Waterjet Thrust Augmentation using High Void Fraction Air Injection

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ABSTRACT

Waterjet thrust can be enhanced by bubble injection in the exit nozzle as demonstrated with earlier experiments with void fractions up to 15% (Wu et al., 2010). Efforts to investigate thrust increases with higher void fractions are presented here. A four inch outlet diameter laboratory scale nozzle was used, and air injections as high as 50% were tested. This was achieved using improved nozzle geometry with a carefully designed air injection section. Net thrust augmentations attaining 70% were measured. The numerical predictions compared well with the experimental results. The analysis was further extended to include compressible shock modeling, and parametric studies are being conducted to explore the feasibility of a new design that exploits a choked flow.

INTRODUCTION

Injection of air into a waterjet to augment thrust has been suggested for decades with the aims to significantly improve the net thrust and overall propulsion efficiency of a water jet. 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 (e.g. Mor and Gany, 2004). Analytical, numerical, and experimental evidence (Tangren et al., 1949, Muir and Eichhorn, 1963, Ishii et al., 1993, Kameda and Matsumoto, 1995, Wang and Brennen, 1998, Preston et al., 2000, Albagli and Gany, 2003, Mor and Gany, 2004, Chahine et al., 2008, Wu et al., 2010, Gany and Gofer, 2011) showing that bubble injection can significantly improve the net thrust of a water jet make the idea of bubble augmented thrust attractive.

Figure 1 illustrates the concept: the liquid entering the diffuser is first compressed and then it is mixed with high pressure gas injected via mixing ports. The resulting multiphase mixture is then accelerated in the converging nozzle. The resulting pressure drop makes the injected bubbles increase volume and this converts the potential energy in the bubbles into liquid kinetic energy, jet momentum, and this boosts the jet thrust.

Various prototypes were developed and tested, e.g.: Hydroduct by Mottard and Shoemaker (1961), MARJET by Schell et al. (1965), underwater Ramjet by Mor and Gany (2004). Anecdotal net thrust increase due to the injection of the bubbles was reported. However, the performance appeared strongly related to the efficiency and proper operation of the bubble injector and the overall propulsion efficiency was typically less than that anticipated from the mathematical models used. Concepts have not been realized in any operational vessel yet (Gany and Gofer, 2011). The discrepancy between the numerical and experimental results may be due to poor mixing efficiency at the injection, possible flow chocking or weaknesses in the modeling (Varshay, 1994, 1996).

By utilizing more detailed analysis of the two-phase flow in numerical models that include the dynamic behavior of bubbles and with better controlled air injection scheme in experiments, better agreement between numerical simulation and experiments were found (Chahine et al., 2008, Wu et al. 2010). These studies also showed numerically that the geometry of the BAP nozzle plays a significant role on the performance and efficiency of a Bubble Augmented Propulsion (BAP) system, and there was an optimal geometry that maximized thrust augmentation.

The present study extends previous results to higher void fractions (up to 50%), and extends the 1D
or the following Keller-Herring equation that considers the effect of liquid compressibility

\[
\rho_b \left( 1 - \frac{R}{c_m^2} \right) RR + 3 \frac{\rho_b}{2 \rho_m} \left( 1 - \frac{R}{3c_m^2} \right) R^2 = \rho_b \frac{|u_{enc} - u_b|^2}{4} + \\
\left[ 1 + \frac{R}{c_m^2} + \frac{R}{c_m} \frac{d}{dt} \left( \frac{R}{R} \right) \right] \left( p_e + p_{\gamma} \right) \left( \frac{R}{R} \right)^{1/3} - P_{enc} - 2\frac{\gamma}{R} - 4\frac{\mu_b R}{R}
\]  

(6)

In the above two equations, \( R \) is the bubble radius at time \( t \), \( R_0 \) is the initial or reference bubble radius, \( \gamma \) is the surface tension parameter, \( \mu_m \) is the medium viscosity, \( \rho_m \) is the density, \( \rho_b \) is the liquid vapor pressure, \( p_{\gamma} \) is the initial gas pressure inside the bubble, and \( k \) is the polytropic compression law constant. \( u_{enc} \) is the liquid average velocity vector at the bubble location, \( u_b \) is the bubble travel velocity vector, and \( P_{enc} \) is the average ambient pressure “seen” by the bubble during its travel, and \( c_m \) is the local speed of sound in the bubbly mixture.

