

Full Length Research Paper

Computational analysis of the effective parameters on two-phase bubbly water flow in a ramjet propulsion system

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Received 30 October, 2012; Accepted 16 April, 2015

A computational study of the flow field characteristics and the performances of two-phase bubbly flow in water jet of a ramjet propulsion system with a diverging-converging nozzle has been performed. The analysis use a finite volume approach for the main flow coupled numerically with the Lagrangian equations for the bubbles motion including the change of bubbles radii with time. Computed results for an experimental two-phase flow in a ramjet propulsion system with a converging-diverging nozzle are presented to validate the numerical model. The performance of the ramjet for different initial velocities of the incoming water and for various locations of the bubbles injections has been studied. Results reveal that the best location for the bubbles injection is at the beginning of the nozzle section and produces a higher thrust.

Key words: Bubble dynamic, water ramjet, thrust, computational fluid dynamics (CFD), two-phase flows.

INTRODUCTION

Considerable interest exists in the engine community in investigating two-phase bubbly flows in waterjet of a ramjet, experimentally, or numerically. This is due to the performance and interactions of the bubbles on the flow and augmenting the ramjet propulsion thrust. In the marine ramjets the water flow enters the ramjet from a diffuser which causes the velocity reduction and pressure increase based on Bernoulli equation. The high pressure flow from the diffuser enters the mixing chamber where the bubbles are injected into the water and after that enters the nozzle. In the nozzle the pressure decrease and the bubbles accelerate the water velocity and this

increasing velocity at the nozzle exit creates a higher value for the thrust.

Computational fluid dynamics (CFD) methods provide an efficient way of investigating the complex flow phenomena within two-phase flows in ramjet propulsion systems. In addition, due to the availability of post-processing and scientific visualization software, the computed flow field can be extensively analyzed. It is also convenient to test within numerical model various control strategies, such as energizing of incoming flow using jets.

The earliest studies on bubbly water jets were

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performed by Witte, who proposed the high pressure gas injection in water flow of a propulsion system (Witte, 1969). Amos and Maxwell presented the numerical simulations of an air-augmented waterjet (Amos et al., 1973; Maxwell et al., 1975). A theoretical study on the characteristics of two-phase bubbly water ramjet propulsion was performed by Varshay and Gany (1997). The detailed investigation of the flow field and ramjet performance was presented by Mor and Gany (1997). AleHosseini and Qin (2007), numerically simulated the cavitating water jets using Rayleigh-Plesset. Chahine et al. (2008) performed the study of bubble-augmented water jet propulsion system of two phase model development and also constructed experimental validations. Chahine (2008) also investigated the effects of the void fraction on the performance of the bubbly ramjet. Fu et al. (2009) predicted the flow field and the produced thrust of a two-phase bubbly ramjet with converging-diverging nozzle using computational fluid dynamic approach. These three sections for the physical processes including the diffuser, mixing chamber, and nozzle and construct separate mathematical models for these sections.

Most numerical studies on the bubbly two-phase water ramjet have been limited to one or two dimensional flow field. In this paper a three dimensional simulation of two-phase bubbly water flow ramjet propulsion system with a converging-diverging nozzle is presented. The model solves the Time-Averaged Navier-Stokes equations for the main water flow using finite volume approach coupled with Lagrangian equations for the bubbles. The paper is organized as follows. At first, governing equations and numerical formulations are described. Next, validation results in the form of velocity and pressure distributions against an experimental two-phase bubbly water flow ramjet are presented. Finally, the effects of various incoming water velocities and the effects of locations of the bubble jets injections on the thrust augmentation are presented.

