DEVELOPMENT OF AN EFFICIENT PHASE SEPARATOR FOR SPACE AND GROUND APPLICATIONS

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ABSTRACT

The limited amount of liquids and gases that can be carried to space makes it imperative to recycle and reuse these fluids for extended human operations. During recycling processes gas and liquid phases are often intermixed. In the absence of gravity, separating gases from liquids is challenging due to the absence of buoyancy. This paper discusses a phase separator that is capable of efficiently and reliably separating gas-liquid mixtures of both high and low void fractions in a wide range of flow rates that is applicable to reduced and zero gravity environments.

The phase separator consists of two concentric cylindrical chambers. The fluid introduced in the space between the two cylinders enters the inner cylinder through tangential slots and generates a high intensity swirling flow. The geometric configuration is selected to make the vortex swirl intense enough to lead to early cavitation which forms a cylindrical vaporous core at the axis even at low flow rates. Taking advantage of swirl and cavitation, the phase separator can force gas out of the liquid into the central core of the vortex even at low void fraction. Gas is extracted from one end of the cylinder axial region and liquid is extracted from the other end. The phase separator has successfully demonstrated its capability to reduce mixture void fractions down to $10^{-8}$ and to accommodate incoming mixture gas volume fractions as high as 35% in both earth and reduced gravity flight tests. The phase separator is on track to be tested by NASA on the International Space Station (ISS). Additionally, the phase separator design exhibits excellent scalability. Phase separators of different dimensions, with inlet liquid flow rates that range from a couple of GPMs to a few tens of GPMs, have been built and tested successfully in the presence and absence of the gravity.

INTRODUCTION

The limited amount of liquids and gases that can be carried to space makes it imperative to recycle and reuse these fluids. On earth, bubbles in a liquid are easily separable by buoyancy. In microgravity, other external forces, such as a centrifugal force, must be utilized to separate bubbles from liquids. Two categories of centrifugal force separators exist: one uses active rotation by mechanically spinning the tank. This is very efficient but requires a shaft, bearings, and a motor, and a lot of energy. In the second, the tank is fixed, and the rotation is induced by eccentric injection of the mixture (Free Vortex Separator or FVS). These passive separators have no moving mechanical parts, require low power, and have been investigated intensively owing to their simplicity and dependability [1-3]. McQuillen et al. at NASA Glenn Research center have been developing the Cascade Cyclonic Separation Device (CSD-C) since the mid 90’s [4,5]. This separator has
been proven to be very efficient for mid-range void fractions (50% to 80% gas) with an efficiency approaching 100%, but is not as efficient for lower void fraction [6,7]. The phase separator that we have developed and are describing here, aims at filling the gap and addressing effectively this aspect.

A. Swirl Flow Separator

The phase separator described here is based on the DYNASWIRL® cavitating nozzles [7]. It combines cavitation and flow rotation to generate cavitation at high cavitation numbers (i.e., low flow rates or pump pressures). These nozzles have been used in applications such as disinfection, underwater painting and surface preparation algae oil extraction, liquid oxidation, organic compound reduction, bubble generation and oxygenation. Although the mechanisms enabling the accomplishment of each of these functions are different, all arise from induced cavitation bubble dynamics, growth, and collapse.

![Figure 1. Sketch of the two-phase swirl flow separator.](image)

The phase separator consists of two concentric cylinders as shown in Figure 1. The two-phase fluid is introduced in the space between the two cylinders and exits through orifices on the end plates of the cylinder. The swirling flow inside the inner cylinder is generated with wall tangential slots which enable flow from the outer cylinder to the inner cylinder. This configuration makes the vortex core very stable even at low flow rates. The ratio between axial and tangential velocities, \( \Omega \), or the swirl parameter, can be controlled by changing the relative areas of the slots, \( A_s \), and the liquid exit area, \( A_e \). By increasing the tangential velocity, the pressure on the axis can be made low enough to induce microbubble growth and collection on the axis into a cylindrical bubble. At even higher tangential velocities cavitation occurs and further enhances gas diffusion and gas transfer into the central vortex core. The phase separator thus combines swirl, cavitation, and rectified gas diffusion to force low to medium void fraction gas out of the liquid into the central core of the vortex and extract the gas from the central cavitation core.

