STABILITY OF THE GAS CORE OF A CYCLONIC TWO-PHASE SEPARATOR IN MICROGRAVITY

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A microgravity experiment was designed to investigate the performance of a cyclonic two-phase separator. Surface tension effects could become important in microgravity, which adversely affects the separator performance. In the present study, the collapse of the gas core due to surface tension was investigated analytically as well as numerically. A control volume analysis and a volume-of-fluid–based computational fluid dynamics (CFD) simulation were employed to determine the condition for the gas core collapse. The predicted critical Weber numbers by both methods agree reasonably well. They predict that the critical Weber number is on the order of unity in the parametric range investigated herein. For practical purposes, the critical condition is also expressed in terms of the injection Weber number.

KEY WORDS: cyclonic separator, two-phase flow, microgravity, gas core instability

1. INTRODUCTION

Gas–liquid two-phase flow separators are devices designed to separate gas–liquid flows into individual liquid and gas streams. Phase separation is essential in many fluid flow systems in microgravity. While droplet and bubble segregation is a spontaneously occurring phenomenon in most terrestrial situations, much reduced buoyancy in a microgravity environment often results in situations where two disparate phases have no distinct inclination to separate them from one another. This can present many problems with respect to spacecraft and space station operations since proper control and sequestration of the individual phases is often essential to the successful functionality of many system-critical components. In environmental control and life support systems, water processing, reclamation, food cleaning, wastewater recovery, oxygen generation, and humidity control systems are all dependent on separators to contend with multiphase flow phenomena. For example, the use of phase separators to maintain phase purity at the entrances of turbomachinery has often been detailed as a crucial concern (McQuillen et al., 2003). The encroachment of droplets into turbine blades and the resulting destructiveness has, in particular, received much attention (McQuillen, 2004).

Several active and passive gas–liquid separation techniques have been proposed and qualitatively evaluated in the past in order to provide this needed phase separation for microgravity applications. McQuillen et al. (2005) gave an overview of various multiphase flow separators that have been employed. Capillary and membrane approaches have been utilized successfully in space; however, their surfaces are seriously prone to clogging and have components that frequently must be replaced. Active devices may avoid some of these worries, but they possess a variety of inherent reliability issues. Vortex separation 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. This static passivity combined with long-duration operability is the device’s greatest advantage compared to the other approaches.

Cyclonic separators have been used for many years in terrestrial applications and their performance is well understood. For liquid–gas cyclonic separators, their operational ranges are limited by hydrostatic pressure in normal gravity: the liquid velocity must be large enough such that its inertia can overcome the hydrostatic pressure effects. However, this limitation is largely removed in a microgravity environment such that the cyclonic separators can per-
form in wider parametric ranges. Moreover, surface tension effects become important with reduced liquid velocities in microgravity. Therefore, more work is needed in order to design effective cyclonic separators for microgravity applications.

The two-phase flow separator experiment (TPFSE) project at the National Aeronautics and Space Administration (NASA) is designed to help close these passive cyclonic separation and multiphase systems knowledge gaps. As part of the TPFSE project, we have been conducting combined experimental, numerical, and phenomenological modeling analyses for the passive separator designed at Case Western Reserve University in order to qualitatively describe its performance (Hoyt et al., 2013; Kang et al., 2014). In the present study, our focus is on the effects of surface tension, or more specifically, the collapse of the gas core due to surface tension. It is important to maintain a stable gas core in order for the separator to perform properly. Therefore, it is necessary to know the conditions under which a stable gas core exists.

In the present study the gas core collapse is investigated analytically as well as numerically. Although the hydrodynamic stability of a rotating liquid layer(s) has been investigated in the past (e.g., Samsonov, 1971; Dávalos-Orozco and Vázquez-Luis, 2003), the present study considers the collapse of a rotating liquid film with net axial flow. In Kawanami et al. (2004, 2006), the stability of the vapor core was investigated in parabolic flight tests. Based on the typical $g$-level force in parabolic flight, the gas core became unstable due to gravity in their experiments. The present study is interested in the much lower $g$-level force of spacecraft, such as in spacecraft at the International Space Station; therefore, the surface tension effects are more important than gravity. Bean et al. (2002) conducted a parabolic flight experiment to investigate gas core instability. The critical Weber number was found to be relatively large, about 100. The reason for this large Weber number may be due to the large disturbances present in the flow in order to create gas core faster in the limited duration of low gravity. Therefore, more research is needed to understand the stability of the gas core in microgravity. Although our eventual objective is to study the performance of a cyclone separator in microgravity, the present study focuses on liquid-only injection in order to obtain the fundamental information regarding the stability of the gas core.
2. SEPARATOR DESIGN