NUMERICAL FORMULATIONS

In this study, three sets of equations have been considered. First, the time-averaged Navier-Stokes equations including the continuity, and momentum equations have been applied into the water mixed flow, which are:

$$\frac{\partial \rho_m}{\partial t} = \text{div}(\rho_m \mathbf{u}_m) \tag{1}$$

$$\rho_m \frac{D\mathbf{u}_m}{Dt} = -\nabla p_m + \nabla \{2\mu_m \delta_{ij} + \lambda_m (\nabla \cdot \mathbf{u}_m)\} \tag{2}$$

Where $\lambda_m = -\frac{2}{3}\mu_m$

The mixture density and viscosity for a void volume fraction α can be shown by:

$$\rho_m = \alpha \rho_b + (1 - \alpha) \rho_f \tag{3}$$

$$\mu_m = \alpha \mu_b + (1 - \alpha) \mu_f \tag{4}$$

Where the void fraction, α , is defined as the volumes of the bubbles in a cell divided by the volume of that cell:

$$\alpha = \frac{\sum \pi d_n^3 / 6}{V} \tag{5}$$

The second set of the equation is related to the bubbles motion and trajectory has been derived by Johnson and Hsieh (1966) which is:

$$\frac{d\mathbf{u}_b}{dt} = F_D(\mathbf{u} - \mathbf{u}_b) + \frac{\rho}{\rho_b} \frac{3R'}{2R} (\mathbf{u} - \mathbf{u}_b) + \frac{\rho}{\rho_b} \mathbf{u}_b \frac{\partial \mathbf{u}}{\partial x} + \frac{1}{2} \frac{\rho}{\rho_b} \left(\frac{d\mathbf{u}}{dt} - \frac{d\mathbf{u}_b}{dt} \right) + \frac{(\rho_b - \rho)}{\rho_b} g + \frac{2.534 v^{1/2} \rho d_{ij}}{\rho_b R (d_{ij} d_{kl})^{1/4}} (\mathbf{u} - \mathbf{u}_b) \tag{6}$$

Where $F_D = \frac{18\mu}{4\rho_b R_b^2} \frac{C_D Re}{24}$

Here the drag coefficient is calculated by (Haberman and Morton, 1953):

$$C_D = \frac{24}{Re} (1 + 0.197 Re^{0.63} + 2.6 \times 10^{-4} Re^{1.38})$$

$$Re = \frac{2R\rho|\mathbf{u} - \mathbf{u}_b|}{\mu} \tag{7}$$

Finally, the third set of the equations computes the changes of the bubble radii using the Rayleigh-Plesset equation:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho} \left[P_v(T_\infty) + P_{g0} \left(\frac{R_0}{R} \right)^{3k} - P - \frac{2\gamma}{R} - \frac{4\mu}{R} \dot{R} \right] + \frac{1}{4}(\mathbf{u} - \mathbf{u}_b)^2 \tag{8}$$

To specify the bubble behavior the Rayleigh-Plesset equation and the bubble motion tracking should be solved simultaneously. In this paper these equations have been solved using Range-Kutta fourth order equations.

Solution algorithm

To study full 3-D two-way interactions, the void fraction is defined in the 3-D space. The bubble number and size in each α -cell are used to compute the void fraction. The procedure for these unsteady computations is as follows:

1. Initialize the flow field, e.g., from steady state solution of liquid only without considering the bubbles effects using time-averaged Navier-Stokes Equations (1) and (2), or from a known initial solution. The solutions are being used for the bubbles dynamic motions.
2. Allow the bubbles to diffuse one time step in the flow field following injection.
3. According to the bubble size and location resulted from previous step, compute the void fraction using Equation (5).
4. Calculate the mean mixture density and viscosity, $\rho_m(x, y, z, t)$ and $\mu_m(x, y, z, t)$, respectively.
5. Solve the flow field including velocity and pressure distributions with the updated mean mixture density, and proceed to the next time step.
6. Repeat from Step 2 to 5 until reaching the desired time.

Configuration and computational grid

The configuration which was used by Chahine has been chosen as

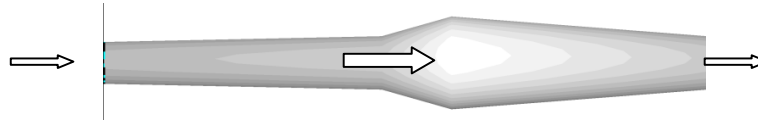


Figure 1. The ramjet nozzle configuration.