The pressure drop at the center of the vortex is a direct function of the vortex strength, \( \Gamma \), and of the radius of the vortex viscous core, \( a_c \). The flow field of a rotating liquid can be considered to be composed of two regions. In the innermost region, of approximate radius \( a_c \), the fluid viscosity is predominant, and the fluid rotates as a solid body. In that region the tangential velocity of the fluid increases linearly with the distance from the vortex axis where the tangential velocity is zero. At a distance \( r \) from the vortex axis the tangential velocity in this viscous region can be related to the angular velocity, \( \omega \), as

\[
v_t = \omega r.
\]

In the outermost region of the vortex, the flow is that of an ideal inviscid fluid. In that region, the circulation, which is equal to the integral of the velocity along a closed line encircling the vortex center, is constant everywhere and equal to the vortex strength, \( \Gamma \). The velocity at a point located at a distance \( r \) from the vortex center in this outermost region is related to \( \Gamma \) by

\[
v_t = \frac{\Gamma}{2\pi r}.
\]

At the transition between the viscous and inviscid regions, where \( r = a_c \) and \( v_t = v_2 \), the following relationship can be derived:

\[
\Gamma = 2\pi a_c^2, \tag{2}
\]

By applying Bernoulli’s equation in the inviscid region and solving the equations of conservation of mass and momentum in the viscous region, the pressure profile along the radial direction can be expressed as:

\[
p(r) = \begin{cases} 
  p_o - \frac{\rho \Gamma^2}{4\pi^2} \left( \frac{1}{a_c^2} - \frac{r^2}{a_c^4} \right), & r \leq a_c \\
  p_o - \frac{\rho \Gamma^2}{4\pi^2} r^2, & r \geq a_c 
\end{cases} \tag{3},
\]

where \( p_o \) is the ambient pressure at the inner chamber boundary. The pressure at the vortex center, \( p_c \), can be determined knowing \( \Gamma \), \( p_o \), \( a_c \), and the liquid density, \( \rho \):

\[
p_c = p_o - \frac{\rho \Gamma^2}{4\pi^2 a_c^2}. \tag{4}
\]

Cavitation in the vortex occurs when \( p_c \) drops locally below the liquid critical pressure or the vapor pressure, \( p_v \), of the liquid at the considered temperature [9]. The challenge to increase the pressure drop or the degree of cavitation is to increase \( \Gamma \) or decrease \( a_c \) faster than the increase of the inlet pressure, \( p_o \).

B. Effects of Gravitation Acceleration

The pressure gradient due to swirl can be expressed as
\[ \frac{dp}{dr} = \frac{\rho g r}{4 \pi a_r^2}, \quad r \leq a_r, \] \[ \frac{dp}{dr} = \frac{\rho g r^3}{4 \pi^2 a_r^2}, \quad r \geq a_r. \] The pressure gradient due to gravity can be expressed as
\[ \frac{dp}{dz} = \rho g. \]
The ratio, \( F \), of these two pressure gradients is:
\[ F = \frac{\frac{dp}{dr}}{\frac{dp}{dz}} = \frac{4 \pi^2 g a_r^4}{r^4}, \quad r \leq a_r, \] \[ F = \frac{4 \pi^2 g}{r^3}, \quad r \geq a_r. \]

When \( F \) is not negligible, gravitational effects are important. This is the case within the core as \( r \) is reduced, and in the inviscid region when \( r \) increases. This illustrates the need for conducting microgravity tests since the gravity on earth affects the test results. However, concerning effective separation, when \( \Gamma \) is high enough, gravity does not affect the efficient operation of the phase separator.

