Published in final edited form as:

Chem Eng Sci. 2016 ; 2: . doi:10.1115/FEDSM2016-7845.

Numerical study of gravity effects on phase separation in a swirl chamber

Chao-Tsung Hsiao*, Jingsen Ma, and Georges L. Chahine

Dynaflow, Inc., 10621-J Iron Bridge Road, Jessup, MD 20794, USA

Abstract

The effects of gravity on a phase separator are studied numerically using an Eulerian/Lagrangian two-phase flow approach. The separator utilizes high intensity swirl to separate bubbles from the liquid. The two-phase flow enters tangentially a cylindrical swirl chamber and rotate around the cylinder axis. On earth, as the bubbles are captured by the vortex formed inside the swirl chamber due to the centripetal force, they also experience the buoyancy force due to gravity. In a reduced or zero gravity environment buoyancy is reduced or inexistent and capture of the bubbles by the vortex is modified. The present numerical simulations enable study of the relative importance of the acceleration of gravity on the bubble capture by the swirl flow in the separator. In absence of gravity, the bubbles get stratified depending on their sizes, with the larger bubbles entering the core region earlier than the smaller ones. However, in presence of gravity, stratification is more complex as the two acceleration fields – due to gravity and to rotation – compete or combine during the bubble capture.

Keywords

Bubble dynamics; Phase separation; Multiphase flow; Swirl flow

1. Introduction

Development of a phase separator capable of efficiently and reliably separating gas-liquid mixtures for wide ranges of void fractions, flow rates, and levels of gravitational force is of great interest for both space and earth applications. This paper focuses on the DynaSwirl[®] phase separator which we have developed for future testing by NASA on the International Space Station where earth gravity effects are absent (Wu and Chahine, 2012). In this separator, centripetal force is induced on the bubbles by high speed tangential injection of the bubbly mixture in a swirl chamber to generate a cavitating vortex core for gas capture. Through a combination of swirl, cavitation, and rectified gas diffusion, the separator is capable of extracting gas out of even very low void fraction mixtures into the central gaseous core of the vortex.

Numerical modeling of the bubbly mixture flow in the separator allows consideration of the effects of the acceleration of gravity on the separation and provides needed information to

*Corresponding author. ctsung@dynaflow-inc.com (C.-T. Hsiao).

understand the physics and to guide system design and optimization. In the current study, an Eulerian-Lagrangian method that we have developed is applied to model the two-phase bubble/liquid mixture flow inside the swirl chamber (Chahine, 2008; Chahine et al., 2014; Hsiao and Chahine, 2012; Hsiao et al., 2013). The method integrates a Discrete Singularity Model (DSM) for the dispersed microbubbles with a viscous continuum model for the two-phase bubbly mixture. DSM simulates the bubbles' dynamics by solving a modified Rayleigh-Plesset equation and tracks their motions in response to the flow field. The two-phase flow field in the viscous continuum model is obtained by solving the Navier-Stokes equations using the mixture density associated with instantaneous bubble volumes and positions.

To enable simulations of bubbles captured by the vortex, a Level-Set method is used to capture the liquid-gas interface when the bubbles coalesce and form a large cylindrical cavity. Schemes are developed to smoothly transition microbubbles that have grown beyond a threshold size into tracked liquid-gas interfaces in the gaseous vortex core.

The numerical simulations enable study of the relative importance of gravity effects on the bubble capture in the swirl separator vortex. It also allows consideration of a much larger range of the parameters than what is feasible without constructing and testing many separators.

2. Numerical method

2.1. Mixture continuum phase model

The Eulerian continuum two-phase model 3DynaFS-Vis solves the continuity and momentum equations for a mixture:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0, \quad (1)$$

$$\rho_m \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu_m \nabla^2 \mathbf{u} + \rho_m \mathbf{g}, \quad (2)$$

where $\mathbf{u}$ is the mixture velocity, p the pressure, and $\mathbf{g}$ the acceleration due to gravity. The mixture density, ρ_m , and the mixture viscosity, μ_m , are related to the void fraction, α ; and the liquid and gas properties through

$$\rho_m = (1 - \alpha)\rho_l + \alpha\rho_g, \quad \mu_m = (1 - \alpha)\mu_l + \alpha\mu_g, \quad (3)$$

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

The continuum has a time and space dependent density since the void fraction α varies in both space and time. This makes the overall flow field problem similar to a compressible

flow problem. In our approach, which couples the continuum medium with the discrete bubbles, the mixture density is not an explicit function of the pressure through an equation of state. Instead, tracking the bubbles and knowing their spatial distribution and sizes provides α and ρ_m as functions of space and time.

