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Development of a passive phase separator for space and earth 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 describes development of a passive 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 for both space and earth applications.

1. Introduction

Fluids are utilized in several systems and subsystems of both manned and unmanned spacecraft. These include the propulsion system, the power system, and the thermal and environmental control and life support systems (ECLSS). Often, two-phase mixtures of gas and liquid occur in the flow via phase changes, degasification, changes in the solubility of dissolved gasses in the liquid medium, or through deliberate introduction or accidental entrainment of one phase into the other. This mixing of the phases needs to be addressed and gas-liquid phase separation is necessary when system-critical components such as centrifugal pumps and catalytic packed bed bioreactors are designed to specifically operate in a single phase mode only. Also, the performance and reliability of some system components can be significantly enhanced by operating in a single-phase mode. This is the case for example for condensers where preventing the liquid phase from entering the condensers minimizes flow instability and enhances efficiency [1].

The limits on the amount of liquids and gases that can be carried to space make it imperative to recycle and reuse these fluids. On earth, bubbles in a liquid are easily separable by buoyancy. In microgravity, another external force, such as an imparted centrifugal force, must be utilized to separate bubbles from liquids. To meet this demand, various methods to produce phase separation in low gravitational environment have been developed. These have included wicking, using membranes and hydrophobic/hydrophilic meshes, designing the flow to contain sudden direction changes or elbows, or a combination of the above [1–11]. For instance, recent publications have discussed the effects of the gravity level on using flow pattern modulation to passively enhance the separation using suspended mesh cylinders [2–4]. Among these phase separation concepts, two categories of centrifugal force separators

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have been applied: one uses active rotation by mechanically spinning the tank. This is very efficient but requires a shaft, bearings, and a motor, and uses significant 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 [1,5–14]. McQuillen et al. at NASA Glenn Research center have been developing the Cascade Cyclonic Separation Device (CSD-C) since the mid 90's [8,9]. This separator has been proven to be very efficient for mid-range void fractions (50–80% gas) with an efficiency approaching 100%, but is not as efficient for lower void fraction [10,11]. The phase separator that we have developed and are being described here, aims at filling the gap and addressing effectively this aspect.

1.1. Swirl flow separator

The phase separator described here is based on the DynaSwirl® cavitating nozzles [15]. It generates flow rotation with high circulation to generate cavitation at the center of the vortex at low flow rates. 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, etc. Although the mechanisms enabling the accomplishment of each of these functions are different, all arise from the induced cavitation bubble dynamics, growth, and collapse.

The phase separator consists of two concentric cylinders as sketched in Fig. 17. The two-phase flow 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 Ω between tangential inlet velocity, V_t and axial outlet velocity, V_o , or the swirl parameter, can be controlled by changing the relative areas of the slots, A_t and the liquid exit area, A_o

$$\Omega = V_t/V_o = A_o/A_t. \quad (1)$$

This non-dimensional parameter is one of the important parameters for the phase separator design.

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 non-dimensional parameter, σ , which characterizes cavitation inception, is introduced later after presenting the theoretical evaluation of the pressure on the vortex axis.

The flow field of a liquid rotating about an axis is composed of two regions. In the innermost region, of 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, ω , as

$$V(r) = \omega r, \quad r \leq a_c. \quad (2)$$

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

$$V(r) = \Gamma/2\pi r, \quad r \geq a_c. \quad (3)$$

Applying (2) and (3) at $r = a_c$, provides the relationship between Γ and ω :

$$\Gamma = 2\pi\omega a_c^2. \quad (4)$$

The pressure drop at the center of the vortex is a direct function of the vortex strength or flow circulation, Γ , and of the radius of the vortex viscous core, a_c . 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:

$$p(r) = \begin{cases} P_o - \frac{\rho\Gamma^2}{2\pi^2} \left(\frac{1}{a_c^2} - \frac{r^2}{2a_c^4} \right), & r \leq a_c \\ P_o - \frac{\rho\Gamma^2}{8\pi^2 r^2}, & r \geq a_c \end{cases}, \quad (5)$$