The separator geometry for the proposed microgravity experiment is depicted in Fig. 1(a) and the pertinent dimensions are given in Fig. 1(b). The separator in this study provides the desired gas–liquid separation action by swirling the gas–liquid flow, causing the gas to accumulate along the axis of the vortex as the denser liquid is forced against the walls, thereby allowing selective extraction of the respective phases. In order to study the basic flow field, including the interfacial phenomena, the liquid-only injection case is considered in the present study.

The separator body is a 152.4-mm-long cylinder with an inner diameter of 57.15 mm. Swirling flow is generated in the separator by tangentially injecting fluid through a tubular nozzle. A baffle plate with a 50.80 mm diameter is used to arrest and prevent the gas phase from going into the liquid outlet. A swirl stop is employed to stop the vortex motion of the liquid flow before the liquid outlet. The baffle plate/swirl stop assembly is movable up and down to control the length of the gas core in the separator: the aspect ratio of the separator section (length/diameter ratio) can be changed from 2 to 4 in the present design. Both liquid and gas outlets are open to room pressure. In the liquid-only injection situation, the basic pressure balance is that the pressure buildup in the liquid flow due to centrifugal force is balanced by the pressure drop at the liquid outlet. Since the gas outlet is open to atmosphere, a gas core exists even for liquid-only injection. Therefore, it is important to have a valve at the liquid outlet to control the separator performance. In the case of two-phase injection, a valve at the gas outlet also controls the performance. Therefore, in the present liquid-only injection study, the important variables are the injection flow rate, liquid outlet valve opening, and separator aspect ratio.

3. ANALYSIS METHODS

In the actual separator design the liquid is injected from a single nozzle, which makes the flow in the separator three-dimensional. However, according to our past analysis, a two-dimensional (or axisymmetric) model, which greatly reduces the computational time, can quite accurately describe the flow field (Hoyt et al., 2013; Kang et al., 2014). Therefore, a two-dimensional model was used in the present study. In order to simulate the actual separator by a two-dimensional model the following relations were used. In the two-dimensional model the liquid was injected from a circular slit of width $s$ (see Fig. 2). The liquid tangential velocity at the slit injection port was equal to the actual $U_{\text{inj}}$. The radial injection velocity from the slit was equal to $Q/(2\pi R_0 s)$, where $Q$ is the actual injection rate.

![FIG. 1: Cyclone separator geometry used in this study: (a) schematic and (b) pertinent dimensions (in mm).]
3.1 Control Volume (CV) Analysis

A CV analysis was successfully used in our previous study (Hoyt et al., 2013) to predict the gas core size. Its prediction is reasonably accurate and can be performed with much less time than the CFD simulation. In the present study the CV analysis was applied to predict the condition for gas core collapse. The analysis accounts for the conservation of angular momentum and the pressure compatibility at the outlets. This has been explained in detail in Hoyt et al. (2013), thus it is discussed only briefly herein. A new feature in the present study is the inclusion of surface tension effects in the pressure balance.

Surface tension causes a pressure change across the liquid–gas interface. For a given surface there exist two principal radii of curvature, $R_1$ and $R_2$. The pressure change across the surface is known to be

$$\Delta p = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$$

where $\sigma$ is the surface tension. As will be shown subsequently, the liquid–gas interface shape in the separator is close to right circular cylinder, as assumed in the CV analysis, in the present low flow rate range where the gas core collapse occurs. In this situation, one radius is nearly infinite and the other is equal to $R_i$ (gas core radius). Then, the pressure change across the interface is given by

$$\Delta p = \frac{\sigma}{R_i}$$

In the present configuration the pressure drops, going from the gas to the liquid side.