The bubble trajectory is obtained from a bubble motion equation similar to that derived by Johnson and Hsieh (1966):

\[
\frac{\rho_b}{\rho_x} \frac{d u}{dt} = F_D \frac{\rho_b}{\rho_m} (u - u_b) + 3 \frac{\rho_b}{2R} (u - u_b) + u_b \frac{d u}{d x} + \frac{1}{2} \left( \frac{d u}{dt} \right)^2 + \frac{\rho_b}{\rho_x} \left( \frac{\rho_b}{\rho_m} - 1 \right) \frac{d x}{d t} + \frac{K v^{1/2} \rho_b \sigma_d}{\rho_m R (d_b d_l) v^{1/2}} (u - u_b),
\]

(7)

The right hand side of Equation (7) is composed of various forces acting on the bubble. The first term accounts for the drag force, where the drag coefficient \( F_D \) is determined by the empirical equation of Haberman and Morton (1953). The second and third term in Equation (7) 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 Equation (7) is the Saffman (1965) lift force due to shear as generalized by Li & Ahmadi (1992). The coefficient \( k \) is 2.594, \( v \) is the kinematic viscosity, and \( d_b \) is the deformation tensor.

1-D MODELING

In the present study, a 1D version of the above approach is used (Chahine et al., 2008, Singh et al., 2010). When average quantities in a cross section of a nozzle are considered, 1-D unsteady model can be reduced from the above governing equations into a simplified form:

\[
\frac{\partial \rho_m}{\partial t} + \frac{1}{A} \frac{\partial \rho_m u_m}{\partial x} = 0,
\]

(8)
\[
\frac{\partial \rho_m u_m}{\partial t} + \frac{1}{A} \frac{\partial \rho_m A_m u_m}{\partial x} + \frac{\partial p}{\partial x} = 0,
\]

where \( A \) is the local cross-sectional area of the nozzle. The liquid is assumed incompressible and the dispersed gas phase contributes to all the compressibility effects of the mixture. It is also assumed that no bubbles are created or destroyed other than at the injection location.

In addition, an analytical 0-D model was used to optimize the nozzle geometry for maximum thrust enhancement (Singh et al., 2010). This approach further simplifies the equations and only requires knowledge of the areas at the inlet, the outlet and the injection section, as well as the pressure and velocity jumps at the injection location.

**THrust AUGMENTATION PARAMETERS**

Based on the application type, two definitions for thrust calculations can be used (Chahine et al., 2008, Wu et al. 2010). For ramjet type propulsion, the thrust of the nozzle is computed as follows:

\[
T_R = \iiint_A \left( \rho + \rho_m u_m^2 \right) \, dA,
\]

where \( u_m \) is the axial component of the mixture velocity, and the surface integration is taken over a control surface, \( A \), that encompass both the inlet and the outlet.

For waterjet type applications, the thrust of the nozzle is computed from:

\[
T_W = \iiint_A \rho_m u_m^2 \, dA,
\]

where \( A_e \) is the exit surface area of the nozzle.

Under the 1-D assumption, the thrust for the ramjet and waterjet can be simplified to:

\[
T_R = \left( p_o A_o - p_i A_i \right) + \left( \rho_m A_o u_m^2 - \rho_m A_m u_m^2 \right),
\]

\[
T_W = \rho_m A_o u_m^2,
\]

where \( A_i \) and \( u_{m,i} \) are respectively the inlet area and medium velocity.

To evaluate the performance of a nozzle design with air injection, we define a normalized thrust augmentation parameter, \( \xi \), as following:

\[
\xi = \frac{T_{i,a} - T_i}{T_i}, \quad i = R \text{ or } W,
\]

in which \( T_{i,a} \) and \( T_i \) are thrusts with and without bubble injection.