### C.3D Coupled Numerical Simulations
Numerical simulations were conducted to gain insight of the two-phase separation physics and to assist the design of an efficient separator. The bubbly mixture flow inside the swirl chamber was treated from the following two perspectives:

- **Microscopic level:** Individual bubbles are tracked in a Lagrangian fashion, and their dynamics are followed by solving the surface averaged Rayleigh-Plesset equation [10,12]. The bubble responds to the surrounding medium as shown in Equation (12).
- **Macroscopic level:** The mixture is treated as a continuum with time and space dependent local density related to the bubble distribution. The mixture density is provided by the microscale tracking of the bubbles and the determination of their locations and volumes.

The two levels are fully coupled: the bubbles respond to the variations of the mixture flow field characteristics, and the flow field depends directly on the bubble size and position variations. This is achieved through a two-way coupling between the unsteady Navier-Stokes solver 3DYNAFS-Visc and the bubble dynamics code 3DYNAFS-DSM [12,13].

The incompressible Navier-Stokes flow solver includes bubbles, cavities, and large free surface deformations. It uses moving overset grids and dynamic grid generation schemes. It enables direct numerical solution in addition to RANS. The mixture medium satisfies the following general continuity and momentum equations:
\[ \frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}_m) = 0, \] where the subscript \( m \) represents the mixture medium. The mixture density and the mixture viscosity for a void volume fraction \( \alpha \) can be expressed as:
\[ \rho_m = (1 - \alpha) \rho_g + \alpha \rho_v, \] \[ \mu_m = (1 - \alpha) \mu_g + \alpha \mu_v, \]
where the subscript \( \ell \) represents the liquid and the subscript \( g \) represents the gaseous bubbles.

The simulation used the Lagrangian bubble tracking to track the dynamics of bubbles present in a flow field. The bubble dynamics is solved by the Rayleigh-Plesset-Keller-Herring equation [10,12]:
\[ \frac{1}{\rho_m} \frac{d \mathbf{u}_m}{dt} = - \nabla p + \mu_m \nabla^2 \mathbf{u}_m + \rho_m \mathbf{f}_m, \] (9)

The first term in Equation (13) accounts for the drag force. The drag coefficient \( C_D \) is determined by empirical equations such as in [15]. The second and third term in Equation (13) 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 (13) is the lift force due to shear [16]. \( \nu \) is the kinematic viscosity, and \( d_i \) is the deformation tensor.

Figure 2 shows a comparison of the tangential velocities obtained from PIV measurements and simulations for a phase separator test section with a 6 inch inner diameter at 6 gpm inlet flow rate. The PIV measurements were conducted in the middle plane of the swirl chamber. Four different areas spanning the radial extent of the chamber were measured separately as indicated with different color symbols in Figure 2. Two numerical simulations were conducted for the same flow...
conditions with one simulation including a Large Eddy Simulation (LES) model and the other one without any turbulence model. It can be seen that the numerical solution matches very well with the experimental measurements when the LES model is used.

![Figure 2. Tangential velocity profile comparison for a swirl phase separator chamber with a 6 in. inner diameter at 6 gpm flow rate. The PIV measurements with different colors covering different areas of the test section are overlaid together. “Without LES” indicates simulation with no turbulence model.](image)

**D. Ground Tests Loop**

Under on-going support from NASA, we have been developing the above described phase separator to fit within the NASA flights constraints for reduced gravity flight test. Extensive tests have been conducted on the ground to evaluate the performance of the various designs. Figure 3 shows an experimental setup used for these ground tests. The desired flow rate is provided by a liquid pump and controlled by a flow control valve. The two-phase mixture flow is formed at the desired void fraction in the development tube by injecting and mixing gas with the liquid. The mixture coming out from the development tube is then injected into the swirl phase separator. The liquid after the separation goes to the secondary reservoir for recirculation and the gas after the separation is exhausted without recirculation. A vacuum pump is used to enhance the gas extraction. There are no specific requirements to the liquid pump and vacuum pump shown in Figure 3 as long as they can provide the required pressure head and vacuum level needed by the phase separator.