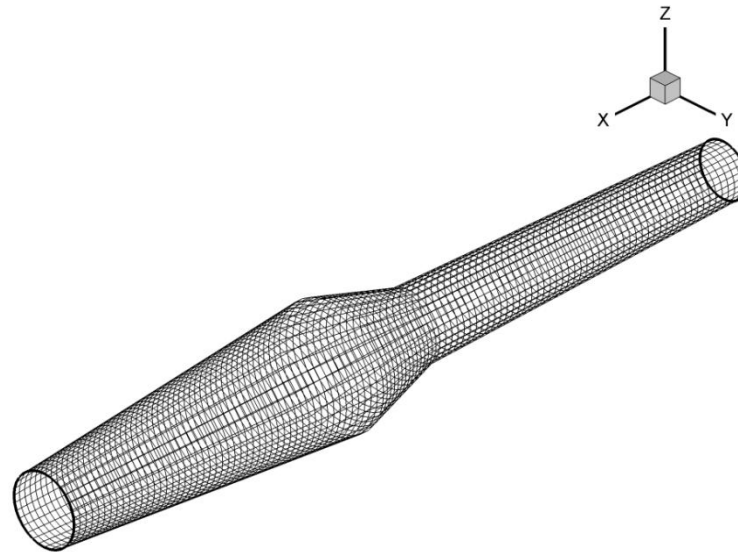


Figure 2. Computational grid.

a reference study to validate the results of the present study. Figure 1 shows the nozzle configuration of the ramjet. A bubble injector is placed at the end of diffuser. Velocity of water at the inlet and the exit pressure are 8 m/s and 1 atm, respectively. Also shown in Figure 2 is the corresponding computational grid used to model the two-phase water flow. The dimensions of the grid are $30 \times 40 \times 175$ in the radial, circumferential, and axial directions, respectively.

RESULTS AND DISCUSSION

For validation purposes, the numerical model was first applied to two-phase bubbly water flow studied experimentally and theoretically by Chahine (2008). To illustrate convergence trend, the radius changes with time of a bubble injected is shown in Figure 3. Initial radius of this bubble is 5 mm and it is injected at pressure 2 atm. Since the pressure inside the nozzle at the injection location is lower than the injection pressure, the bubble expands after the injection and then oscillates with time which finally reaches to a constant value, as illustrated in Figure 3.

Figure 4a and b depict the axial velocity distribution and velocity contour plot on the center line and center plane of the nozzle, respectively. The velocity inside the nozzle decreases with increasing the cross sectional area up to the bubble injector, as it is expected, and then increases

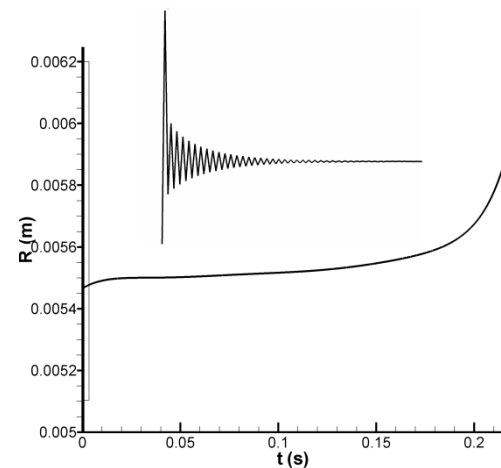


Figure 3. Change of bubble radius with time.

toward the exit plane. In the vicinities of the injected bubbles velocity can exceed the inlet velocity unlike the situation in which air is absent. The axial velocity reaches the value of 13.8 m/s which is higher than the exit velocity of the water without bubbles. The computed results are in good agreement with the Chahine data. Figure 5a