We can also define a normalized thrust augmentation parameter, \( \xi_m \), as the net thrust increase with bubble injection normalized by the inlet momentum flux, \( T_{m-inlet} \), as following:

\[
\xi_m = \frac{T_{i,a} - T_i}{T_{m-inlet}}, \quad i = R \text{ or } W.
\]

**OPTIMIZED 3-D NOZZLE GEOMETRY**

Numerical simulations have shown that thrust augmentation can be optimized with geometrical dimensions selected (Wu et al. 2010). For instance, the ratio of the exit area to the inlet area or the contraction,

\[
C = A_e / A_i,
\]

is an important design parameter. Figure 2 shows the variation of the normalized thrust augmentation, \( \xi_m \), with the contraction for an inlet velocity of 2.4 m/s. The numerical results (Sing et al, 2010) show that the exit area has to be large enough to satisfy \( C > 0.6 \) to obtain thrust augmentation, i.e. \( \xi_m > 0 \). Figure 2 also shows that there exists an optimal \( C \) value for different bubble injection void fractions, and that the optimal \( C \) value is around 1.0. Additionally, Figure 2 indicates that for a given nozzle inlet area, the net thrust increase is determined only by the exit area and is not controlled in a major way by nozzle length and cross sectional variation between the inlet and the outlet, since the 0D-BAP, which ignores those parameters, provides answers very close to the more complete simulation.

**Figure 2:** Variation of the normalized thrust augmentation with normalized nozzle exit area at inlet velocity 2.4 m/s for TR, ramjet thrust.
Based on these numerical simulations, an optimized nozzle with equal inlet and exit areas were designed and built for this study. Figure 3 shows the dimension of this nozzle used in the experimental study presented below.

Figure 3: Dimensions of the half 3-D nozzle designed and built for optimal thrust augmentation.

**MODELING OF A CHOKE FLOW**

When bubbles are injected continually and steady state conditions are achieved, the 1-D model described above reduces to the following form:

\[
\frac{\partial}{\partial x} \left( \rho_m u_m A \right) = 0, \quad \left(16\right)
\]

\[
\frac{1}{A} \frac{\partial}{\partial x} \left( \rho_m u_m A u_m \right) + \frac{\partial p}{\partial x} = 0. \quad \left(17\right)
\]

By neglecting the density of the injected air relative to the liquid density, \( \rho_m \) reduces to

\[
\rho_m = \rho_l \left(1 - \alpha\right). \quad \left(18\right)
\]

The void fraction, \( \alpha \), can be connected to the pressure through an equation of state for the mixture, which depends on the gas polytropic compression law constant \( k \), as follows (Brennen, 1995):

\[
\frac{p}{p_{ref}} = \left[ \frac{\alpha_{ref} \left(1 - \alpha\right)}{\alpha \left(1 - \alpha_{ref}\right)} \right]^{\frac{1}{k}}, \quad \left(19\right)
\]

where \( p_{ref} \) is the reference pressure corresponding to a reference void fraction of \( \alpha_{ref} \). Here \( k \) can be taken to be 1 (isothermal conditions) since the gas bubbles execute relatively slow and small amplitude oscillations.

Equation (17) can be integrated accounting for (18) and (19) to obtain the mixture velocities in the nozzle as functions of the local gas volume fraction and the reference quantities \( \left( u_{m,ref}, c_m \right) \) of the mixture where the pressure is \( p_{ref} \) and the void fraction is \( \alpha_{ref} \).

\[
u_m^2 - u_m^2 = \frac{2 k p_{ref} \alpha_{ref}}{\rho_l \left(1 - \alpha_{ref}\right)} \left[ \frac{1 - \alpha}{\alpha_{ref}} - \frac{1 - \alpha_{ref}}{1 - \alpha_{ref}} \right] \frac{1}{\alpha_{ref} (1 - \alpha_{ref})} \ln \left( \frac{1 - \alpha_{ref}}{1 - \alpha_{ref}} \right). \quad \left(20\right)
\]

Of the two solutions in (20), one solution corresponds to subsonic flow and the other to supersonic flow.