The system of equations is closed using an artificial compressibility method (Chorin, 1967) in which a pseudo-time derivative of the pressure multiplied by an artificial-compressibility factor, β , is added to the continuity equation as:

$$\frac{1}{\beta} \frac{\partial p}{\partial \tau} + \frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0 \quad (4)$$

As a consequence, a hyperbolic system of equations is formed and can be solved using a time marching scheme. The solution is advanced in the pseudo-time to reach a steady-state solution. To obtain a time-dependent solution, a Newton iterative procedure is performed at each physical time step in order to satisfy the continuity equation.

The solver uses a finite volume formulation. First-order Euler implicit differencing is applied to the time derivatives. The spatial differencing of the convective terms uses the flux-difference splitting scheme based on Roe's method (Roe, 1981) and van Leer's MUSCL method (van Leer and Woodward, 1979) for obtaining the first-order and the third-order fluxes, respectively. A second-order central differencing is used for the viscous terms, which are simplified using a thin-layer approximation near rigid boundaries (Steger, 1977). The flux Jacobians required in the implicit scheme are obtained numerically. The resulting system of algebraic equations is solved using the Discretized Newton Relaxation method (Vanden and Whitfield, 1995) in which symmetric block Gauss-Seidel sub-iterations are performed before the solution is updated at each Newton iteration.

2.2. Turbulence model

To simulate the vortex flow inside the swirl chamber, a Large Eddy Simulation (LES) model is used. A filtering function (Leonard, 1974) is applied to the momentum equation, resulting in an additional term, $\nabla \cdot \bar{\tau}$, from the non-linear convection terms. $\bar{\tau}$ is the subgrid scale stress which can be modeled using the Smagorinsky model (Smagorinsky, 1963). Using the Boussinesq approximation, the subgrid scale stress can be related to the strain rate tensor;

$$\bar{\tau} = -2\mu_T \bar{\mathbf{S}}, \quad (5)$$

where μ_T is the eddy viscosity and $\bar{\mathbf{S}}$ is the filtered strain rate tensor. With the Smagorinsky approximation the eddy viscosity is modeled using;

$$\mu_T = \rho(C_s \Delta)^2 \sqrt{2\bar{\mathbf{S}}\bar{\mathbf{S}}}. \quad (6)$$

2.3. Discrete singularity model

The Lagrangian discrete bubble model uses a Surface Average Pressure (SAP) approach to average fluid quantities along the bubble surface (Chahine, 2008; Chahine et al., 2014; Hsiao and Chahine, 2012; Hsiao et al., 2013). This model has been shown to produce accurate results when compared to full 3D two-way interaction computations (Hsiao and Chahine, 2004). The averaging scheme allows one to consider only a spherical equivalent bubble and use the following modified Rayleigh-Plesset equation to describe the bubble dynamics,

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho_l} \left(p_v + p_{g0} \left(\frac{R_0}{R} \right)^{3k} - p_{enc} - \frac{2\gamma}{R} - \frac{4\mu\dot{R}}{R} \right) + \frac{|\mathbf{u}_s|^2}{4}, \quad (7)$$

where R and R_0 are the bubble radii at times t and 0, p_v is the liquid vapor pressure, p_{g0} is the initial bubble gas pressure, k is the polytropic compression constant. $\mathbf{u}_s = \mathbf{u}_{enc} - \mathbf{u}_b$ is the bubble slip velocity relative to the liquid where $\mathbf{u}_b$ is the bubble travel velocity. $\mathbf{u}_{enc}$ and p_{enc} are respectively the liquid velocity and the ambient pressure “seen” by the bubble during its travel. With the SAP model, $\mathbf{u}_{enc}$ and p_{enc} are respectively the averages of the liquid velocities and of the pressures over the bubble surface.