where P_o is the ambient pressure at the inner chamber boundary. The pressure at the vortex center, p_c , can be determined knowing Γ , P_o , a_c , and the liquid density, ρ :

$$p_c = P_o - \frac{\rho\Gamma^2}{8\pi^2 a_c^2}. \quad (6)$$

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 [16]. The challenge to increase the pressure drop or the degree of cavitation is to increase Γ or decrease a_c faster than the increase of the inlet pressure, P_o . The dimensionless number, which characterizes the propensity of the flow to cavitate is the cavitation number, σ ,

$$\sigma = \frac{P_0 - p_v}{0.5\rho V_{inlet}^2}. \quad (7)$$

This number is also one of the important parameters for the design of the DynaSwirl[®] separator.

The total pressure drop across the phase separator, p_T can be estimated from the pressure needed to inject the flow into the phase separator, P_{inj} through the slots and the pressure needed to push the liquid out of the exit orifice, P_o i.e.

$$\Delta p_T = \Delta P_{inj} + \Delta P_o. \quad (8)$$

If the liquid flow rate through the phase separator is Q , the mixture flow rate, Q_m is:

$$Q_m = \frac{Q}{1 - \alpha}, \quad (9)$$

where α is the inlet volume fraction of air.

The pressure drop through the injection slot can be estimated as follows after neglecting the air density relative to the water density and the liquid velocity outside of the swirl chamber relative to the injection velocity into the tangential flow:

$$\Delta P_{inj} = \frac{1}{2}(1 - \alpha)\rho \left(\frac{Q}{C_{ds}A_t(1 - \alpha)} \right)^2, \quad (10)$$

where C_{ds} is the injection slot discharge coefficient.

The pressure drop across the liquid exit orifice can also be estimated neglecting the axial velocity in the swirl chamber relative to the axial exit velocity:

$$\Delta P_o = \frac{1}{2}\rho \left(\frac{Q}{C_{do}A_o} \right)^2, \quad (11)$$

where C_{do} is the liquid exit orifice discharge coefficient.

Assuming, $C_{do} = C_{ds} = C_d$ for simple estimation purposes, the total pressure drop across the phase separator can then be estimated as:

$$\Delta P_T = \frac{1}{2}\rho \left(1 + \frac{\Omega^2}{(1-\alpha)} \right) \left(\frac{Q}{C_d A_o} \right)^2 \quad (12)$$

1.2. Effects of gravitation acceleration

In order to estimate the effects of gravity on the separator we compare below the various pressure gradients, which have a key influence on the bubbles motion. The pressure gradient due to swirl is given by:

$$\frac{dp}{dr} = \begin{cases} \frac{\rho \Gamma^2}{4\pi^2 a_c^4} r, & r \leq a_c, \\ \frac{\rho \Gamma^2}{4\pi^2 r^3}, & r \geq a_c. \end{cases} \quad (13)$$

The pressure gradient due to gravity can be expressed as

$$\frac{dp}{dz} = \rho g. \quad (14)$$

The ratio, F , of these two pressure gradients determines the relative importance of gravity on the separation, and is expressed as:

$$F = \frac{\frac{dp}{dz}}{\frac{dp}{dr}} = \begin{cases} \frac{4\pi^2 g a_c^4}{\Gamma^2} \frac{1}{r}, & r \leq a_c, \\ \frac{4\pi^2 g}{\Gamma^2} r^3, & r \geq a_c. \end{cases} \quad (15)$$

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. In both cases F increases significantly. This illustrates the need for conducting microgravity tests since the gravity on earth affects the test results. However, concerning effective separation, when Γ is high enough, it makes F small and gravity does not affect the efficient operation of the phase separator.