The momentum equation (17) can be expanded and rewritten in the following form:

\[
1 \frac{dA}{dx} u_m^2 \rho_m + u_m \frac{d \rho_m}{dx} + 2 \rho_m u_m \frac{du_m}{dx} = - \frac{dp}{dx}, \quad \left(21\right)
\]

which after use of the continuity equation (16), simplifies to:

\[
\rho_m dA u_m dx = \frac{dp}{dx}. \quad \left(22\right)
\]

By combining (21) and (22) and rearranging, we obtain the following expression:

\[
1 \frac{dA}{dx} = \frac{1}{u_m^2 \rho_m} \frac{dp}{dx} - \frac{1}{\rho_m} \frac{d \rho_m}{dx}. \quad \left(23\right)
\]

Using the expression for the sound speed,

\[
c_m^2 = \frac{dp}{d \rho_m}, \quad \left(24\right)
\]

\[
c_m^2 = \frac{k p_{ref} \left(1 - \alpha\right)^{\alpha_{ref} - 1}}{\rho_l \alpha_{ref}^{\alpha_{ref} - 1} \left(1 - \alpha_{ref}\right)} \left[ \frac{1}{k} \right], \quad k \neq 1,
\]

\[
c_m^2 = \frac{p_{ref}}{\rho_l} \left[ \frac{1}{\alpha} \left(1 - \alpha_{ref}\right) \right], \quad k = 1,
\]

Equation (23) gives the following relation connecting the area gradient to the pressure gradient within the 1-D nozzle:

\[
1 \frac{dA}{dx} = \frac{1}{\rho_m} \frac{d \rho_m}{dx} \left[ 1 - c_m^2 \right]. \quad \left(25\right)
\]

From Equation (25), one can see that if the nozzle geometry is such that \( dA/dx = 0 \) at a given location, then either a zero pressure gradient occurs at that location, \( dp/dx = 0 \), or the liquid speed equals the sound speed of the medium, \( u_m = c_m \) (choke flow). Therefore, if a throat is present in the nozzle, the mixture speed can reach there the sound speed and the flow can transition from a subsonic regime (upstream of the throat) to a supersonic regime (downstream of the throat).
Under choked conditions, the void fraction at the throat, \( \alpha_r \), can be computed by equating the mixture speed, \( u_m \) (20), to the sound speed, \( c_m \) (24):

\[
\frac{1}{2\alpha_r^2} = \frac{1}{\alpha_r} - \frac{1}{\alpha_s} + \ln \left( \frac{(1-\alpha_{ref})\alpha_r}{(1-\alpha_r)\alpha_{ref}} \right) \frac{u_m^2}{2p_{ref}\alpha_{ref}}. 
\] (26)

For a typical nozzle designed for thrust enhancement by bubble injection sketched in Figure 4, if choked flow occurs then the problem may be broken down into three regions:

- Liquid flow through a diverging nozzle,
- Flow across the injection section,
- Bubbly choked flow after the injection section.

Equations (16), (17), (18), (19), (20) and (26) can be solved for flow quantities in the nozzle after the injection section. The velocity and the pressure immediately after the injection, \( V_{inj} \) and \( p_{inj} \), can be related to the injected void fraction, \( \alpha_i \), by the following relationships (Singh et al., 2010):

\[
V_{inj} = (1-\alpha_i)V_{m}, \\
p_{inj} = p_{m} + \rho_i V_{inj}^2 (1-\alpha_i), \\
A_{inj}V_{inj} = A_{inlet}V_{inj}, \\
p_{inj} + \frac{\rho_i}{2}V_{inj}^2 = p_{m} + \frac{\rho_i}{2}V_{inj}^2.
\] (27)

In the above relations, \( V_{inj} \) is the mixture velocity just before injection, \( p_{inj} \) is the pressure just before injection, \( A_{inj} \) is the area of the injection section, and \( A_{inlet} \) is the area of the inlet section. Given the geometry of the nozzle and the injected void fraction, the above system of equations can be solved (with specified inlet/upstream pressure) to compute the exit pressure, the exit velocity and the inlet velocity under choked conditions.

Once the throat void fraction is obtained by solving equation (26), the velocity and void fraction at any location after the injection section can be obtained by simultaneously solving the continuity equation (16) along with the equation for mixture velocity (20). Two solutions result each for the mixture velocity and the void fraction. The solution pair with a void fraction greater than the throat void fraction apply for the region downstream of the throat and the solution pair with a void fraction less than the throat void fraction apply for the region upstream of the throat. Once the void fraction at a given location is known, the pressure at that location is obtained using the equation of state (19). Once these flow quantities are known, the thrust for the geometry under choked conditions can be computed.