The CV is defined in Fig. 2. It covers only the region above the baffle plate because this is the region of interest. The flow after the plate, through the swirl stop and liquid outlet valve, is represented by the overall pressure drop, which is expressed as $\rho K Q^2$ (where $K$ is the pressure coefficient). The gas and liquid outlets are open to atmospheric pressure. The gas core shape is assumed to be a right circular cylinder. The liquid annulus is assumed to be in solid-body rotation with the maximum rotational velocity equal to $U_0$ just outside the boundary layer along the separator wall (see Fig. 2). Only liquid-only injection is considered in the present study.

The conservation of angular momentum can be written in dimensionless form (Hoyt et al., 2013) as

$$1 = u + \Gamma A s C_f u^2$$

where the second term on the right-hand side represents the angular momentum reduction in the separator due to friction at the wall; and $C_f$ is the skin friction coefficient representing the tangential shear at the wall.
In the present study the pressure compatibility condition (Hoyt et al., 2013) is augmented by taking into account the pressure ($\sigma/R_i$) due to surface tension. Then, it is written in dimensionless form as

$$u^2 \left(1 - r_i^2\right) - \frac{2}{\text{We}_0} r_i = \kappa \quad (4)$$

Equation (4) shows that the pressure built up in the liquid annulus due to centrifugal force (the first term on the left-hand side) is balanced by the pressure drop in the liquid outlet (the term on the right-hand side), after being reduced by the pressure drop at the interface (the second term on the left-hand side). As $\text{We}_0$ becomes smaller, or as the surface tension effects are increased, the interfacial pressure drop becomes too large such that the above balance cannot be maintained and the gas core collapses. Therefore, there exists a minimum $\text{We}_0$ number below which the gas core collapses and the separator does not function properly.

The skin friction coefficient $C_f$ needs to be known before the previous equations are solved. Based on dimensionless analysis it can be shown that $C_f$ is generally a function of the following dimensionless variables:

$$C_f = F \left(\text{Re}, \kappa, \text{We}, \text{Vr}, \text{As}, \frac{s}{R_0}\right) \quad (5)$$

The velocity ratio is defined as $V_r = \frac{U_{inj}}{Q/A_{out}}$, which represents the ratio of the tangential velocity to the axial velocity in the liquid annulus. As such, $V_r$ is considered to be the swirl number (Kang et al., 2014). Since many parameters are involved in the present study, for simplicity, the value of $\Gamma$ is kept constant at 82, which is the value of the present separator. Since the main purpose of the present study is to find the condition for the core collapse, the value of $C_f$ is determined by comparing the computed $r_i$ by the CFD and that obtained by solving Eqs. (3) and (4) under the same conditions. As shown in Hoyt et al. (2013), it is appropriate to use the Reynolds number for the tangential flow in the liquid annulus, namely

$$\text{Re}_f = \frac{\rho u_0 (R_0 - R_i)}{\mu} = \frac{\rho U_{inj} R_0}{\mu} u (1 - r_i) = \text{Re}_0 u (1 - r_i) \quad (6)$$

It is found that $C_f$ depends mainly on $\text{Re}_f$, $\kappa$, and $\text{As}$ in the parametric range of interest. The effects of the other parameters are felt implicitly through $u$ and $r_i$ in $\text{Re}_f$. For convenience of later calculation, $C_f$ is correlated with respect to $\text{Re}_f$, $\kappa$, and $\text{As}$, and the result is shown in Fig. 3, in which the regression curve is used to compute $C_f$.

With $C_f$ specified, the minimum $\text{We}_0$ is found by solving Eqs. (3) and (4) for $u$ and $r_i$ with decreasing $\text{We}_0$. Here, $\text{We}_0$ is reduced incrementally until no solution exists. The increment is made small enough such that the value

![Image of Fig. 3: Skin friction coefficient correlation.](image)
of minimum $W_{e0}$ is determined within 0.1% accuracy. The Weber number appropriate for the core collapse is that evaluated at the gas–liquid interface, which is defined as

$$\text{We}_i = \frac{\rho U_{\theta,i}^2 R_i}{\sigma} = We_0 r_i \left( \frac{U_{0,i}}{U_{\text{inj}}} \right)$$

(7)

With assumed solid-body rotation in the liquid annulus, it can be shown that $U_{\theta,i}/U_{\text{inj}} = ur_i$, such that

$$\text{We}_i = We_0 r_i^3 u^2$$

(8)

The minimum $W_{ei}$ is called the minimum interfacial Weber number, $W_{ei, \text{min}}$, or the critical Weber number herein. It will be shown subsequently that if $C_f$ is a constant, $W_{ei, \text{min}}$ is exactly equal to unity. This fact is used to check the previous computational procedure to find $W_{ei, \text{min}}$.

