Cyclonic Two-Phase Flow Separator Experimentation and Simulation for Use in a Microgravity Environment

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Abstract. Devices designed to replace the absent buoyancy separation mechanism within a microgravity environment are of considerable interest to NASA as the functionality of many spacecraft systems are dependent on the proper sequestration of interpenetrating gas and liquid phases. Cyclonic separators provide the gas-liquid separatory action by swirling the multiphase flow – causing the gas to accumulate along the axis of the vortex as the denser liquid is forced to the walls – thereby allowing segregated extraction of the respective phases. Passive cyclonic separators utilize only the inertia of the incoming flow to accomplish this task. In the current work, combined experimental, numerical, and scaling analyses have been performed to quantitatively assess and delimit the operability of these separators. Specifically, steady-state features including velocity profiles have been examined experimentally and compared to computational fluid dynamics results, scaling laws for the gas core size have been created, and the transient behavior of the device with respect to both device and system-level conduct has been modeled.

1. Introduction
Phase separators are devices designed to separate two-phase gas-liquid flows into individual liquid and gas streams. Phase separation is essential to many fluid flow systems in microgravity. While droplet and bubble removal is a spontaneously occurring phenomenon in most terrestrial situations, the absence of the gravity-induced separatory action in a microgravity environment often results in situations where two disparate phases have no distinct inclination to separate from one another. This can present many problems with respect to spacecraft and space station operations as proper control and sequestration of the individual phases is often essential to the successful functionality of many system-critical components.

Multiphase conditions arise in these flow systems for different reasons. Some systems are unavoidably multiphase in character, such as those involving boiling. Multiphase conditions may also impose themselves upon nominally single phase systems. In order to ensure continued functionality, these systems must therefore be necessarily made tolerant of the encroachment of other phases. Other systems may have possible single phase guises, but the addition of multiphase flow can often result in substantial performance enhancement.

Regardless of the origin of the two phases, all of these systems have critical subcomponents that will be intolerant of multiphase flow. Phase separation thus can be an end unto itself, or it can be a necessary function in order to exploit the advantages of multiphase flow – permitting multiphase behavior where it is advantageous within a given flow system while preventing its drawbacks elsewhere in the system. Inasmuch, the number of spacecraft and space-station systems where these
factors come into play is vast, ranging from Environmental Control and Life Support Systems (ECLSS) to power conversion.

Many phase separation systems have been designed and employed in the past to provide this needed phase separation. Broadly speaking there are five main types: capillary separators (hydrophilic/hydrophobic screens, porous media, face wicking), membrane separators (hydrophilic and hydrophobic), centrifugal/rotary (active), inertial (elbows and impingement separators), and passive centrifugal (also known as vortex separation). While all approaches have shown merit, the passive centrifugal option represents a promising technology that has been, to date, underutilized.

One such device, NASA Glenn Research Center’s Cascade Cyclonic Separation Device (CSD-C) was designed to provide separation amenable for the use in a variety of spacecraft systems. It is a passive approach to separation in that it affords the phase separation without the requirement of moving mechanical components or power input. It is classified as being static in the sense that it has no moving parts (that would otherwise entail rotating seals and bearings). This static passivity combined with long-duration operability is the device’s greatest advantage compared to the other approaches – issues limiting the operational lifespan of other devices, such as clogging of membranes, are not present. This approach employs the inertia of the multiphase flow itself to provide the desired phase-parting action. The conceptual basis of these devices involves the creation of a swirling flow by tangential injection of a multiphase fluid stream into the separator device. This eccentric injection thereby creates a buoyancy-like separation action via the pressure gradient that arises to maintain the necessary centripetal acceleration of the fluids as they swirl within the device housing. A gas core forms along the axis of the device, and the separate phases are removed via their respective outlets. The general concept is shown in figure 1.

The CSD-C has received experimental and numerical attention in the past [1,2]. It was demonstrated to function adequately over the duration of a start-up cycle that subsequently proceeds toward steady state within the time allotments provided by microgravity aircraft research. While experimental apparatuses of the CSD-C have, at minimum, shown efficacy for certain specified input conditions, failures with off-design conditions (such as mist development, etc.) and the incomplete delimitation of what constitutes “off-design” dictate that the flow characteristics of this device be more fully investigated.