![Figure 4: Typical Nozzle Design for thrust enhancement by bubble injection.](Image)

**CHOKED NOZZLE DESIGN STUDY**

The BAP geometry with a throat shown in Figure 5 is used to demonstrate a choked flow computation, using the 0-D BAP model. The geometrical conditions \( A_{throat}/A_{inlet}=1.06 \), \( A_{exit}/A_{inlet}=2.4 \), an upstream pressure, \( p_{inlet}=5 \) atm, and \( \alpha_i=0.2 \) are used for the computations.

Figure 6 through Figure 8 show the axial distributions of flow quantities downstream of the injection section. Under choked conditions, the flow makes a transition from the subsonic regime to the supersonic regime across the throat where the mixture velocity becomes equal to the mixture sound speed at the throat (about 30 m/s for these conditions). This can be seen clearly in Figure 7. Because of this transition, in the section after the throat, the void fraction and the mixture velocity continue to increase (contrary to the subsonic case) and the pressure continues to decrease even though the cross-sectional area of the nozzle increases. This, in turn, results in very high exit velocities and thereby very high momentum thrust.

Would the flow have remained subsonic (as illustrated in the figures), the presence of a throat merely increases the flow velocity and decreases the pressure in the converging section and then bring them back to the previous state in the expansion section. In subsonic flow, the throat does not provide any gain in thrust.

![Figure 5: Geometry of an expanding-contracting nozzle incorporating a throat.](Image)
Considering a $A_{\text{throat}}/A_{\text{inlet}}=1.06$ and $p_{\text{inlet}}=5$ atm, a parametric study was performed to understand the effect of the influence of the contraction area ratio, $A_{\text{exit}}/A_{\text{inlet}}$, on the normalized thrust augmentation parameter, $\xi_m$. Figure 9 shows the resulting thrust augmentation curves. This shows that under choked conditions, the optimum $A_{\text{exit}}/A_{\text{inlet}}$ is found to be about 2.4 for an injected void fraction of 0.2 and about 2.0 for an injected void fraction of 0.4, while the optimum $A_{\text{exit}}/A_{\text{inlet}}$ was 1.0 under subsonic conditions.

**SETUP FOR EXPERIMENTAL STUDY**

The test setup used in this study is shown in Figure 10. The flow can be driven by two 15 HP pumps (Goulds Model 3656) with each pump capable of a flow rate of 2.1 m$^3$/min (550 gpm) at 170 kPa (25 psi) pressure head. 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 below the free surface in DYNAFLOW’s wind wave tank, which is used here as a very large water reservoir, so that accumulation of air bubbles generated from the testing is minimized. A flow adaptor is used to convert the flow from the inlet pipes circular cross section to match the cross section shape of the nozzle assembly.
geometry. A flow straightening section is inserted between the flow adaptor and the nozzle inlet.

We used a 3-dimensional set up, which was half of the full three dimensional axisymmetric nozzle with a vertical cut through a center plane. This set up represents the flow of the full three dimensional nozzle more closely and enables good flow visualization through the flat transparent center-plane.

Instrumentation was provided for flow rate, pressures, velocities, and void fractions measurements as in (Chahine et al., 2008, Wu et al. 2010). Additionally, a direct momentum force measurement scheme was designed using a submerged PCB load cell. A high capacity air compressor (Campbell Hausfeld DP5810-Q) had a rating of 0.72 m³/min (25.4 CFM) at 620 kPa (90 psi).

Figure 10: Sketch of the test setup for the Bubble Augmented Jet Propulsion experiment.

In order to achieve a bubble distribution as uniform as possible, a half circular air injector made from a flexible porous membrane was used to cover the inner half circular boundary of the nozzle (Figure 11). In order to achieve higher void fraction and better air distribution near the centerline of the nozzle, a center-body was inserted in the nozzle (Figure 12). This center-body air injector consisted of a flat plate with a porous face and a half cylinder with porous surfaces on both sides.

Figure 11: 3D rendering 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.

Figure 12: A sketch of the inner air injector.

Figure 13: Picture of the nozzle with direct force measurement.

Figure 13 shows a picture of the 3D nozzle at low air injection rates for an incoming water flow rate of 0.76 m³/min (200 gpm). Figure 14 shows a close up of the contraction section at 0.87 m³/min (230 gpm) inlet water flow and 16% void fraction.