The bubble trajectory is obtained from the following bubble motion equation:

$$\frac{d\mathbf{u}_b}{dt} = \left(\frac{\rho_l}{\rho_b} \right) \left[\frac{3}{8R} C_D |\mathbf{u}_s| \mathbf{u}_s + \frac{1}{2} \left(\frac{d\mathbf{u}_{enc}}{dt} - \frac{d\mathbf{u}_b}{dt} \right) + \frac{3\dot{R}}{2R} \mathbf{u}_s - \frac{\nabla p}{\rho_l} + \frac{(\rho_b - \rho_l)}{\rho_l} g + \frac{3C_L \sqrt{v}}{4\pi R} \frac{\mathbf{u}_s \times \boldsymbol{\Omega}}{\sqrt{|\boldsymbol{\Omega}|}} \right], \quad (8)$$

where ρ_b is the bubble content density, C_D is the drag coefficient given by an empirical equation such as from Haberman and Morton (1953), C_L is the lift coefficient and $\boldsymbol{\Omega}$ is the deformation tensor. The 1st right hand side term is a drag force. The 2nd and 3rd terms account for the added mass. The 4th term accounts for the presence of a pressure gradient, while the 5th term accounts for gravity and the 6th term is a lift force (Saffman, 1965).

2.4. Level-Set approach

In order to simulate liquid-gas interfaces of large cavities such as the gaseous core in the swirl chamber or bubbles that have become larger than the characteristic grid size, a Level-Set method is used. A smooth function $\phi(x, y, z, t)$, is defined in the whole physical domain (i.e. in both liquid phase - negative ϕ and gas phase - positive ϕ) as the signed distance $d(x, y, z)$ from the interface:

$$\varphi(x, y, z, 0) = d(x, y, z) \quad (9)$$

$\varphi = 0$ coincides with the liquid/gas interface when the level set is introduced. This function is enforced to be a material surface at each time step using:

$$\frac{d\varphi}{dt} = \frac{\partial\varphi}{\partial t} + \mathbf{v} \cdot \nabla\varphi = 0, \quad (10)$$

where $\mathbf{v}$ is the velocity of the interface. Integration of Eq. (10) does not ensure that $\varphi(x, y, z, t)$ remains the exact distance function in space and time for all grid points during the computations due to numerical diffusion and to distortion by the flow field. To avoid this problem, a new distance function $\tilde{\varphi}$ is constructed by solving a “re-initialization equation” using the previous $\varphi(x, y, z, t)$ as the initial solution (Sussman et al., 1998):

$$\frac{\partial\tilde{\varphi}}{\partial\tau} = S(\varphi)(1 - |\nabla\tilde{\varphi}|), \quad (11)$$

where τ is the pseudo time and $S(\varphi)$ is the sign function based on the value of $\varphi(x, y, z, t)$. Eq. (11) is iterated until $\partial\tilde{\varphi}/\partial\tau$ approaches zero and thus recovers the distance function with $|\nabla\tilde{\varphi}| = 1$.

In a standard Level-Set approach, liquid and gas phases are solved separately using Eqs. (10) and (11) after identifying to which phase a concerned cell belongs and applying a smoothed Heaviside function over the interface to smooth the fluid properties. Here, instead of solving both phases, a single phase Level-Set method using the Ghost Fluid Method enabled us to maintain a sharper interface. This method allows imposing the dynamics boundary conditions at the interface without using smoothing functions. The shear due to gas/vapor flow is neglected, and the dynamic boundary conditions (balance of normal stresses and zero shear) are as follows:

$$p = \frac{\tau_{ij}n_i n_j}{\rho_l} + \frac{gz}{\rho_l} + \frac{\gamma\kappa}{\rho_l}, \quad \tau_{ij}n_i t_j^1 = 0, \quad \tau_{ij}n_i t_j^2 = 0. \quad (12)$$

where τ_{ij} is the stress tensor, g is the acceleration of gravity, and γ is the surface tension. $\kappa = \nabla \cdot \nabla\varphi/|\nabla\varphi|$ is the surface curvature and $\rightarrow n, \rightarrow t, \rightarrow t^2$ are the normal to the surface and two tangential unit vectors, respectively.