**EFFECTS OF DESIGN PARAMETERS**

Extensive ground experiments and numerical simulations have been conducted to study the effects of the main design parameters on the performance of the phase separator. This helps in better understanding of the physics of the separation and facilitates the development and optimization of the phase separator at the system and component levels.

**Figure 3. Experimental setup for ground testing the phase separator.**

**A. Effects of Orifice Size**

The exit orifice diameter has a significant effect on the phase separator performance. Numerical simulations were performed on a 3.5 cm chamber diameter by varying the liquid exit orifice size from a diameter of 5 mm to a diameter of 20 mm. Figure 4 shows contour maps of the tangential velocity distribution for an injection velocity of 1 m/s. The maximum tangential velocity increases with increased orifice size and then decreases with further increase. A quantitative comparison at the middle section of the phase separator chamber is shown in Figure 5, which clearly shows that for this particular chamber studied, there is an orifice size that gives the highest peak tangential velocity and smallest core size. A further increase or decrease of the orifice size generates a lower peak tangential velocity. As shown in the figure, the effects of the orifice size affect only the vortex core region. Further outside, the velocity profiles fall on top of each other regardless of orifice size. This is because in the inviscid region only the circulation, which is constant here, is relevant.

**Figure 4. Orifice size effects on tangential velocity distribution.**
Figure 5. Effects of orifice size on the tangential velocity profile at middle section of the chamber.

Figure 6 shows contour maps of the corresponding pressure distributions. The pressure at the chamber wall is the highest for the case with the smallest orifice size (5 mm) and lowest for the case with the biggest orifice size (20 mm). The overall pressure drop in the separator decreases monotonically with increased orifice size as the restriction to the flow due to the orifice decreases with increased orifice size.

Figure 6. Orifice size effects on the pressure distribution in the swirl chamber.

Figure 7. Orifice size effects on the normalized radial pressure profile shown at the location of the mid-length of the chamber.

To quantitatively compare the pressure profiles, we show in Figure 7 a normalized pressure, \( \bar{P} = 2(p - P_{\text{ref}})/(\rho V_o^2) \), in which \( P_{\text{ref}} \) is a reference pressure (\( P_{\text{ref}} = 1 \text{ atm} \) was used in the calculations) and \( V_o \) is the average velocity in the exit orifice. The normalized pressure profile is shown along the radial direction in the cross section at mid-length of the chamber. For the smallest orifice size of 5 mm, the pressure changes little with the radial location. The largest pressure drop at the core is achieved for the orifice size of 10 mm. Further increase in the orifice size results in the core pressure increasing again. As for the effects of the tangential velocity, the effect of orifice size on vortex core pressure is also not monotonic.

Figure 8 shows sample radial pressure profiles for different orifice diameters obtained from experiments using a 6 inch diameter test chamber. As seen in the figure, for the same flow rate, the pressure at the chamber inlet drops significantly as the orifice diameter increases, i.e. for a given injection pressure, the maximum flow rate achievable increases (increase of injection velocity) as the orifice diameter increases. As shown in the numerical simulations described earlier, even though the pressure decreases radially when moving toward the core axis regardless of the orifice diameter, the pressure at the core axis actually increases as the flow rate increases if the orifice diameter is too small (e.g. \( d = 0.8 \text{ cm} \)). The axis pressure decreases with increasing flow rate only if the orifice diameter is large enough (e.g. \( d = 1.5 \text{ cm} \)). Therefore optimization of the orifice diameter is very important to the overall performance of the phase separator.
With increasing flow rates, the pressure at the vortex axis decreases for the single orifice until it reaches a plateau while the corresponding core axis pressure for 6-orifice configuration keeps increasing, indicating that the exit orifice layout significantly affects the swirling flow pattern and needs to be optimized based on the operation conditions of the phase separator.

