NUMERICAL STUDY OF GRAVITY EFFECTS ON PHASE SEPARATION IN A SWIRL CHAMBER

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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.

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 ground applications. This paper focuses on the DYNA SWIRL® phase separator which we have developed for future testing by NASA on the International Space Station where earth gravity effects are absent [1]. 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 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 [2–5]. 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 in 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.

**NUMERICAL METHOD**

**Mixture Continuum Phase Model**

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

\[
\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0, \\
\rho_m \frac{D \mathbf{u}}{Dt} = -\nabla p + \rho_m \nabla^2 \mathbf{u} + \rho_m \mathbf{g},
\]

where \( \mathbf{u} \) is the mixture velocity, \( p \) the pressure, and \( \mathbf{g} \) the acceleration due to gravity. The mixture density \( \rho_m \) and the mixture viscosity \( \mu_m \), are related to the void fraction, \( \alpha \), and the liquid and gas properties through

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

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 \( \alpha \) 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 concentration provides \( \alpha \) and \( \rho_m \) as functions of space and time.

The system of equations is closed using an artificial compressibility method [6] in which a pseudo-time derivative of the pressure multiplied by an artificial-compressibility factor, \( \beta \), is added to the continuity equation as:

\[
\frac{1}{\beta} \frac{\partial p}{\partial t} + \frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0.
\]

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 [7] and van Leer’s MUSCL method [8] 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 [9]. The flux Jacobians required in an implicit scheme are obtained numerically. The resulting system of algebraic equations is solved using the Discretized Newton Relaxation method [10] in which symmetric block Gauss-Seidel sub-iterations are performed before the solution is updated at each Newton iteration.

**Turbulence Model**

To simulate the vortex flow inside the swirl chamber when the turbulence is important, a Large Eddy Simulation (LES) model is used. A filtering function [11] is applied to the momentum equation, resulting in an additional term, \( \nabla \cdot \mathbf{h} \), from the non-linear convection terms. \( \mathbf{h} \) is the subgrid scale stress which can be modeled using the Smagorinsky model [12]. Using the Boussinesq approximation, the subgrid scale stress can be related to the strain rate tensor:

\[
\mathbf{h} = -2\mu_T \mathbf{S},
\]

where \( \mu_T \) is the eddy viscosity and \( \mathbf{S} \) is the filtered strain rate tensor. With the Smagorinsky approximation the eddy viscosity is modeled using:

\[
\mu_T = (C_s \Delta)^2 2SS,
\]

where \( C_s \) is the Smagorinsky constant and \( \Delta \) is the filter size.

**Discrete Singularity Model**

The Lagrangian discrete bubble model uses a Surface Average Pressure (SAP) approach to average fluid quantities along the bubble surface [2–5]. This model has been shown to produce accurate results when compared to full 3D two-way interaction computations [13]. 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,

\[
RR + \frac{3}{2} R^2 = \frac{1}{\rho_l} \left( p_i + p_{ig} \left( \frac{R_0}{R} \right)^{3\gamma} - p_{enc} \right) - \frac{2\gamma}{R} \frac{4\mu_k}{R} \frac{\| \mathbf{u} \|^2}{4},
\]

where \( R \) and \( R_0 \) are the bubble radii at time \( t \) and \( 0 \), \( p_i \) is the liquid vapor pressure, \( p_{ig} \) is the initial bubble gas pressure, \( k \) is the polytropic compression constant. \( \mathbf{u}_b \) is the bubble travel velocity, while \( \mathbf{u}_{enc} \) 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. \( \mathbf{u}_t = \mathbf{u}_{enc} - \mathbf{u}_b \) is the bubble slip velocity relative to the liquid.

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

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

where \( \rho_b \) is the bubble content density, \( C_D \) is the drag coefficient given by an empirical equation such as from 2

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Haberman and Morton [14]. $C_l$ is the lift coefficient and $\Omega$ is the deformation tensor. The 1st right hand side term is a drag force. The $2^{nd}$ and $3^{rd}$ terms account for the added mass. The $4^{th}$ term accounts for the presence of a pressure gradient, while the $5^{th}$ term accounts for gravity and the $6^{th}$ term is a lift force [15].

**Level-Set Approach**

In order to simulate liquid-gas interfaces of large cavities such as the gaseous core in the swirl chamber, a Level-Set method is used. A smooth function $\varphi(x,y,z,t)$, is defined in the whole physical domain (i.e. in both liquid and gas phases) as the signed distance $d(x,y,z)$ from the interface:

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

$\varphi$ 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:

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

where $\mathbf{v}$ is the velocity of interface. Integration of Equation (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” with $\varphi(x,y,z,t)$ as the initial solution [16]:

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

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

In a standard Level-Set approach liquid and gas phases are solved separately using Equations (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:

$$p = \frac{\tau_{ij} n_i n_j}{\rho_l} + g n_z + \frac{\gamma}{\rho_l}, \quad \tau_{ij} n_i n_j = 0, \quad \tau_{ij} n_i t_j = 0.$$ (12)

where $\tau_{ij}$ is the stress tensor, $g$ is the acceleration of gravity, and $\gamma$ is the surface tension. $\kappa = V \cdot V \varphi|V \varphi|$ is the surface curvature. $n, \tau^1, \tau^2$ are the normal to the surface and two tangential unit vectors, respectively.