Even though passive cyclonic separation is a seemingly mature technology, large knowledge-gaps exist with respect to the performance that can be expected from these types of devices — gaps large enough to preclude their use from mission-critical spacecraft systems. This research seeks to provide the complete analysis and understanding of the fluid physics phenomena that is necessary to make this mission-enabling technology available for use within multiphase space systems.

Figure 1. Passive cyclonic separator concept. Two-phase flow is injected tangentially into the separator housing; the baffle plate allows for the stable existence of an annular liquid layer and a cylindrical gas core.
1.1. Experimental Setup

The experimental system has been developed at Case Western Reserve University (CWRU) with instrumentation to allow discernment of typical passive separator device operations. The current work has consisted of ground-based experimentation operating in a high flow rate, gravity-independent mode. The flow loop was constructed to provide metered quantities of gas and liquid to the test separator (see figure 2). A steady flow of liquid is provided from a water tank and circulated by a centrifugal pump. The flow rate of city water is measured by two turbine flow meters (TM series, GPI, Inc. with an accuracy of ±3%) installed in parallel. The flow ranges of these two turbine flow meters are 0-4 L/min and 4-16 L/min. Both the gas and liquid flows are introduced to a T-junction mixer after which they are allowed to develop in a representative two-phase flow piping section. The two phase mixture is then injected into the separator.

The pressure and temperature are measured prior to entering the test separator and at a location immediately upstream of two phase flow pipe. The data acquisition and control system software is written in LabView. The control of flow loop functions as well as the data acquisition and storage are done by a National Instruments data acquisition board with a workstation.

Experimentation with simplified straight-cylinder vortex separators has been performed using this loop to understand the fluid physics and to permit validation and verification of CFD approaches under development. Two different designs have been tested.

The schematic of the first separator is given in figure 3. It was manufactured from transparent acrylic. Swirl flow is generated in the test separator due to tangential injection of liquid from an injection nozzle. The characteristics of the swirl flow depended on the flow rate, the inner diameter of the separator and the injection nozzle. The present experiments were carried out under the conditions of flow rate between 4 to 15 L/min, as these proved to be necessary to operate independently of gravity. The inner diameters of the separator and injection nozzle were 57 mm and 5.6 mm, respectively. A honeycomb type of axial swirl-stop is located at 100 mm from the top wall to eliminate vortex flow extending to downstream.
An alternative design including a radial inflow swirl-stop has also been manufactured and undergone testing. In this design, the flow is constrained to move inward under the baffle plate through a series of radially oriented straightening vanes that extend to a fraction of the baffle plate radius. Both swirl-stop concepts are shown in figure 3. It will be shown that the differing pressure balancing properties of these approaches has a significant effect on the equilibrium size of the gas core that develops.

Ground testing is generally performed in a high-flow rate, gravity-independent manner with the separator axis situated perpendicular to the earth’s gravitational vector. The separator would still function if operated with the axis vertically aligned, however many features of the flow would be disaffected by gravity.

Figure 3. Baseline separator design for fluid physics studies and CFD validation and verification – shown with axial swirl-stop. Details of axial swirl-stop and radial inflow swirl-stop design showing path of liquid under the baffle plate shown to the right (separator walls have been omitted for clarity)

The measurements of axial velocity and the tangential velocity distributions in the liquid layer were carried out using pulsed Doppler ultrasonic velocimetry (PDUV). In ultrasonic Doppler velocimetry a piezoelectric probe emits ultrasound pulse, and the echoes are detected by the same probe. By sampling the incoming echoes at the same time relative to the emission of the pulses, the variation of the positions of scatters are measured. The measurement of the time lapse between the emission and the reception of the pulse gives the position of the particles. Measuring the shift in frequency, the target velocity component along the probe axis is detected. The ultrasonic Doppler velocimeter used in this study is Model DOP 2000 manufactured by Signal Processing S.A. A 4 MHz probe with a diameter of 8 mm and a Doppler angle of 80° were used in the present experiments. Uncertainties in the measurements are mostly in the ± 2.5 % range. A photograph of the experimental set-up is presented in Figure 4.
1.2. Computational Modeling

With respect to numerical modeling, the current work entails the extension of past computational fluid dynamics studies by the authors. The multifluid simulations that worked satisfactorily in the past have been improved; in particular, some of the work of Rusche [3] have been included to handle the high volume fractions of gas that are often present in separators. This particular approach is used where the separation process itself is of interest, but it is deficient when capillary forces become important.