C. Effects of the Phase Separator Orientation

The ratio $F$, defined in Equation (7), dictates the importance of gravitational acceleration for ground applications. For the phase separator, ground based experiments show that the orientation does not have significant effects on the performance of the phase separator. The steady gaseous core remains steady as the orientation of the experiment setup is changed from horizontal to vertical. However, the hydrostatic head is different at different locations along the vortex axis when the axis is vertical.

Figure 10 illustrates the effects of the orientation of the phase separator on the radial pressure profile. The tests were conducted on a swirl phase separator which had a 6 inch swirl chamber and a single liquid exit orifice. The pressures in the viscous core are very similar in both orientations, although differences in the pressure profile can be seen and are related to changes in the hydrostatic head between the two orientations. This low sensitivity of the phase separator to the orientation makes it more versatile to be integrated into either space or ground applications.

Additionally, a very strong gas core can be formed in all ground test conditions, indicating that the phase separator can be readily used for ground phase separation applications.

EXPERIMENTS ON REDUCED GRAVITY FLIGHTS

Different versions of the phase separators have been tested so far on five reduced gravity flights organized by NASA. The first two flight tests in 2009 concentrated on low void fraction and the phase separator was able to reduce the exit liquid void fraction down to $10^{-3}$ [17].
With further developments of the phase separator, two additional reduced gravity flights were performed in 2012 and 2013 respectively. Figure 11 shows the variation of the instantaneous gas extraction rate and the gravitational acceleration in a reduced gravity flight test in 2012. The liquid flow rate was 18.5 gpm and the average void fraction of the mixture was about 3%. Regardless of the value of the gravity intensity during the flight, the gas extraction continued normally as the airplane maneuvered through parabolas. Figure 12 shows the cumulative gas extracted and the gravitational acceleration. The accumulated gas removed increases at an almost constant rate during the 40 minutes flight time.

**A. Small Test Rig Separator**

The phase separator used in the reduced gravity flight tests until 2013 was a version that had a test section with a 3 gallons volume and operated at flow rates that exceeded 10 gpm. In order to integrate the separator with a new test rack designed by NASA Glenn Research Center to be compatible with the ISS, a smaller version of the phase separator was designed and developed. The new test rack flow specifications are:

- Water liquid volume: 1.0 gallon.
- Water flow rate: 4.5 gpm to 5.8 gpm.
- Gas flow rate: 1.1 scfm to 1.8 scfm.
- Maximum operating pressure: 36 psia to 65 psia.
- Vacuum capability: 0.35 scfm at 25.5 inch Hg to 0.7 scfm at 26.5 inch Hg.
- Total power consumption: 1 kW.

The newly designed phase separator has since been successfully integrated with the NASA test rack. Figure 14 is a 3D rendering of the NASA breadboard test rack with a smaller version of the phase separator in place. The test rack was successfully tested during two reduced gravity flight tests in 2015. Figure 15 shows pictures of the test chamber taken during a flight in almost zero gravity when the mixture entering the phase separator was 8% and 31% respectively. As seen in the pictures, a clear gas core is formed...
and the gas collects into the core enabling removal. The flight tests showed that the phase separator always formed such a steady gas core at the full range of the test matrix during the flight tests.

A relatively small phase separator was integrated with the NASA breadboard test rack for ground and reduced gravity flight tests. Flight test data indicated that the gas was always collected in a vortex core formed at the full range of the test matrix during the flight tests regardless of the gravitation acceleration change, and this gas was efficiently extracted in the gas exit line.

**CONCLUSIONS**

A phase separator for both ground and space applications based on the DYNA SWIRL® technology has been developed. Tests have shown that the phase separator can be configured for phase separation efficiently and reliably at both very low void fraction and at void fraction up to 35% in a wide range of flow rates.

**REFERENCES**