2.5. Transition model

The inception of a vaporous/gaseous core is due to the coalescence and growth of bubble nuclei captured on the vortex axis. Since the bubbles are tracked using a Lagrangian scheme, the bubble sizes and locations are known at every time step. A criterion based on bubble size

is set to “activate” the bubbles for computation of a local distance function for neighboring cells (Hsiao et al., 2014, 2015). For each cell i , the distance function is then defined by:

$$\varphi_i = \min(\varphi_{LS0}, \varphi_{b,j}); \quad j = 1, N_i \quad (13)$$

where φ_{LS0} is the distance function value for cell i at the previous time step or an initial very large negative value at the beginning of the computation. $\varphi_{b,j}$ is the local distance between the center of cell i and the surface of bubble j as shown in Fig. 1, and N_i is the number of bubbles which are “activated” around cell i . This scheme allows multiple bubbles to merge together into a large cavity, and single bubbles to be absorbed by a large cavity as illustrated in Fig. 2. This approach does not consider the fine mechanics of bubble coalescence and interaction between very close bubbles. Instead it uses numerical criteria of bubble overlapping to merge the bubbles or cavities when they are very close. This will be improved in future developments.

The criterion to determine which bubble to “activate”, i.e. transform from a singularity into an actually gridded interface, is based on its radius, R_b , exceeding a threshold dimension given by:

$$R_b \geq \max(R_{thr}, m_{thr}\Delta L) \quad (14)$$

where R_{thr} is a threshold bubble radius, L is the characteristic size of the local grid which hosts the bubble, and m_{thr} is a multiplier. This indicates that a bubble-singularity becomes a discretized bubble represented by a zero value level set only when it grows beyond a threshold bubble radius and its radius exceeds a selected number of local grids. The latter ensures enough grid resolution to define properly the bubble volume. In the current study R_{thr} is chosen to be 200 μm and $m_{thr} = 1$. These selections are based on our previous systematic parameter-independency study (Hsiao et al., 2017), which showed that there is little dependency of the results on the activation criterion as long as transforming the singularity bubbles into discretized cavities is not done too early, i.e. the criterion should ensure that a bubble has grown significantly before being discretized.

3. Computation of swirl chamber flow field

A conceptual overall scheme of the swirl phase separator is shown in Fig. 3. The separator consists of two concentric cylinders with the inner one being the swirl chamber. The flow enters the swirl chamber by means of tangential injections slots and produces a vortex core in the center of the swirl chamber. As the two-phase bubbly flow enters the swirl chamber, due to the pressure gradients the bubbles move towards the vortex center and form a gaseous core. The swirl chamber is connected to the outside flow lines through two orifices: one for liquid extraction and the second from which the gas is extracted. In the present modeling, the small opening for gas extraction is ignored. Table 1 shows the key dimensions of the swirl chamber.

To numerically study the phase separation, only the flow field inside the swirl chamber is finely resolved using fine grids. To speed up the numerical simulations, only a quarter of the cylindrical domain is considered as illustrated in Fig. 4. The outer cylindrical chamber shown in Fig. 3 is not considered in the simulation and the liquid exit chamber is replaced with a large container to impose constant pressure outlet conditions.

The quarter of the inside of the swirl chamber is discretized using 71 radial nodes $\times$ 81 axial nodes $\times$ 41 azimuthal nodes. The grid is stretched in the radial direction away from the axis. The inside of the liquid exit orifice is discretized using a $21 \times 31 \times 41$ grid. Near the chamber walls and the axis, much finer grids are used to capture the large velocity gradients. A large exit chamber is used to impose a constant pressure outlet condition and is gridded using $21 \times 61 \times 41$ grids.

Fig. 5 shows the boundary conditions imposed at the boundaries of the computational domain. No-slip wall boundary conditions are imposed at all chamber walls. A slip boundary condition is imposed at the air exit cylinder end plate. To simulate a quarter of the cylindrical domain, periodic boundary conditions are imposed at the two side boundaries. A constant velocity is imposed in the injection slots according to the flow rate, while a constant pressure is imposed at the outlet boundary.