For those scenarios, a custom phase-field surface implementation has been developed and has been used to simulate some of the capillary instabilities that affect the functionality of the separator – features that could not be captured with the previous modeling efforts. Phase field is a diffuse interface method that has recently found use in the simulation of free-surface fluid mechanics; the approach has in particular been developed and applied by several authors in the study of fluids in microgravity. The structured/staggered grid approaches used by these previous researchers [4,5] to study microgravity fluid motion using phase-field methodologies have been adopted and made amenable to unstructured, cell-centered grids – the type of mesh characteristics required for complicated separator geometries.

In order to make the models pertinent to the complete separation process, hybridization of this code with a multifluid Eulerian-Eulerian treatment for dispersed phase constituents has been begun. This will allow the simultaneous calculation of the bubbly, unseparated two-phase flow at the inlets along with the surface tension phenomena associated with the stratified fluids – thereby providing modeling capability for all flow conditions (in a similar manner to the continuum surface forcing methods that were investigated previously [1]).

Device level analyses, however, are insufficient to classify the performance that can be expected of a separator. System-level conduct has been found to be crucial to the proper functionality of the separator – as such, efforts have been made to model the upstream and downstream components that are invariably present. To do so, one-dimensional two-phase flow modeling techniques have been coupled to the device-level three-dimensional simulations. Compressible homogeneous equilibrium method (HEM) and multifluid approaches have both been employed. The results from various microgravity experimental efforts [6] have permitted the inclusion of a number of general system components within the simulation framework. For example, microgravity data exists for many of the individual components including pipes, valves, quick-disconnects, etc. [7]. Large knowledge gaps exist, but it is hoped that this approach will create a general predictive framework for the simulation of
two-phase flow systems in microgravity – one that should ultimately allow for the prediction and analysis of multiphase instabilities. Our experimental testing has not yet included microgravity testing, and, hence, for the current analyses the subcomponent models are handled in a manner that is generally consistent with terrestrial multiphase thermal-hydraulic codes (e.g. [8, 9, 10]). The experimental two-phase flow loop is thus modeled as in figure 5. Typically several hundred cells are used for the 1-D flow sections, 50,000 are used for the 2-D axisymmetric representations of the separator geometry, and several hundred thousand are used for the full 3-D mesh.

Figure 5. Coupled 1-D and 3-D CFD solvers (not to scale).

2. Steady Device-level Conduct
While the previous CFD work by the authors was found to at least be qualitatively correct, there was no rigorous validation or verification of the modeling approach. This work has sought to address that shortcoming. The first issue investigated was the device-level performance of the separator. While global metrics for separator performance were examined previously, it is important to examine the fundamental aspects of the fluid physics as that is from where the separatory action arises.

2.1. Velocity Profiles
As the velocity distributions are so fundamental to the separatory process, agreement between experimental and numerical velocity profiles within the separator were first sought in order to ensure that the complex effects of streamline curvature were being properly captured by the modeling procedure.

Figure 6 shows the computed tangential velocity profiles along a radius at the midplane of the separator (i.e. as compared to the experimental values for various injection flow rates). The cylindrical coordinate system is indicated in figure 1 wherein the axial coordinate is measured from the baffle plate, and the accompanying subfigures show the location of the ultrasonic transducer and the beam direction used to capture the Doppler shift. Excellent agreement between experiment and simulation is found near the wall, but the experimental data drops off quickly when approaching the free surface of the liquid annulus. This is due to the impedance change from the liquid into the gas core; the reflection effects therein make the error large and the returned values spurious.
Figure 6. Numerical and experimental tangential velocity profiles for various volumetric flow rates plotted along the indicated radius at the midplane of the separator (i.e. half way between the top wall and the baffle plate — a distance of 50 mm from the top wall).