1.3. Estimation of bubble capture in the separator

A key function of the gas-liquid phase separator is to ensure that the bubbles are captured by the vortex before they exit the separator. To estimate the time, T_p , required by a bubble to be captured in the phase separator vortex, we neglect temporarily bubble volume change and acceleration and consider only the force balance between the pressure gradient in the radial

direction for the bubble in the potential region, i.e. for $r \geq a_c$ before it enters the viscous core [17]. Using Eq. (6) and the drag force on a spherical bubbles we obtain:

$$\frac{\rho \Gamma^2}{2\pi^2 r^3} \left(\frac{4}{3} \pi R_b^3 \right) = \frac{1}{2} \rho C_D (\pi R_b^2) V_r^2, \quad (16)$$

where R_b is the bubble radius, V_r is the bubble velocity in the radial direction, and C_D is the bubble viscous drag coefficient. C_D depends on the Reynolds number of the relative flow and can be approximated by

$$C_D \sim \frac{24}{\text{Re}_b} = \frac{12\nu}{R_b V_r}. \quad (17)$$

The above results in the following radial velocity of the motion of the bubble towards the viscous core:

$$v_r = \frac{\Gamma^2}{\pi^2 r^3} \frac{R_b^2}{18\nu}. \quad (18)$$

The capture time can then be obtained as follows after neglecting the core radius size relative to the initial radial distance of the bubble from the axis, R_{cyl} , the radius of the swirl chamber:

$$T_r = \int_{R_{cyl}}^0 \frac{dr}{v_r} = \int_{R_{cyl}}^0 \frac{\pi^2 r^3}{\Gamma^2} \frac{18\nu}{r_b^2} dr = \frac{9\nu\pi^2 R_{cyl}^2}{2\Gamma^2 R_b^2}. \quad (19)$$

The bubble capture time decreases with increasing circulation and bubble size and reducing chamber radius.

For a properly designed phase separator, the time for a bubble to remain in the phase separator, T_x , which can be approximated by

$$T_x = \frac{L}{V_x} = \frac{QL}{\pi R_{cyl}^2}, \quad (20)$$

in which Q is the flow rate and L is the distance between the injection slots and the liquid exit orifice. For complete separation, we need $T_r < T_x$, or

$$T^* = \frac{T_r}{T_x} = \frac{9\nu A_t^2}{8\pi L Q r_b^2} < 1. \quad (21)$$

1.4. Numerical model

Numerical simulations were conducted to gain insight into 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 an equation of motion and a surface averaged Rayleigh-Plesset equation [18,19].

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 knowledge at each instant of the bubble 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-Vis[®] and the bubble dynamics code 3DynaFS-Dsm[®] [20,21].

The 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 Reynolds Averaged (RANS) equations. The mixture medium satisfies the following general continuity and momentum equations:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}_m) = 0, \quad (22)$$

$$\rho_m \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu_m \nabla^2 \mathbf{u} + \rho_m \mathbf{g}, \quad (23)$$

where the subscript m represents the mixture. The mixture density and the mixture viscosity for a void volume fraction α can be expressed as:

$$\rho_m = (1 - \alpha)\rho_\ell + \alpha\rho_g, \quad (24)$$

$$\mu_m = (1 - \alpha)\mu_\ell + \alpha\mu_g, \quad (25)$$

where the subscript ℓ represents the liquid and the subscript g represents the gaseous bubbles.

The bubble volume versus time is obtained by solving a modified Rayleigh-Plesset-Keller-Herring equation for the sphere of equivalent radius $R(t)$ [18,20]:

$$\begin{aligned} \left(1 - \frac{\dot{R}}{c_m}\right) R \ddot{R} + \frac{3}{2} \left(1 - \frac{\dot{R}}{3c_m}\right) \dot{R}^2 &= \frac{|\mathbf{u}_{enc} - \mathbf{u}_b|^2}{4} \quad (26) \\ + \frac{1}{\rho_m} \left(1 + \frac{\dot{R}}{c_m} + \frac{R}{c_m} \frac{d}{dt}\right) &\left(p_v + p_{g0} \left(\frac{R_0}{R}\right)^{3k} \right. \\ \left. - P_{enc} - \frac{2\gamma}{R} - \frac{4\mu_m \dot{R}}{R}\right), \end{aligned}$$