Tangential velocity magnitude contours and pressure contours inside the vortex separator are shown in Fig. 6. It is seen that a line vortex is formed along the axis of the swirl chamber with a high tangential velocity at the vortex core edge and a low pressure at the core center.

Fig. 7 shows a comparison of the tangential velocities obtained from PIV measurements and numerical simulations for a swirl chamber test section with a 7 cm inner diameter and a 6 gpm inlet flow rate. The PIV measurements were conducted in the middle plane of the swirl chamber. Four different sections along the radial direction were measured separately as indicated with different color symbols and overlaid together in Fig. 6. Two numerical simulations were conducted for the same flow conditions with one simulation including the Large Eddy Simulation (LES) model and the other one with no turbulence model. It can be seen that the numerical solution matches very well with the experimental measurements when the LES model is used in the numerical simulations.

4. Gravity effects on bubbly flow

The flow field shown in the previous section is used to study gravity field effects on the bubble behavior inside the swirl chamber. For computations of bubble dynamics using the current numerical model, all gas and water properties are defined at 20 °C. Table 2 lists the gas and liquid properties used in the current study.

Fig. 8 shows the instantaneous locations of the bubbles in a bubbly stream entering the swirl chamber through one of the injection slots. The bubble trajectories for different initial bubble radii and for two values of the gravitational acceleration: $0g$ and $1g$ are compared. In these computations, the axis of the phase generator is horizontal, i.e. perpendicular to the direction of the acceleration of gravity. It can be seen that, in absence of gravity, the bubbles get stratified depending on their size with the larger bubbles entering the core earlier than the

smaller bubbles. On the other hand, in presence of earth gravity, stratification is more complex as the two acceleration fields – gravity and the rotational field - compete.

At the beginning of the bubble trajectory, as the larger bubbles move downwards, gravity slows their motion towards the vortex center with some bubbles tending to escape from the vortex influence. However, this trend gradually changes and is reversed when the bubbles cross the vertical plane below the vortex axis. Later, as in the absence of gravity, the effects of the two acceleration fields add up and the larger bubbles move much faster than the smaller ones into the vortex core. This simulation shows the relative importance of gravity on bubble capture in the separator vortex core, and highlights the fact that tests on earth and in zero gravity do not reproduce the same flow details making preservation of the non-dimensional parameters necessary.

This trend is strengthened as the body force further increases, as seen in Fig. 9. The time needed for a bubble of initial size 1 mm to be entrained into the vortex center, under $1g$, is about 5 times larger than under $0g$, while it actually escapes from the domain when the gravity increases to $2g$. A similar trend is found for smaller bubbles of initial size of $150\ \mu\text{m}$, though the difference becomes less obvious.

As the phase separator is designed to enable injection of the two-phase mixture using multiple slots, the dependency on the injection location in the presence of gravity is also evaluated. As shown in Fig. 10, for bubbles of an initial size of 0.6 mm, the capture time is about 0.25 s when the bubble is injected from the left and bottom slots. This capture time increases to about 0.45 s for the top slot and becomes as long as 0.6 s for the right slot. This indicates that the buoyancy force helps vortex capture for the left and bottom slots while it does the opposite for the right and top slots. As a result, the time for bubbles to be captured by the vortex will depend on the injection locations as gravity may help or impede bubble capture.

5. Modeling of the gaseous vortex core

Fig. 8 results imply that a gaseous vortex core will be formed on the axis of the swirl chamber as the bubbles coalesce on the vortex axis. For the purpose of prediction of the gas core formation, the Level-Set approach is applied with a transition model to simulate the gaseous core after the bubbles are collected at the vortex center. Fig. 11 shows the development of such a gaseous core on the axis of the swirl chamber as the bubbles coalesce on the vortex axis. As the bubbles grow beyond a threshold size and/or merge to increase volume beyond that size, the numerical model initiates tracking them as gas-liquid gridded interfaces, which are modeled via the Level-Set method. As seen in Fig. 11, an elongated cavity then forms along the axis of the vortex and develops into a gaseous-vaporous tube. Fig. 12 displays a side view of a time sequence of the gas/vapor core formation and shape evolution on the swirl axis. The gas in the cavity can then be sucked out of the axis through an orifice. The balance flow formed through gas capture and extraction is the next challenge of this modeling project and will be addressed in future work.

