below, we evaluate the nozzle performance using a ramjet thrust by including the loss from inlet pressure changes. The air injection causes inlet pressure increase, which means that the water jet pump needs to work harder to overcome this additional resistance from the air injection. To examine this effect, the variation of the normalized inlet pressure increase with the void fraction is plotted in Fig.34. This figure shows that the normalized inlet pressure increases almost linearly with the void fraction.

Fig.32 Experimental conditions showing the coverage range of air injection and liquid flow rate

Fig.33 Variation of normalized net thrust with void fraction

Fig.34 Normalized pressure increase at inlet versus void fraction

This effect does not however cancel out the thrust gain observed in Fig.33. As shown in Fig.35, with increasing void fraction, the normalized thrust gain, obtained by subtracting the normalized inlet pressure force from the normalized thrust increase, increases. As a result, the net total thrust becomes larger and larger indicating increased thrust gain with higher void fraction even after factoring in the inlet pressure force increase.

Fig.35 The net thrust increase vs. void fraction, obtained from subtracting the inlet pressure force in Fig.34 from the thrust gain in Fig.33

5. Conclusions

This contribution described experimental and numerical investigations of waterjet nozzle propulsor thrust enhancement thorough bubble injection. Numerical modeling was based on two-way coupling between a model of the mixture flow field and Lagrangian tracking of the injected bubbles. The experimental studies were performed on a laboratory large scale nozzle to validate and compare with the numerical results.

To better study the physics of a real BAP while maintaining good accessibilities for experimental measurements, half 3-D nozzles were built and studied. Numerical studies were used to obtain an optimal nozzle geometry to produce the best net thrust increase. An efficient thrust measured scheme was implemented to directly measure the exit momentum force. Comprehensive experiments were conducted to cover a wide range of air injection condition. Results from numerical simulation and experiment agree very well and proved that a well designed nozzle can obtain net thrust increase with air injection, and the nozzle performance of net thrust increase improves with increase void fraction. Thrust increases as high as ~100% were measured with a void fraction of ~50%. Corrections with pump output pressure increases reduce the enhancement to about 70%, still a very significant improvement.

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