where R is the bubble radius at time t and R_0 is the initial or reference bubble radius. γ is the surface tension parameter, μ_m is the medium viscosity, ρ_m is the continuum density. p_v is the liquid vapor pressure, p_{g0} is the initial gas pressure inside the bubble, and k is the polytropic compression law constant. $\mathbf{u}_{enc}$ is the liquid convection velocity vector and $\mathbf{u}_b$ is the bubble travel velocity vector. P_{enc} and $\mathbf{u}_{enc}$ are the pressure and velocity “seen” by the bubble during its travel, obtained by averaging the surrounding quantities over the surface of the bubble. c_m is the speed of sound in the mixture medium.

The bubble trajectory is obtained by expressing the balance of all forces acting on the bubbles [22]. The resulting bubble motion equation is given by:

$$\begin{aligned} \frac{d\mathbf{u}_b}{dt} &= \frac{3}{8} \frac{C_D}{R_e} (\mathbf{u} - \mathbf{u}_b) + \frac{\rho_m}{\rho_b} \frac{3\dot{R}}{2R} (\mathbf{u} - \mathbf{u}_b) + \frac{\rho_m}{\rho_b} \mathbf{u}_b \frac{\partial \mathbf{u}}{\partial x} + \frac{1}{2} \frac{\rho_m}{\rho_b} \left(\frac{d\mathbf{u}}{dt} - \frac{d\mathbf{u}_b}{dt} \right) \quad (27) \\ &+ \frac{(\rho_b - \rho_m)}{\rho_b} g + \frac{K\nu^{1/2} \rho_m d_{ij}}{\rho_b R (d_{lk} d_{kl})^{1/4}} (\mathbf{u} - \mathbf{u}_b). \end{aligned}$$

The first term in Eq. (27) accounts for the drag force. The drag coefficient C_D is determined by empirical equations such as in [23]. The second and third term in Eq. (27) 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 Eq. (27) is the lift force due to shear [24]. ν is the kinematic viscosity, and d_{ij} is the deformation tensor.

1.5. Numerical modeling of the swirl chamber

To numerically simulate the phase separator discussed in this paper, we use fine grids inside the swirl chamber to finely resolve the important flow field there. To speed up the numerical simulations, a quarter symmetry is assumed and a quarter of the cylindrical domain is considered as illustrated in Fig. 1. The outer cylindrical chamber shown in Fig. 17 is not considered in the simulation and the liquid exit chamber is replaced with a large container to impose a constant outlet pressure condition.

The quarter of the inside of the swirl chamber is discretized using 71 radial nodes by 81 axial nodes by 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. The large exit chamber used to impose a constant outlet pressure is gridded using a $21 \times 61 \times 41$ grid.

Fig. 2 shows the 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.

Fig. 3 shows a comparison of the tangential velocities obtained from PIV measurements and simulations for a phase separator test section with a 152.4 mm inner diameter, 328 mm length, 4 slots each with the dimensions of 328 mm by 2 mm, and a liquid orifice diameter of 15 mm. The flow rate was 22.7 liter per minute (lpm) inlet flow rate. The PIV measurements were conducted in the middle plane of the swirl chamber. 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.

1.6. Laboratory tests

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. Fig. 4 shows an experimental setup used for these ground tests. Table 1 shows the dimensional details of a DynaSwirl® Phase Separator. 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 extracted 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 Fig. 4 as long as they can provide the required pressure head and vacuum level needed by the phase separator.

2. 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.

2.1. Effects of orifice size

As mentioned earlier one of the important design parameter is the swirl parameter, Ω . For a given cross section area of the injection slots, the variation of the exit orifice diameter shows the effect of the swirl parameter on the phase separator performance. Numerical simulations were performed on a swirl chamber with an inner diameter of 121 mm by varying the liquid exit orifice size from a diameter of 3.2 mm to a diameter of 12.7 mm for a fixed area of injection slots of 25.6 mm². This corresponds to variations of Ω from 0.31 to 4.9.