**Transition Model**

The inception of a vaporous/gaseous core is due to the rapid growth of captured bubble nuclei. Since the bubbles are tracked using the 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 [17,18]. For each cell $i$, the distance function is then defined by:

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

where $\varphi_{LS0}$ is the original distance function value for cell $i$, $\varphi_{b,j}$ is the local distance between the center of cell $i$ and the surface of bubble $j$ as shown in Figure 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 Figure 2. The criterion to determine which bubble to “activate” is as follows:

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

where $R_b$ is the bubble radius, $\Delta L$ is the size of local grid which hosts the bubble, $R_{th}$ is a threshold bubble radius, and $m_{th}$ is a threshold multiplier of the local grid size. 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.

![Figure 1: Definition of local distance $\varphi_{b,i}$ between the level zero surface and a cell center.](image1)

![Figure 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.](image2)
**COMPUTATION OF SWIRL CHAMBER FLOW FIELD**

A conceptual overall scheme of the swirl phase separator is shown in Figure 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.

![Figure 3. Sketch of the swirl phase separator.](image)

To numerically study the phase separation, the flow field inside the swirl chamber has to be accurately resolved. This requires fine enough grid. To speed up the numerical simulations, only a quarter of the cylindrical domain is considered as illustrated in Figure 4.

![Figure 4. Multi-block grid generated for the numerical simulations of the DYNASWIRL® phase separator.](image)

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

![Figure 5. Boundary conditions imposed for the numerical simulations of the flow field inside the swirl chamber.](image)

Figure 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 swirl chamber where air may accumulate. 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 Figure 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.

![Figure 6. Non-dimensional tangential velocity magnitude contours and pressure contours inside the vortex separator.](image)
Figure 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 Figure 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.

Figure 7. Validation of flow field computations by comparing with PIV measurements.

**GRAVITY EFFECTS ON BUBBLY FLOW**

The flow field shown in the previous section is used to study gravity filed effects on the bubble behavior inside the swirl chamber. Figure 8 shows the instantaneous locations of 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 are injected 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.

Figure 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.

This trend is strengthened as the body force further increases, as seen in Figure 9. The time needed for a bubble of initial size 1mm 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 μm, 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 Figure 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 near 0.45 s for the top slot and becomes as long as
0.6 s for the right slot. This indicates that 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.

Figure 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).

Figure 10. Effect of gravity on the trajectories of bubbles entrained in a line vortex flow for different two-phase mixture injection locations.

Figure 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, $P_{\text{gas}}$, in Pascal. The aqua blue iso-surface is the gas/vapor-liquid interface resulting in the formation of a large free surface interface.

**MODELING OF GASEOUS VORTEX CORE**

Figure 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 a full-stage 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. Figure 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 a Level-Set method. As seen in Figure 11, an elongated cavity then forms along the axis of the vortex and develops into a gaseous-vaporous tube. Figure 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.

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.

NOMENCLATURE

\[a_c = \text{vortex core radius}\]
\[a_g = \text{gas extraction orifice radius}\]
\[C_D = \text{drag coefficient}\]
\[C_L = \text{lift coefficient}\]
\[C_S = \text{Smagorinsky constant}\]
\[m_{thr} = \text{threshold multiplier of the local grid size}\]
\[\hat{n} = \text{surface normal unit vector}\]
\[\hat{t}^1, \hat{t}^2 = \text{surface tangential unit vectors}\]
\[K = \text{gas constant}\]
\[P_{enc} = \text{encountered pressure}\]
\[p_{go} = \text{initial gas bubble pressure}\]
\[p_l = \text{liquid vapor pressure}\]
\[R = \text{bubble radius}\]
\[R_0 = \text{initial bubble radius}\]
\[R_{thr} = \text{threshold bubble radius}\]
\[\tilde{S} = \text{filtered strain rate tensor}\]
\[t = \text{time}\]
\[u = \text{velocity vector}\]
\[u_s = \text{slip velocity}\]
\[u_{enc} = \text{encountered velocity}\]
\[\alpha = \text{void fraction}\]
\[\beta = \text{artificial compressibility}\]
\[\gamma = \text{surface tension}\]
\[\kappa = \text{curvature}\]
\[\mu = \text{dynamic viscosity}\]
\[\mu_f = \text{eddy viscosity}\]
\[\rho = \text{medium density}\]
\[\Delta = \text{filter size}\]
\[\varphi = \text{distance function}\]
\[\tau = \text{pseudo time}\]
\[\tau = \text{subgrid scale stress}\]
\[\Omega = \text{deformation tensor}\]

Subscripts:

\[b = \text{bubble}\]
\[g = \text{gas}\]
\[l = \text{liquid}\]
\[m = \text{mixture}\]

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