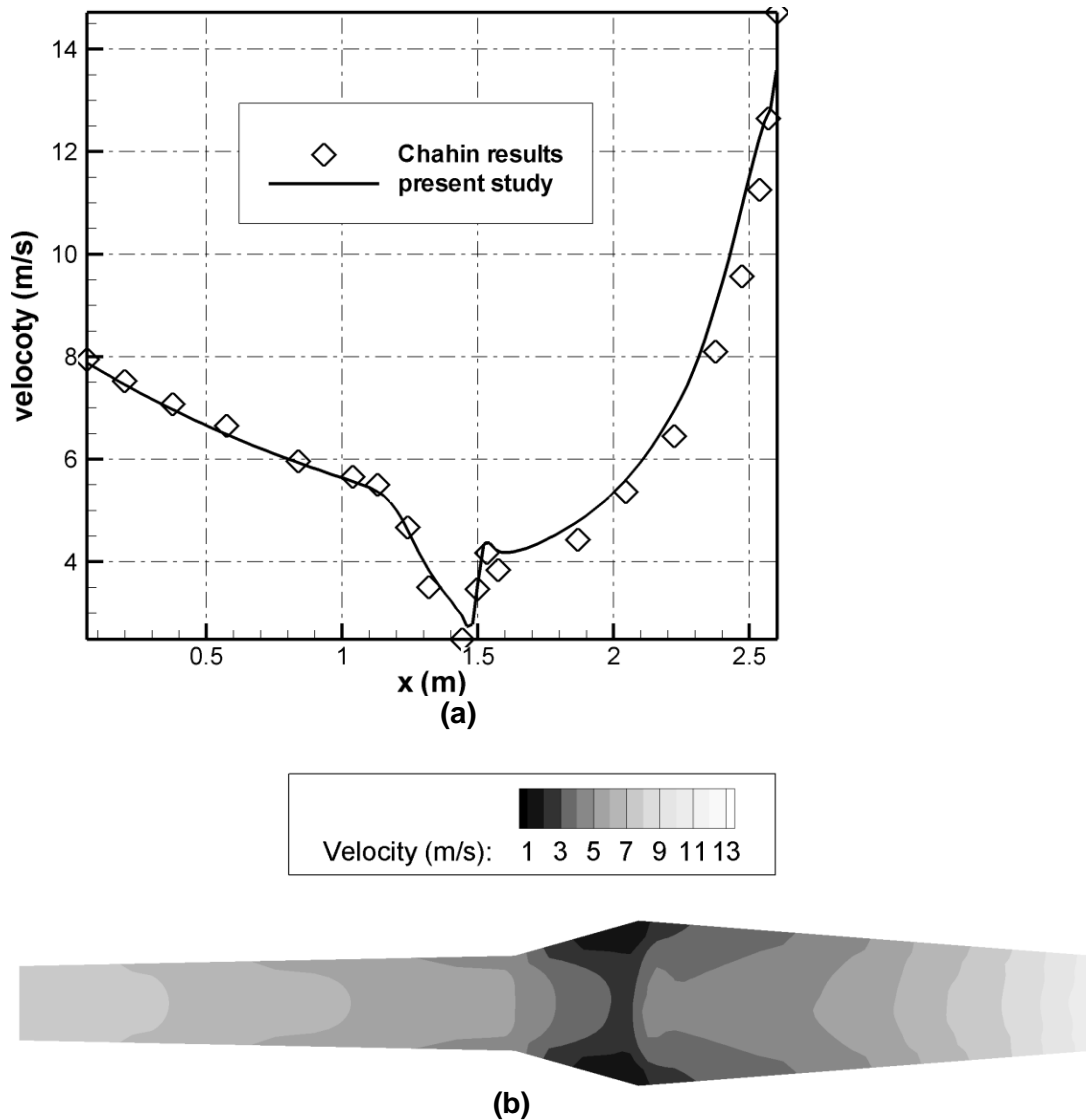


Figure 4. (a) Axial Velocity on the centerline; (b) contour of axial velocity on center plane of ramjet.