### 3.2 CFD Simulation

As in the CV analysis, the computational domain is the separator section where the liquid annulus and the gas core are present. The liquid-only injection case is considered. The gas core still exists because the gas outlet is open to the atmosphere. Only steady-state solutions are considered.

One important aspect of the simulation is the existence of the liquid–gas interface. A well-known interface tracking scheme called the volume-of-fluid (VOF) method was employed in the present analysis. Both fluids were assumed to be incompressible. Only one set of volume fraction transport and momentum equations were solved for the two fluids. Surface tension was included as a source term in the momentum equation. The two fluids were distinguished by a scalar variable called the volume fraction, which was computed by solving a transport equation. The interface location was then identified as the location where the volume fraction changes sharply. The VOF method available in an open source software package called OpenFOAM (OpenFOAM User Guide version 2.0.1; available from http://openfoam.org/download/version2.0.1.php) was used in the present work. A detailed description of the VOF method can be found in Rusche (2002). The no-slip condition was applied on all solid surfaces. The contact angle was assumed to be 90°. As for the computational mesh, it was found that a 90 × 200 (radial × axial) computational mesh was sufficient for the present simulation. The computational mesh is shown in Fig. 4.

The following procedure was followed to find the conditions for the gas core collapse. First, a steady flow condition was employed. Then, the Weber number was decreased stepwise until the core collapsed. Since it takes some time for each case to compute (several hours on a PC-based work station), it is not feasible to use a very fine incremental change in the Weber number. Moreover, it is not possible to find the collapse condition accurately because near the critical point, due to small numerical disturbances, the core may collapse if the case is run for several days. For these reasons the incremental change used in the present simulation was 5% of the Weber number.

![Image of separator section](image-url)

**FIG. 4:** Skin friction coefficient correlation.
4. RESULTS AND DISCUSSION

The shape of a typical stable liquid annulus is shown in Fig. 5. The gas core shape is close to a right circular cylinder, which justifies the assumption made in the CV analysis. If the Weber number is reduced from that shown in Fig. 5, then the gas core will eventually collapse. Figure 6 shows the gas core in the process of collapsing, which starts near the bottom wall. The interfacial Weber number is proportional to the gas core radius and the square of the tangential velocity at the interface, thus it is sensitive to the tangential velocity variation in the axial direction. The liquid layer collapses near the bottom of the separator mainly because the azimuthal velocity gradually decreases in the axial direction starting from the injection port due to the friction from the side wall. As a result, the surface tension effects are largest near the baffle plate such that the gas core collapses starts from this region, as seen in Fig. 6.

Before the computational results are discussed, an important observation can be made regarding Eqs. (3) and (4). Equation (4) can be written as follows:

\[ r_i \left(1 - r_i^2\right) - \frac{\kappa}{u^2} r_i = \frac{2}{W_{e0} u^2} \]

\[ (9) \]
If \( C_f \) is a constant, then \( u \) is also a constant according to Eq. (3). Then, it can be shown that the left-hand side of Eq. (9) has a maximum value at \( \frac{1}{3} \left[ 1 - \left( \frac{\kappa}{u^2} \right)^2 \right]^{1/2} \left( \equiv r_0 \right) \) with the maximum value being equal to \( 2r_0^3 \). Therefore, Eq. (9), or Eq. (4), has a solution only when the right-hand side of Eq. (9) is less than or equal to this maximum value, namely

\[
\frac{2}{W_{0} u^2} \leq 2r_0^3 \quad \text{or} \quad W_{0} u^2 r_0^3 \geq 1 \quad \text{or} \quad W_e \geq 1
\]

Therefore, the critical interfacial Weber number is exactly equal to unity, if \( C_f \) is a constant. In reality, \( C_f \) depends on \( Re_f \), which contains \( u \) and \( r_i \), such that \( C_f \) and thus \( u \) are no longer independent of \( r_i \) and the previous argument is not valid. However, since \( C_f \) is not a strong function of \( Re_f \) (see Fig. 3), \( W_{e, min} \) is expected to be near unity.