Figure 7 shows the axial velocity profiles. The agreement is generally good near the wall, but, again, the experimental values fall away rapidly toward smaller radii. Due to the prevailing tangential direction of the flow, the axial velocity experimental results did show large sensitivity with respect to the imposed beam angle; the axial velocities were found to be easily overwhelmed by the incursion of the comparatively larger tangential velocities when there are small experimental errors in placement. The overall error did become unsatisfactorily large when the velocities were low, as can be seen for the lowest flow rate case of 7.0 L/min liquid injection.

Figure 7. Numerical and experimental axial velocity profiles for various volumetric flow rates plotted along the indicated radius at the midplane of the separator (i.e. half way between the top wall and the baffle plate — a distance of 50 mm from the top wall).
The axial velocity profiles show strong peaks near the wall and areas of reverse flow near to the free surface. The thinness of the liquid annulus in these specific experimental runs, however, makes the reverse flow relatively slow. Any inward flow is accordingly also small. The effects thereof are apparent in the tangential velocity profiles where, as shown, the flow adopts a solid-body rotational character as opposed to that of a Rankine vortex.

Another issue of great importance in separator design [11] is the decay of the swirl along the axis of the device. In order to aid in the design of cyclonic separators, correlations are often used in order to describe the swirl decay pattern along the axis of such devices. These correlations however are generally valid only for axial length to diameter ratios greater than 2; as the separator designs considered in this paper are shorter than minimum, it is important to ensure that CFD is able to predict the swirl decay accurately (a difficult task for turbulence models to calculate). Figure 8 shows the values of the maximum of the tangential velocity plotted versus the axial distance. The swirl is concentrated around the 7 cm location as this is where the injector is situated. Experimental values only exist for the liquid-only injection case, and good agreement is found. Also included in the figure are profiles for different injection volumetric qualities, \( \beta \), which is the ratio of the volumetric flow rate of the gas compared to the total volumetric flow rate. In general, the tangential velocity (which is providing the separatory action) can, as expected, be seen to be dependent on the total volumetric flux and not simply the superficial velocity of the liquid alone. This will later be shown to affect the behavior of the separator.

![Figure 8](image.png)

**Figure 8.** Swirl decay as a function of axial distance for fixed 7.0 L/min volumetric flow rate of water and differing injector volumetric qualities.

![Figure 9](image.png)

**Figure 9.** Mechanistic model nomenclature (geometry shown includes the radial swirl-stop)

2.2. Steady Flow Scaling Model

Alongside the velocity profiles, another value critical to separator performance is that of the depth of the liquid annulus. Maintaining a properly sized liquid annulus is clearly essential to maintaining separation and preventing carry-over or carry-under (i.e. allowing liquid to encroach on the gas outlet or vice versa).

The sensitivity of the liquid annulus thickness to the injection rates can be determined in a mechanistic model similar to the one performed by Arpandi, et al [12]. In general, the depth is
determined by balancing the pressure drops through the liquid and gas outlets with respect to the variable free surface depth. Figure 9 shows the geometry and symbols of interest. The liquid thickness \( H \) can be determined simply by ensuring that the pressure drops along the paths to the respective outlets are consistent with the common pressure at the injector.

The path to the gas outlet will be considered first. The overall pressure drop, \( \Delta p_1 \), is the difference between the pressure at the wall of the separator and the pressure at the gas outlet. This quantity is imposed by \( \Delta p_{\text{annulus,1}} \), which is the centripetal gradient across the annular distance \( H \), and \( \Delta p_{\text{gas flow}} \), which is the drop from the gas core pressure to \( p_{0,\text{gas}} \) (i.e. the downstream pressure at the gas outlet that is regulated or open to atmosphere). These terms can be expressed as

\[
\Delta p_1 = \Delta p_{\text{annulus,1}} + \Delta p_{\text{gas flow}} = \int_{R_{\text{sep}}}^{R_{\text{sep}} - H} \frac{\rho_l u_{\text{inj}}^2}{r} \, dr + C_g \rho_g Q_g^2
\]

where \( Q_g \) is the total volumetric flow rate of the gas, and \( C_g \) is a generalized pressure loss coefficient, \( R_{\text{sep}} \) is the radius of the separator, \( \rho_l \) is the liquid density, and \( \rho_g \) is the gas density.