Fig. 5 shows contour maps of the tangential velocity distribution for an injection flow rate of 5.8 lpm (average inlet velocity at injection slot is 3.9 m/s). The maximum tangential velocity is seen to increase with increased orifice size and then to decrease with further orifice size enlargements. A quantitative comparison of these tangential velocities at the middle section (along the length) of the phase separator chamber is shown in Fig. 6. The figure clearly shows that for this particular chamber studied, there is an orifice size that gives the highest peak tangential velocity while maintaining a relatively small core size. A further increase or decrease of the orifice size reduces the peak tangential velocity. The figure also shows that the orifice size affects only the vortex core region. Outside of this region, 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.

Fig. 7 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 ($D = 3.2$ mm) and lowest for the case with the biggest orifice size ($D = 12.7$ 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.

To quantitatively compare the pressure profiles, Fig. 8 show the pressure profiles along the radial direction in the cross section at mid-length of the chamber for different exit orifice sizes. For the smallest orifice size of 3.2 mm, even though there is a significant pressure drop in the core, the absolute pressure is significantly higher than all the other cases due to the strong constriction of the flow by the small orifice diameter. For the orifice size of 6.4 mm, there is also significant pressure drop in the core. This orifice size also produces the lowest core pressure. Further increase in the orifice size results in the core pressure increasing again. As for the effects of the tangential velocity, the effects of orifice size on the vortex core pressure are also not monotonic.

Fig. 9 shows the radial pressure profiles for three exit orifice diameters obtained from experiments conducted on a swirl chamber with an inner diameter of 152.4 mm, a length of 240 mm and a swirl parameter $\Omega = 1.18$. As shown in the figure, for the same flow rate, the pressure at the chamber inlet drops significantly as the orifice diameter increases. This is due to the decrease in the pressure loss at the orifice. For a given injection pressure, the maximum flow rate achievable increases as the orifice diameter increases. Similar to the results obtained in the numerical simulations described above, even though the pressure decreases radially when moving toward the vortex axis, regardless of the orifice diameter, the pressure at the core axis actually increases if the orifice diameter is too small (e.g. $d = 0.8$ cm). The core pressure decreases only if the orifice diameter is large enough (e.g. $d = 1.5$

cm). A properly selected orifice diameter is very important to the overall performance of the phase separator.

2.2. Effects of the liquid outlet layout

One way to prevent or minimize the gas from escaping from the gaseous core into the liquid outlet is to arrange the liquid outlets in an off-axis annular configuration. Here we examine the effects of such a geometric configuration of the exit orifice(s) on the phase separator performance. Fig. 10 compares the radial pressure profiles of a single orifice exit centered on the chamber axis with those of six off-centered orifices symmetrically arranged around the chamber axis (annular outlets). The total area of the six exit orifices is the same as the single centered orifice.

The figure shows the differences in the pressure distributions between the two geometric locations of the exit orifices. For the single orifice, the pressure at the core axis is lower than the annular 6-orifice configuration. However the pressure at the chamber inlet follows the opposite trend. Consequently, the off-centered 6-orifice configuration allows higher maximum flow rate for a given inlet injection pressure compared with the single orifice but the swirl intensity is lower.

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.

2.3. Effects of the phase separator orientation

The ratio F , defined in Eq. (15), dictates the importance of gravitational acceleration for ground applications. Qualitatively, ground based experiments show that the orientation does not have significant effects on the operation 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.

Fig. 11 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 swirl chamber with inner diameter of 152.4 mm 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.

3. 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^{-8} [25].

With further developments of the phase separator, two additional reduced gravity flights were performed in 2012 and 2013 respectively. Fig. 12 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 70 lpm 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. Fig. 13 shows the cumulative gas extracted and the gravitational acceleration. The accumulated gas removed increases at an almost constant rate during the 40 min flight time.