FLOW STRUCTURING OF EXIT FLOW

Flow visualizations were conducted using high speed motion pictures. These showed clear large scale flow structures of the mixture once the two-phase medium exited the BAP nozzle. Figure 15 shows an example of such flow structuring at the exit.

To quantify the flow structuring, the video images were analyzed to extract the frequency of the main flow structures. Figure 16 shows the variation of the average flow structure frequency with the void fraction at different flow rates. This indicates that the flow structure frequency increases with the flow rate and decreases with the void fraction. The frequency, f, can be normalized as a Strouhal number:

\[ S = \frac{fD}{V}, \]

(28)

where \( D \) is the nozzle exit diameter, and \( V \) is the mean exit velocity. As show in Figure 17, normalization brings the different flow rate curves almost on top of each other, and the Strouhal number decreased with the void fraction regardless of the water flow rate.
Figure 14: View of the contraction section of the BAP nozzle. Higher void fraction are seen in the top section as bubbles rise under gravity. Nominal inlet velocity is 3.57 m/s and nominal void fraction at injection is 16%.

Figure 15: Visualization of the large flow structures in front of the BAP nozzle exit.

Figure 16: Variation of the flow structuring frequency with the void fraction at different water flow rates.

Figure 17: Normalized flow structure frequency variation with void fraction at different flow rate.

FORCE MEASUREMENTS

In our previous studies, the thrust augmentation was computed from velocity and pressure measurements. In the present study, force was measured by using a setup as sketched in Figure 18. The part of the exit momentum force impacting directly on a force measurement plate was recorded.

Figure 19 shows a picture of the plate mounted in front of the BAP exit. The plate had the dimensions of 30.5 cm (12 in.) by 15.2 cm (6 in.) and was placed downstream of the nozzle exit at prescribed distances. Flow of the mixture coming out from the nozzle impinged on the plate, and the force applied on the plate was measured by a load cell (PCB Load & Torque Model 1102-115-03A with full scale of 890 N (200 lbf)).

In order to capture as much of the exit momentum as possible 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 in one direction which was parallel to the impact plate. The influence of the distance between the plate and the nozzle exit was examined and was found, as expected, to have a noticeable effect on the measured force.

Figure 20 shows the force measured by the load cell at different void fraction and inlet flow rate conditions for three different standoff distances of the measurement plate from the nozzle exit. It is clear from the tests that at the largest standoff distance of 13.6 cm (5.34 in.), the force measurement plate captures the most of the exit momentum force. When the plate was closer, the interaction between the plate and the exit flow reduced the force acting on the plate. Therefore all the force measurements results reported below were obtained at this location.
The efficiency of the force measurement plate in capturing the exit momentum force was also examined. Figure 21 shows the variations of the normalized force captured by the plate, $F / \rho \cdot Q \cdot V_m$, versus the exit mixture flow rate, $Q / (1 - \alpha)$. Here $Q$ is the liquid flow rate and $V_m$ is the medium velocity at the nozzle exit assumed to be the same as the liquid velocity. As shown in the figure, the fraction of the captured exit momentum force decreases with the increased exit mixture flow rate and reaches a plateau. This may be attributed to the flow interaction between the nozzle flow and the flow deflected by the plate, which increases with the nozzle flow rate.

In order to obtain the momentum thrust of the nozzle, $T$, the force $F$, directly measured by load cell is corrected by the above measured capture efficiency, $e$, using:

$$T = \frac{F}{e}.$$  \hspace{1cm} (29)

Figure 20: Load cell force measurement versus void-fraction for different water flow rates and different stand-off distances of the measurement plate from the exit.

Figure 21: Fraction of the total exit momentum force captured by the force measurement plate at different exit mixture flow rates (with and without air injection).
EFFECTS OF AIR INJECTION ON INLET FLOW

The effects of air injection on the inlet flow behavior were examined systematically with the pump and valve settings being maintained untouched. Figure 22 shows the signal output of the flow meter that measures the inlet flow rate. Very little effect of the air injection can be seen.

Figure 23 shows the inlet flow rate fluctuations with and without air injection at different flow conditions. The fluctuations in the flow rate were less than 4% of the flow rate for all test conditions, and air injection did not have any noticeable effects on the inlet flow rate or its fluctuations. Therefore, no flow rate adjustment was made 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.