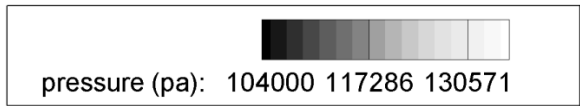
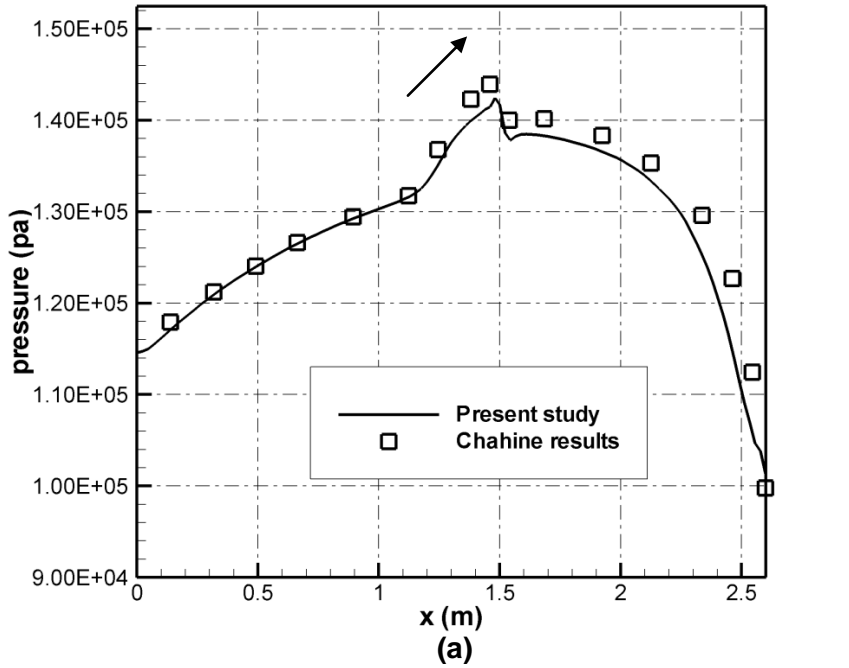
shows the pressure profile on the center line, and the pressure distribution on the center plane of the nozzle is presented in Figure 5b. As illustrated in Figure 5a, the corresponding pressure reaches to its maximum value just downstream of the bubble injector. The comparison of pressure distribution obtained from this study shows good agreement with previous studies, too.

Figure 6 shows the void fraction variation inside the nozzle if a set of bubbles were injected at $x=1.5$ m. It is zero before injection occurs. Then it suddenly rises just after the injection point. It then rises gradually till the outlet due to the pressure drop along the nozzle. Effect of void fraction on velocity distribution in the nozzle also investigated in this study. Figures 7 and 8 show the results for velocity and pressure distribution along the axis of ramjet for two different initial void fractions. It is

clear that injection increases the axial velocity and velocity at the outlet is much higher in comparison with water only flow. Also as expected, it is observed that pressure increases at the inlet of ramjet after bubble injection.

Thrust of the nozzle

The main part of this study is to detect the effects of initial incoming water velocity and the positions of the bubbles injections on the performance and the thrust of the ramjet. The thrust equation of the nozzle has two main parts; momentum term and pressure term. Consider a control volume that contains the nozzle. The thrust can be computed by integrating the pressure and the



(b)

Figure 5. (a) Pressure distribution on the centerline; (b) Contour of pressure on center plane of ramjet.

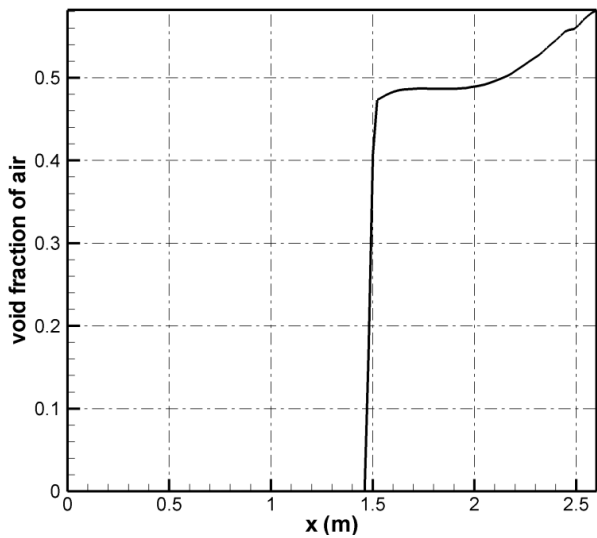


Figure 6. Void fraction variation in the ramjet.

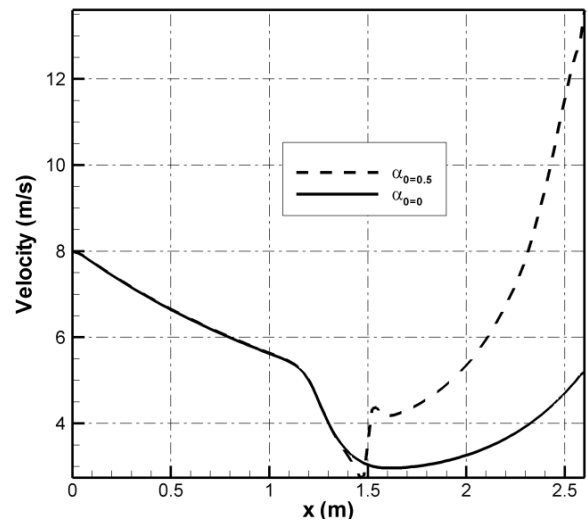


Figure 7. Velocity profile on the centerline for two different initial void fractions.