3.1. 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 37.8 lpm. 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 were:

- Water liquid volume: 3.78 l.
- Water flow rate: 17–21.9 lpm.
- Gas flow rate: 31–51 slpm.
- Maximum operating pressure: 248–448 kPa.
- Vacuum capability: 9.9 slpm at 15 kPa to 19.8 slpm at 11 kPa.
- Total power consumption: 1 kW.

The smaller version of the phase separator chamber that we developed has a volume of 0.44 gallons and operates at liquid flow rate from 5.7 to 18.9 lpm. Ground tests have shown that this smaller phase separator can operate smoothly in the designed operation range. Fig. 14 shows an example of the balance of the air injection and gas extraction measured in a ground test. Both the 6-orifice liquid outlet version and the single orifice liquid outlet version were tested. Both have shown that the air injected can be removed and the phase separator can operate steadily during the test. The corresponding void fraction in this test was about 31%.

The newly designed phase separator has since been successfully integrated with the NASA test rack. Fig. 15 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. Fig. 16 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.

4. Conclusions

A phase separator suitable for both earth and space applications based on the DynaSwirl® 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. Compared to other phase separator designs, this phase separator can easily accommodate different separation conditions by adapting the design parameters properly to the desired conditions. The separator was shown to be able to take in a large air volume fraction inlet mixture and enable good phase separation with an extremely low air volume fraction in the liquid exit line.

A smaller version of the phase separator was integrated in the NASA breadboard test rack for ground and reduced gravity flight tests. Flight test data indicated that the gas was successfully collected in a stable vortex core formed for the full range of the test matrix during reduced gravity flights, and the gas collected in the gas core was successfully extracted into the gas exit line.

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Fig. 1.
Sketch of the two-phase swirl flow separator.

Fig. 2.
Multi-block grid generated for the numerical simulations of the flow field in the inner chamber of the swirl phase separator.

Fig. 3. Boundary conditions imposed for the numerical simulations of the flow field inside the swirl chamber.

Fig. 4. Tangential velocity profile comparison for a swirl phase separator chamber with a 152.4 mm inner diameter at 22.7 liter per minute (lpm) flow rate. The PIV measurement results are compared with results from two numerical simulation models with and without turbulence model.

Fig. 5.
Experimental setup for ground testing the phase separator.

Fig. 6.
Orifice size effects on tangential velocity distribution.

Fig. 7.
Effects of orifice size on the tangential velocity profile at middle section of the chamber.

Fig. 8.
Orifice size effects on the pressure distribution in the swirl chamber.

Fig. 9. Orifice size effects on the normalized radial pressure profile shown at the location of the mid-length of the chamber.

Fig. 10. Effects of orifice size on the radial pressure profile inside the inner cylinder of the phase separator.

Fig. 11. Effects of the layout of the liquid outlet orifices on the radial pressure profile at mid-length of the inner cylinder. Positive values of r correspond to crossing the vortex axis.

Fig. 12.
Effects of test rig orientation on the swirl chamber radial pressure profile.

Fig. 13.
Variation of instantaneous gas extraction rate and gravitational acceleration.

Fig. 14.
Variation of accumulated gas extraction rate and gravitational acceleration.

Fig. 15.
Variation of air input and gas extraction in a ground test.

Fig. 16.
3D rendering of the NASA breadboard test rack with a DYNASWIRL® phase separator in place (courtesy of NASA Glenn Research Center).

Fig. 17.
Zoom of the vortex core of the phase separator under almost zero gravity at 8% void fraction (left) and 31% void fraction (right).

Table 1

Dimensional features of one of the DYNASWIRL[®] phase separators.

Feature	Dimensions, mm
Separator chamber length	240
Inner cylinder inner diameter	140
Mixture inlet slot width	1.5
Mixture inlet slot length	25
Liquid exit orifice diameter	15
Gas exit orifice diameter	2