The minimum interfacial Weber number \( (W_{e, min}) \) for the stable core predicted by the CV analysis is shown in Fig. 7 for various conditions. As can be seen in Fig. 7, \( W_{e, min} \) is not significantly affected by \( \kappa \) and the aspect ratio. As shown previously, if \( C_f \) does not depend on \( Re_f \), then \( W_{e, min} \) will be exactly equal to unity for any \( \kappa \) and \( As \). Therefore, any deviation of \( W_{e, min} \) from unity is due to \( C_f \) variation with \( Re_f \), which means that \( W_{e, min} \) is a function of \( Re_f \) only, as Fig. 7 shows.

Figure 7 also shows that the gas core collapses when \( W_e \) is about unity. This number is much smaller than the values obtained in the aforementioned parabolic flight tests by Bean et al. (2002), but it is close to the value obtained in the analysis by Samsonov (1971) for the pure solid-body rotation case without injection. Physically, the unit-order Weber number means that the surface tension is on the same order as the centrifugal force, which makes sense because the core collapses only when the surface tension becomes important.

Although Fig. 7 is a result of theoretical analysis, it requires knowledge of \( u \) and \( r_i \) in order to compute \( Re_f \) and \( W_e \), which is not convenient in practice. Since \( Re_0 \) and \( W_0 \) are the controlled variables, it is useful to specify the condition for core collapse in terms of these parameters. The collapse condition in terms of these parameters could depend on \( As \), \( \kappa \), and other parameters. However, a simple correlation is found based on the data given in Fig. 7. In Fig. 8, the values of \( W_{0, min} \) are plotted against \( Re_0/As^{2.0} \), which shows a good correlation of all the data in the present parametric range.

Finally, the CV prediction is compared with the CFD results in Fig. 9. The CV results are represented by the regression curve of the data in Fig. 8. As shown in Fig. 8, the collapse condition does not depend on \( \kappa \), thus the CFD results obtained under various conditions are presented in Fig. 9. The CFD results show both stable conditions just before the collapse and the conditions for the collapsed core. It is noted that when \( Re_0 \) is relatively small, the

**FIG. 7: Minimum Weber number for the stable core versus the film Reynolds number covering a range of aspect ratios (As) and the non-dimensional backpressure coefficient of the underflow (κ).**
FIG. 8: Collapse condition in terms of the injection Reynolds and Weber numbers covering a range of aspect ratios (As) and the non-dimensional backpressure coefficient of the underflow (κ).

FIG. 9: Comparison of the critical conditions between the CV analysis and CFD simulation.

collapsing process is very slow such that the error involved in finding the collapse condition increases. Moreover, according to Fig. 8 the critical Weber number increases sharply when the parameter $Re_0/As^{2.0}$ is small, which makes it difficult to identify the collapse condition accurately in the CFD. For these reasons, the range below $Re_0/As^{2.0}$ of 1000 is not included in the comparison. Overall, the agreement between the CV analysis and the CFD simulation is reasonable. Knowing that the CV analysis can be performed much faster than the CFD simulation, the former can be used as a tool in selecting the operational range for microgravity experiments.

In the CFD simulation the contact angle at the baffle plate and at the separator top was assumed to be 90°, which is the only case that can be dealt with by the CV analysis. Apparently, the surface condition and shape of the wall have effects on the core behavior. The study of these effects is left for future work.
5. CONCLUSIONS

A microgravity experiment was devised to investigate the performance of a gas–liquid two-phase cyclonic separator. In a microgravity environment, surface tension destabilizes the gas core, which adversely affects the performance. This surface tension effect was investigated analytically as well as numerically in the present study. Liquid-only injection was investigated herein to understand the basic physics of the surface tension effect. Our earlier CV analysis was extended to include surface tension. No solution exists for the CV equations below a certain Weber number, which is called the minimum Weber number for a stable gas core. The CFD analysis, based on the VOF scheme, showed stable as well as unstable gas cores. The gas core started to collapse from the region near the bottom plate where the fluid velocity was reduced due to the no-slip condition. The CV predictions agreed reasonably well with the CFD results such that CV analysis can be used to design microgravity experiments.

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