However, there was a noticeable pressure increase in the upstream of the nozzle when air was injected. This was accepted by the pump without any noticeable change of flow rate. This change in the upstream pressure is examined below.

\[ \rho_1 (1-\alpha)u_{L,\text{outlet,}a}^2 = \rho_2 u_{L,\text{inlet,}a}^2. \]  
(31)

Therefore,

\[ \frac{T_{p,\alpha} - T_{p,0}}{T_{p,0}} = \frac{(1-\alpha)}{(1-\alpha)^2 - 1} = \frac{\alpha}{1-\alpha}. \]  
(32)

Extensive experiments were conducted to study the effects of air injection on the nozzle thrust. In addition to the direct force measurement using the load cell, pressure measurements at the nozzle inlet were also conducted. Figure 24 shows the range of tested void fraction (0 to 50%) and the inlet liquid flow rate 0.76 m³/min (200 gpm, inlet velocity = 3.1 m/s) to 2.27 m³/min (600 gpm, inlet velocity = 9.3 m/s).

![Figure 22: Signal output of flow meter measuring the inlet flow rate with and without air injection.](image)

![Figure 23: Pump flow rate percent fluctuations versus flow rate. Air injection appears to have no noticeable effects on these fluctuations.](image)

![Figure 24: Nominal void fraction coverage range for different air injection rates (in standard gallon per minute (SGPM), 1 SGPM = 0.00379 m³/min of air at 1 atm) at different liquid inlet flow rates.](image)
Figure 25 shows the normalized net thrust increase vs. the exit void fraction. Results from numerical simulations and experiments shown in the figure agree well with each other. The results also follow the simplified theoretical curve, $\alpha/(1-\alpha)$, which shows that air injection becomes more efficient and produces further net thrust increase with increased void fraction.

![Figure 25: Variation of normalized (water jet) net thrust enhancement with void fraction.](image)

The air injection causes an increase in the inlet pressure, which means that the water jet pump needs to work harder to overcome this negative effect from the air injection. To examine the effect of the void fraction on the inlet pressure, the normalized inlet pressure increase is plotted in Figure 26. As shown in the figure, this effect increases almost linearly with the exit void fraction.

![Figure 26: Normalized pressure increase at the inlet versus void fraction.](image)

Figure 27 compares the thrust gain due to air injection and the thrust loss due to inlet pressure rise as functions of the void fraction at the exit. As the void fraction increases, the difference between the thrust increase and the inlet pressure force rise becomes larger. Figure 28 shows the net thrust gain obtained by subtracting the pressure force loss from the thrust gain. This illustrates again that injection of higher void fractions results in significant thrust gains, with measured 70% increase at 50% void fraction.

![Figure 27: Comparison between momentum thrust increase due to air injection and thrust decrease due to inlet pressure increase.](image)

![Figure 28: Variation of normalized (Ramjet) net thrust gain with void fraction. 70% net thrust enhancements are seen with 50% air fraction at the nozzle exit.](image)

CONCLUSIONS

Experimental and numerical studies of the influence of bubble injection on the thrust of waterjet propulsion were presented. The numerical model was based on a 1D version of the two-way coupled Eulerian-Lagrangian method, which models the bubbly flow and tracks bubbles. Optimum nozzle geometry was obtained using the numerical prediction method.

The 1-D model was extended to include supersonic flow modeling to be applied experimentally in future efforts. This new extension of the method can provide a useful design tool to study the choked flow in the BAP. Further studies are underway to examine the
feasibility of taking advantage of a supersonic exit flow to achieve higher thrust augmentation.

With a 4 in. outlet diameter laboratory scale nozzle and carefully designed air injection, significantly high void fractions (~ 50%) injections were achieved. The exit momentum was measured using an impact plate based thrust measurement scheme. The experiments showed good nozzle performance and significant net thrust increases with increasing void fractions, even after accounting for inlet pressure increases due to the bubble injection. Net thrust augmentation was as high as 70% for an exit void fraction of 50%. This study indicated that a well-designed nozzle with a proper air injection scheme can provide significant performance improvement with high void fraction air injection.

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