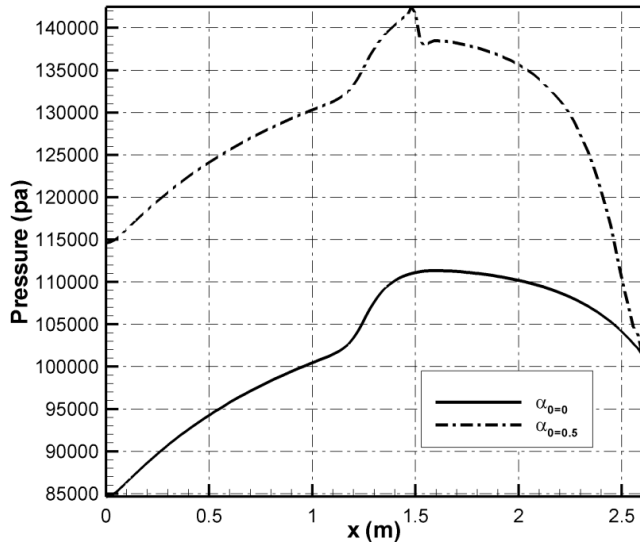


Figure 8. Pressure Distribution on the centerline for two different initial void fractions.

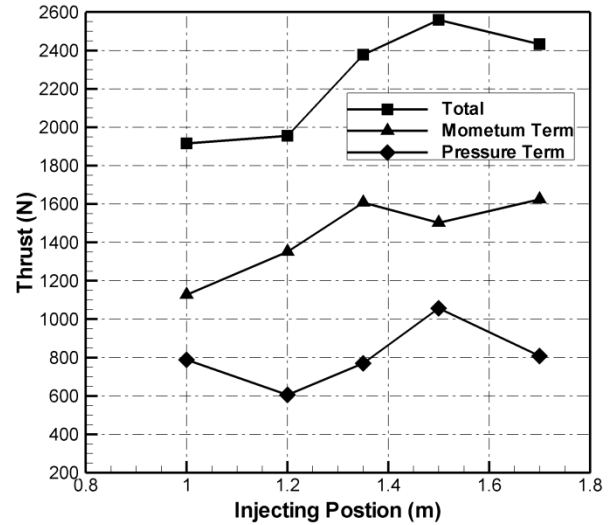


Figure 10. Effects of various bubbles injections positions on the computed thrust.

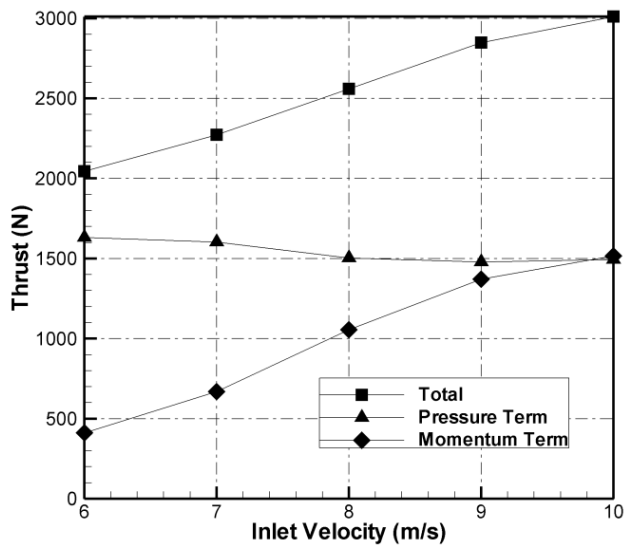


Figure 9. Thrust of the nozzle for different inlet velocities.

momentum flux over the surfaces of this control volume:

$$F_{Thrust} = (m'_e u'_e - m'_i u'_i) + (A_e P_e - A_i P_i) \quad (9)$$

The results for different inlet water velocities in the range of 6 to 10 m/s were computed. The predicted thrust from the 3-D model over a range of inlet velocities is depicted in Figure 9. As the inlet velocity increases, there is a large increment in the momentum contribution to the thrust, but a loss in the pressure component occurs. As a result, the total thrust increases as the inlet velocity increases.