The balancing pressure drop across the path to the liquid outlet can be expressed similarly, but the included terms are dependent on the type of swirl-stop. The overall pressure drop \( \Delta p_2 \) is the difference between the pressure at the wall of the separator and the pressure at the liquid outlet. For the radial swirl-stop, this quantity is imposed by the centripetal gradient that is allowed to persist under the baffle plate up until the presence of the vanes, \( \Delta p_{\text{annulus,2}} \), and \( \Delta p_{\text{liquid flow}} \), which consists of the minor losses proceeding to \( p_{0,\text{liquid}} \) (i.e. the downstream pressure for the liquid outlet). Hence,

\[
\Delta p_2 = \Delta p_{\text{annulus,2}} + \Delta p_{\text{liquid flow}} = \int_{R_{\text{sep}}}^{R_{\text{stop}}} \frac{\rho_l u_{\text{inj}}^2}{r} \, dr + C_l \rho_l Q_l^2
\]

where \( Q_l \) is the total volumetric flow rate of the liquid, \( C_l \) is a generalized pressure loss coefficient for the components of the liquid outlet leg, and \( R_{\text{stop}} \) is the radial extent of the radial swirl-stop. \( R_{\text{stop}} \) is the lower limit of the centrifugal integral as at smaller radii the tangential velocity of the liquid is constrained to be zero by the straightening vanes.

The pressure drop for the axial swirl-stop is constructed in the same way, but it lacks the centrifugal pressure drop term as there is no contributing swirl beneath the baffle plate (as the flow is immediately constrained into the axial direction). Thus, the centrifugal term is absent and the pressure drop is instead expressed as

\[
\Delta p_2 = C_l \rho_l Q_l^2
\]

Knowledge of the velocity distribution (perhaps through the use of correlations) along with specification of the various parameters allows for the computation of the \( H \) that allows this balance to be satisfied. The number of parameters involved can obfuscate the basic physics of what is occurring. A scaling analysis approach that yields much the same information has been done. Several simplifying assumptions must be made.

First, the analysis will be done for the inward radial swirl-stop. It is assumed that the liquid layer is small relative to \( R_{\text{sep}} \). Furthermore, the centripetal gradients are assumed to be scaled by \( u_{\text{inj}} \) which is the injection velocity based off of the total volumetric flux through the injector nozzle. The scaling of the pressure drop supported by the liquid annulus above the plate (i.e. the first term of the right-hand side of equation 1) is thus

\[
\Delta p_{\text{annulus,1}} \sim \frac{\rho_l u_{\text{inj}}^2}{R_{\text{sep}}} H = \frac{\rho_l (Q_l + Q_g)^2}{A_{\text{injector}}} \frac{H}{R_{\text{sep}}}
\]

\( A_{\text{injector}} \) is the area of the injector and hence dictates the characteristic velocity along with the respective liquid and gas volumetric flow rates.

The scaling of the pressure drop supported by the liquid annulus below the plate can be performed similarly. Assuming that the profiles have a similar character (which requires a properly sized baffle plate gap so as not to effect large peaks in the tangential velocity profile), the term is scaled by the same velocity as before. However, as mentioned, the gradient is only created up until the vane location, and, hence, only acts over the distance \( R_{\text{sep}} - R_{\text{stop}} = L \). Specifically,
\[ \Delta p_{\text{annulus,2}} \sim \frac{\rho L^2}{R_{\text{sep}}} = \frac{\rho L}{A_{\text{injector}}^2 R_{\text{sep}}} \left( Q_i + Q_g \right)^2 \] (5)