6. Conclusions

An Eulerian/Lagrangian two-phase flow approach is used to study the effects of gravity on phase separation in a phase separator, which utilizes high intensity swirl flow to separate air bubbles from the liquid.

In absence of gravity, the bubbles are found to stratify depending on their sizes, with the larger bubbles entering the core region earlier than the smaller bubbles. However, in presence of gravity, stratification is more complex as the two acceleration fields – gravity and acceleration due to rotation – alternatively compete or combine during the swirling motion. As a result, the time for bubbles to be captured by the vortex depends on the injection location as gravity may help or impede bubble capture.

Finally, the Level-Set approach with a transition model was applied to simulate the gaseous core after the bubbles are collected at the vortex center. This allows smooth switching between individual isolated microbubbles and large cavities tracked as liquid-gas interfaces such as the interface of the gaseous core.

Acknowledgments

This work is supported by NASA under Grants No. NNX11AO76A and NNX16AB85A. The authors would like to thank Ms. Lauren Sharp/Mr. Eric Golliher, NASA project scientists, and Mr. Nan Pham, NASA project manager, for their support and advice.

Nomenclature

a_c	vortex core radius
a_g	gas extraction orifice radius
C_D	drag coefficient
C_L	lift coefficient
C_S	Smagorinsky constant
m_{thr}	threshold multiplier of the local grid size
$\rightarrow n$	surface normal unit vector
$\rightarrow t^1 \rightarrow t^2$	surface tangential unit vectors
k	gas constant
P_{enc}	encountered pressure
p_{g0}	initial gas bubble pressure
p_v	liquid vapor pressure
R	bubble radius
R_0	initial bubble radius

R_{thr}	threshold bubble radius
$\bar{S}$	filtered strain rate tensor
t	time
$\mathbf{u}$	velocity vector
$\mathbf{u}_s$	slip velocity
$\mathbf{u}_{enc}$	encountered velocity
α	void fraction
β	artificial compressibility
γ	surface tension
κ	curvature
μ	dynamic viscosity
μ_T	eddy viscosity
ρ	medium density
	filter size
ϕ	distance function
τ	pseudo time
$\bar{\tau}$	subgrid scale stress
Ω	deformation tensor
b	bubble g gas
l	liquid
m	mixture

References

- Chahine GL. Numerical simulation of bubble flow interactions. *J Hydrodyn.* 2008; 21(3):316–332.
- Chahine GL, Hsiao CT, Raju R. Scaling of cavitation bubble cloud dynamics on propellers. *Adv Exp Numer Tech Cavitation Eros Predict.* 2014; 160:345–373.
- Chorin AJ. A numerical method for solving incompressible viscous flow problems. *J Comput Phys.* 1967; 2:12–26.
- Haberman WL, Morton RK. An Experimental Investigation of the Drag and Shape of Air Bubble Rising in Various Liquids. DTMB Report. 1953; 802
- Hsiao CT, Ma J, Chahine GL. Multi-scale two-phase flow modeling of sheet and cloud cavitation. 30th Symp Nav Hydrodyn. 2014
- Hsiao CT, Chahine GL. Prediction of vortex cavitation inception using coupled spherical and non-spherical models and navier-stokes computations. *J Mar Sci Technol.* 2004; 8(3):99–108.