To investigate the effects of the position of the injection

point on thrust of the ramjet, five different locations have been considered. The results of this part are presented in Figure 10. The contribution of pressure term has more changes in comparison with its changes with the inlet velocity. It is observed that maximum thrust achieved when the injection occurs at the beginning of the nozzle.

In addition to the planar injection, injection from one point was also investigated. The affected zone of bubble injection is showed in Figure 11. The bubbles move only in the upper part of ramjet until they leave the ramjet.

Another way to improve the performance of the ramjet is changing the shape of diffuser. In this research a curved diffuser was also studied. The curve equation is given by Equation (10). The thrust for this type of ramjet was computed to be 3006.57 (N), which indicates that the curved diffuser increases thrust about 17.5%.

$$Y = -0.027x^3 - 0.009x^2 - 0.005x - 0.076 \quad (10)$$

Conclusion

A three dimensional, time-averaged Navier-Stokes solver coupled with the Lagrangian equations for the bubble motions and time bubbles radii variations have been used to simulate the flow field of a two-phase bubbly water flow of a ramjet with diverging-converging nozzle. The flow solver uses a finite volume approach. Validation results against an experimental two-phase water ramjet were presented and good agreement was observed. The effects of the various initial velocity of the incoming water on the performance and the thrust of the ramjet were investigated. Results reveal that the increasing of the initial incoming velocity will increase the momentum parts of the thrust while decreasing the pressure parts, and

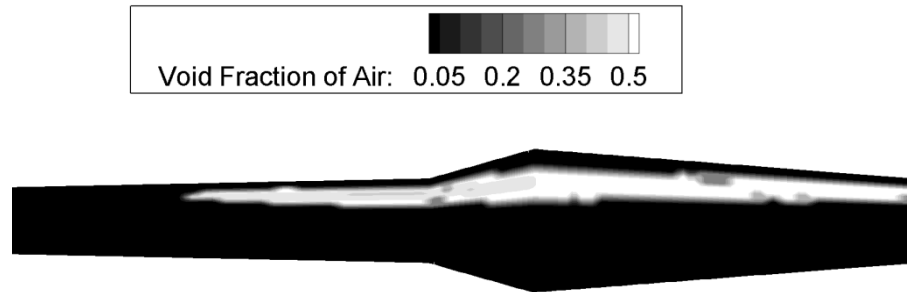


Figure 11. Contour of void fraction for injection from a point.

totally increase the thrust. Five different locations were used to implement the bubble injection and computed results showed that the bubble injection at the beginning nozzle section developed the highest thrust. Also it was shown that the ramjet thrust can be augmented by changing the difusser profile.

Conflict of Interest

The authors have not declared any conflict of interest.

Nomenclature:

Greek Symbols: A , Cross-sectional area (m^2); α , void fraction; C_D , Drag coefficient; α_0 , initial void fraction; P_v , liquid vapor pressure (pa); μ , Viscosity ($N \cdot s \cdot m^{-2}$); P_{G0} , initial gas pressure (pa); ρ , Density ($kg \cdot m^{-3}$); P , Pressure (pa); ν , Kinematic viscosity ($m^2 \cdot s^{-1}$); R , radius of bubble (m); γ , Surface tension ($N \cdot m^{-1}$); R_0 , reference bubble radius (m); δ_{ij} , Kronecker delta; Re , Reynolds number; T , temperature (K);
Indices: V , Volume (m^3); b , property of a bubble; d_{ij} , deformation tensor; n , number of the bubble class; g , constant of gravity acceleration ($m \cdot s^{-2}$); i , Inlet; m^i , mass rate ($kg \cdot s^{-1}$); e , Exit; t , time (s); f , liquid phase; u , velocity ($m \cdot s^{-1}$); m , mixture medium.

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