The general philosophy of the inward radial swirl-stop design is to make the two centripetal terms dominant. To do so, the gas outlet and liquid outlet components have been constructed as large as possible in order to remove the frictional wall losses that result from those components. Thus, with the \( C_i \) and \( C_g \) terms in equations 1 and 2 tending to zero, and with the downstream pressures regulated to be equal (i.e. \( p_{0,\text{gas}} = p_{0,\text{liquid}} \)), \( \Delta p_{\text{annulus,1}} \) is exactly balanced by \( \Delta p_{\text{annulus,2}} \). For this equality to hold, the necessary depth of the liquid annulus can be found by equating equations 4 and 5 to obtain the simple result

\[ H - L = R_{\text{sep}} - R_{\text{sep}} \] (6)

This result is saying that, for the radial swirl-stop design, the liquid level becomes invariant of the flows that are injected — at least within the context of the various assumptions that have been made. The slower flow rates permissible in microgravity entail numerable problems (capillary effects, insufficient separatory gradients, etc.) which make maintenance of this equality unlikely. Nonetheless, the ability of the design to maintain a fixed gas core size is extremely advantageous for the separation process, helping to prevent carry-over and carry-under dysfunction.

The axial swirl-stop behaves less optimally. There is no underflow centripetal pressure gradient present nor is there any pressure recovery from the honeycomb. In this case, the annular pressure drop is now balanced by the now contributing term of the frictional pressure drop on the liquid leg (the minor losses on the overflow leg again being assumed negligible). Thus, the scaling therefore takes the form

\[ \frac{\rho \left( Q_i + Q_g \right)^2}{A_{\text{injector}}^2} \frac{H}{R_{\text{sep}}} = \rho C_i Q_i^2 \] (7)

with the net result that

\[ H \sim \frac{Q_i^2}{\left( Q_i + Q_g \right)} A_{\text{injector}}^2 C_i R_{\text{sep}} \] (8)

or, equivalently,

\[ H \sim \left(1 - \beta \right)^2 A_{\text{injector}}^2 C_i R_{\text{sep}} \] (9)

The result is not a constant as before. Moreover, the coefficient \( C_i \) has a liquid flow rate dependence at low flow rates where viscous forces dominate. Use of the axial swirl stop is therefore predicted to allow greater undesired variation of the gas core size.

For the experimental device, it should be noted that, when run with the axial swirl-stop, the liquid outlet requires a valve to be slightly closed to create a sufficiently large liquid-leg pressure drop term to complete the balance. If the liquid outlet had not been adjusted this way, the \( C_i \) term would be too small to counterbalance the annular-induced pressure drop, and the liquid layer would shrink into a small film thereby allowing carry-under.

To examine the utility of this scaling analysis, figure 10 shows numerically predicted liquid annulus depth results for a single fixed liquid flow rate. Data for both the axial and radial swirl-stop designs are shown. As predicted, the liquid layer depth for the radial swirl-stop is very nearly constant and, in fact, is close to the vane clearance \( L \) of the separator (which is indicated by the solid line). The data for the axial swirl-stop also follows the expected trend; by changing the injector area or flow quality (and also keeping the rest of the separator geometry identical), the inconsistency in the balancing pressure term for the axial swirl-stop is revealed. Specifically, because the centripetal gradient and the post-swirl-stop losses are not scaled by the same velocity measure, \( H \) must adjust to account for the differences, whether they result from a change in the injector area or from the inclusion of gas flow.
It must be emphasized that this simplified mechanistic model assumes pressures downstream of the gas and liquid outlets are matched through exhausting to atmospheric pressure or through regulation to a common pressure; if this cannot be assured, large system-level pressure differences can easily overwhelm any separator’s ability to maintain an adequate liquid level and active control valves must be used to assist the balance.

3. Unsteady Separator Response

The above experimentation, mechanistic modeling, and simulations were performed for nominally steady flow injection into the two-phase separator. Under these conditions, the radial swirl-stop design was predicted to have a very stable gas core size. Steady behavior, however, does not tell the complete story; the dynamic response of the separator is important not only for transient conditions such as set-point changes, but it is critically essential in general multiphase systems where unsteadiness and unstable flow are common.