- Hsiao CT, Chahine GL. Effect of a propeller and gas diffusion on bubble nuclei distribution in a liquid. *J Hydrodyn Ser B*. 2012; 24(6):809–822.
- Hsiao CT, Ma J, Chahine GL. Simulation of Sheet and Tip Vortex Cavitation on Rotating Propeller Using a Mutiscale Two-Phase Flow Model. *Fourth Int Symp Mar Propulsor Second Int Work Cavitating Propeller Perform*. 2015
- Hsiao CT, Ma J, Chahine GL. Multiscale two-phase flow modeling of sheet and cloud cavitation. *Int J Multiph Flow*. 2017; 145:68–84.
- Hsiao CT, Wu X, Ma J, Chahine GL. Numerical and experimental study of bubble entrainment due to a horizontal plunging jet. *Int Shipbuild Prog*. 2013; 60(1):435–469.
- Leonard A. Energy cascade in large-eddy simulations of turbulent fluid flows. *Adv Geophy*. 1974; A18:237–248.
- Roe PL. Approximate riemann solvers, parameter vectors, and difference schemes. *J Comput Phys*. 1981; 43:357–372.
- Saffman PGG. The lift on a small sphere in a slow shear flow. *J Fluids Mech*. 1965; 22(02):385–400.
- Smagorinsky J. General circulation experiments with the primitive equation. *Mon Weather Rev*. 1963; 91(3):99–164.
- Steger JL. Implicit finite difference simulation of flow about arbitrary geometries with application to airfoils. *AIAA Pap*. 1977:77–665.
- Sussman M, Smereka P, Osher S. An improved level set approach for incompressible two-phase flows. *J Comput Phys*. 1998; 148:81–124.
- Van Leer B, Woodward PR. The MUSCL Code for Compressible Flow: Philosophy and Results. *TICOM Conferece*. 1979
- Vanden KJ, Whitfield DL. Direct and iterative algorithms for the three-dimensional euler equations. *AIAA J*. 1995; 33(5):851–858.
- Wu X, Chahine GL. Development of a DynaSwirl Phase Separator for Space Applications. *50th AIAA Aerosp Sci Meet*. 2012

HIGHLIGHTS

- A swirl chamber is used to separate bubble and liquid phases.
- An Eulerian-Lagrangian two-phase flow model is used to simulate the bubbly flow.
- Effect of gravity on the bubble capture by the vortex is numerically studied.
- In absence of gravity bubbles are found to stratify due to swirling flow.
- The gravity field results in a more complex bubble stratification.

Fig. 1.
Definition of the local distance, $\varphi_{b,j}$, between the level zero surface and a cell center.

Fig. 2. Illustration of a bubble merging into a preexisting free surface. The green dash curve is the old free-surface and the red dash curve is the new surface after merger.

Fig. 3.
Sketch of the swirl phase separator.

Fig. 4. Multi-block grid generated for the numerical simulations of the flow field in the inner chamber of the swirl phase separator.

Fig. 5. Boundary conditions imposed for the numerical simulations of the flow field inside the swirl chamber.

Fig. 6. Non-dimensional (a) tangential velocity magnitude contours and (b) pressure contours inside the swirl chamber of the vortex separator.

Fig. 7.
Validation of flow field computations inside the swirl chamber by comparing with PIV measurements.

Fig. 8.

The effects of gravity on bubbles entrained in a line vortex flow. Comparison of trajectories of bubbles of different initial bubble sizes as they are captured in the vortex core. The bubbles are colored according to their sizes.

Fig. 9. Effect of gravity on the trajectories of bubbles entrained in a line vortex flow for different initial bubble sizes: 150 μm (top), 1 mm (bottom).

Fig. 10. Effect of gravity on (a) the trajectories and (b) the time of capture of bubbles entrained in a line vortex flow for different two-phase mixture injection locations.

Fig. 11.
Time sequence of bubble capture and the development of a cavitation core on the axis of the vortex. The bubbles are colored by their gas pressure, P_{gas} , in Pascal. The aqua blue iso-surface is the gas/vapor-liquid interface resulting in the formation of a large free surface interface.

Fig. 12. Modeling of the two-phase flow inside a swirl chamber. Time sequence of the development of a cavitation core (white color) on the axis of the chamber.

Table 1

List of key dimensions of the swirl chamber used in the tests.

Chamber length	32.8 cm
Inner cylinder ID	14.0 cm
Outer cylinder OD	20.3 cm
Outer cylinder ID	19.0 cm
Slot length	32.8 cm
Slot height	0.2 cm
Total number of slots	4
Liquid outlet orifice diameter	1.5 cm
Gas outlet orifice diameter	0.2 cm

Table 2

Gas and liquid properties used in the current study computations.

Liquid density, ρ_l	1000 kg/m ³
Surface tension, γ	0.0728 n/m
Vapor pressure, p_v	2300 pa
Viscosity, μ	0.001 kg/ms
Air density, ρ_g	1.225 kg/m ³
Gas constant	1.4