As was shown in the steady flow results, the separator can handle different flow rates through the interplay of the balance of the pressure drop terms via mechanisms such as thickening or thinning of the liquid layer. Variability in injection flow rates can be handled by a similar balancing process, but in unsteady flow there are now differing time scales that come into play. For example, while during steady operations the wall-frictional pressure drops may be precisely countered by the pressure drop across the swirling annular layer, the spin-up or spin-down of the annular layer will take much longer than the time necessary for the flows in the piping sections to adjust. Thus, rapid set-point changes and unstable injection can be expected to be associated with large variability of the liquid thickness and, perhaps, failure to successfully separate the flows.

As both a demonstration of the ability of the separator to handle transient injection and as a demonstration of the ability of the coupled CFD solvers to simulate unsteady multiphase flow, the experimental two-phase flow system was run with a set of flow rates such that a pulsating dynamic instability was set up in the inlet pipe, which is a 2 m long, 12.7 mm diameter two-phase development.
pipe upstream of the single injection 2 mm diameter nozzle into the separator. The gas flow rate was fixed by the mass flow controller while the water flow rate was dictated by a centrifugal pump set to a constant rotational velocity. Under pure liquid injection situations, the pump produced 3 L/min, but the flow delivered at the separator inlet was observed to drop to as low as 0 L/min during the course of the instability.

The nature of the instability that arises is that of a heavily pulsating density-wave oscillation (DWO). The instability caused large oscillations of the gas and liquid flow rates at the injector that proved challenging for the separator. While this particular instability is limited to special combinations of the respective gas and liquid superficial velocities in relation to the specific pump curve of the experimental apparatus, the occurrence is representative of the potentially challenging injection conditions that the separator is expected to ingest. Furthermore, while design tools and methodologies exist to create terrestrial systems that do not acquire the pulsating nature of the above flows, the knowledge to predict and avoid of microgravity multiphase instabilities remains limited; as such, it is essential to ensure that the passive cyclonic separator can handle such flows.

The compressible HEM solvers used for the two-phase flow in the upstream piping components proved able to capture the essence of the instability. The CFD in turn predicts substantial volumetric flow rate variability that must be handled by the separator. The large oscillations of the injection velocity at the injector are shown in figure 11.

![Figure 11](image.png)

Figure 11. Predicted total injector volumetric flow rate versus time for the representative pulsating dynamic instability

Both experiment and CFD showed that the design featuring the radial swirl-stop works well enough that it is able to successfully handle the highly variable flow rates. Figure 12 shows the behavior therein: even during the very high quality gas injection periods the liquid layer is able to persist. Shown in the figure is the radial extent of the swirl-stop’s straightening vanes, and the location of the core’s free surface can be seen to deviate little from its expected value. The precise evolution of the gas holdup is shown in figure 13. In this plot, the average gas volume fraction within the separator (a quantity representative of the gas core size) is plotted versus time. As shown, the gas core expands, contracts, and is able to accommodate the imbalances caused by the pulsating flow.
4. Conclusion
Gas-liquid separation is an important multiphase flow issue that arises in the absence of gravity. The fluid physics within one such family of devices, cyclonic gas-liquid microgravity separators, is quite complicated and represents a considerable challenge to study. In the present work, combined experimental, numerical, and scaling analyses have been performed to quantitatively assess and delimit the operability of these separators.

First, steady-state features including velocity profiles were examined experimentally and compared to the results from numerical modeling. The results, in general, showed satisfactory agreement and give confidence in both the modeling approach and in the use of PDUV for the study of the flow fields in gas-liquid separators. Next, scaling laws for the gas core size were created. Comparison with CFD results showed that the variation of the liquid annulus thickness did match the general character of the scaling relationships. Finally, the transient behavior of the device with respect to both device and system-level conduct was modeled. The coupled 1-D and 3-D CFD solvers proved able to model transient multiphase flows and demonstrated the ability of the separator to accommodate highly variable liquid and gas flow rates.

It is hoped that the resulting insight into phase separation, distribution, and control offered by this, and future, work will help to afford NASA designers the latitude to take greater advantage of the benefits offered by the use of multiphase systems in spacecraft applications.

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