A Criterion for Predicting Shear-driven Film Separation at an Expanding Corner with Experimental Validation

J.L. Wegener*, M.A. Friedrich, H. Lan, J.A. Drallmeier, and B.F. Armaly
Department of Mechanical and Aerospace Engineering
Missouri University of Science & Technology
Rolla, MO 65409-0050 USA

Abstract
The dynamics of thin liquid films that develop on a solid surface and are driven by an adjacent gas flow have many engineering applications including fuel systems in internal combustion engines, liquid atomizer systems, flows in evaporators and condensers, and re-entrainment in demisting applications. However, details of the interaction between inertial, surface tension, and gravitational forces that affect the behavior of these shear-driven thin liquid films at a sharp, expanding corner are not clear. Of particular interest is the determination of conditions which cause a partial or complete separation of the film from the surface at the corner. A criterion is proposed to predict the onset of shear-driven film separation from the surface at an expanding corner. The criterion is validated with experimental measurements of the fraction of liquid film mass separated, as well as with comparisons to other observations found in the literature. The results show that the proposed force ratio correlates well to the onset of film separation over a wide range of experimental test conditions, including a variation of the surface tension of the liquid. The correlation suggests the gas phase impacts the separation process only through its effect on the liquid film momentum.

*Corresponding author: jlwqm2@mst.edu
1 Introduction

The dynamics of thin liquid films that develop on a solid surface and are driven by an adjacent gas flow have applications in many engineering problems, and as such have been studied extensively. The dynamics of the separation of such films from the solid surface due to a sudden expansion in geometry and its atomization by the separated/reattached gas shear layer (see Fig. 1), however, have received little attention. The films that are considered in this study can be classified as thin (~100 µm), shear driven, and interacting with the adjacent separated gas flow. Such complex interaction between the liquid film and the gas in separated flow is encountered in fuel and air mixture preparation for spark ignition engines, as well as in atomizer design, flows in evaporators and condensers, and wave plate mist eliminators.

For example, in a port-fuel-injection engine, the liquid fuel will normally accumulate as a film on the surfaces of intake valves and port walls during the cold-start period and enter into the cylinder by the shearing force of the intake air flow. It has been shown in many works (such as Felton et al. [1] and Dawson and Hochgreb [2]) that the liquid fuel usually deposits as thin films on the intake valve and port surfaces during the engine cold start period, and these films are seen to atomize to varying degrees with the inflowing air and enter the cylinder as droplets and ligaments. The presence of these films has been correlated to the formation of uHC emissions (Landsberg et al. [3], Stanglmaier et al. [4] among others). Knowledge of the fuel film separation at sharp valve and port edges is essential to accurately predict the fuel/air mixture preparation for improved fuel efficiency and reduced emissions. To model these processes, a clearer understanding must be developed of the dynamics between the coupled gas phase (separated/reattached flow) and liquid phase, along with the details of the dominant interfacial instabilities. Of particular interest in this study is the prediction of film separation from the solid surface as a function of gas phase velocity, liquid film flow rate, and wall angle.

![Figure 1. Schematic of shear driven film interaction with separated gas phase flow resulting in partial film separation from the substrate at the corner.](image-url)

2 Background

Gas-liquid flows have application in a multitude of engineering problems and as a result have been studied for many years. While a significant amount of work can be found for related problems, such as annular flow [5] or prefilming atomizers [6-8], limited studies have considered film separation at a corner.

A few general theories have been proposed in the literature to predict film separation. The first, put forth by O’Rourke and Amsden [9], considers a balance between the inertia of the liquid film at a sharp corner and the pressure difference between the gas phase and the film at the wall. No experimental validation of this model was done. The second approach is that of Maroteaux et al. [10,11] who argued the separation at a corner to be analogous to a Rayleigh-Taylor instability. In this approach, instabilities in the liquid film are amplified by a body force (i.e. normal acceleration) developed as the film rotates around the corner. Calibration of the model was done using a limited number of experiments. Other investigations have commented on the accuracy of this approach, including Gubaidullin [12] who points out several inconsistencies with the approach of Maroteaux et al. [10] including differences in the definition of the acceleration of the film at the corner. In addition, recent work by Steinhaus et al. [13] suggest the analysis of Maroteaux et al. [10] shows different trends than what is observed experimentally.

Two separation models are presented in the literature that consider a balance of liquid phase forces at the corner to establish a separation criterion. In the work of Owen and Ryley [14], three forces are used to estimate the radial stress of a film traveling on a rounded corner. A positive radial stress in this case represents a compressive stress acting to keep the film attached to the wall. A negative stress is a tensile stress causing the film to separate from the wall. In this analysis, the three forces are the inertial force, gravitational force, and one surface tension force located on the surface of the film. A separation criterion can be established by considering the liquid film conditions when the radial stress goes to zero at some point in the film, for example at the wall. This criterion has seen limited testing by others in the literature (e.g. [15]).

The second force balance model is presented here. As in the case of the Owen and Ryley model, the proposed model is designed to work in conjunction with any currently available numerical model for film propagation which provides accurate estimates of film thickness and velocity at the corner. A comparison of these two force balance models will be made in light of experimental measurements of film separation.
3 Scope

The key objective of this study is the analytical development and experimental validation of a comprehensive separation criterion for predicting the shear-driven film behavior at the corner. The criterion must be able to capture whether the film will separate from the corner and break up into droplets or negotiate the corner and stay attached. To this end, the development of a test facility to create, control, and observe a shear-driven liquid film up to a sudden expansion (corner) is discussed. The criterion was formulated and developed to be a submodel of a larger numerical model used to predict film propagation along a surface. Hence, quantitative estimates of the film thickness and average film velocity just before separation are required as inputs to the separation criteria. For this study, these are obtained using a simple two-dimensional shear-driven film simulation model, based on the work of Wittig and coworkers [6-8]. This film simulation model was chosen based on its extensive use and validation presented in the literature. The focus of this study, then, is not the film propagation before the corner, but the development of a force balance model to predict the onset of film separation at the corner, given these inputs of film thickness and average film velocity. Observations using high speed imaging of the film separation phenomena, as well as quantitative measures of liquid film mass attached to the wall after the corner are used to discuss the effectiveness of the developed force balance model. A comparison is also made to the radial stress model of Owen and Ryley [14]. The predictions of both models are correlated to the experimental measures of liquid film mass attached to the wall after the corner.

4 Experimental Facility

4.1 Shear-driven Film Test Section

The flow facility consists of a four part test section mounted to an optics table platform. Flow is pulled through the test section using a large liquid ring vacuum pump. The gas phase velocity, \( U_g \), through the test section is determined using a laminar flow element. Corrections are made for local temperatures and pressures resulting in uncertainties of less than 3% in the flow rate.

A schematic of the test section is shown in Fig. 2. A 1.43 m long entrance region (not shown) provides for two-dimensional flow span-wise across the test section at the point of film introduction. The dimensions of the test section at the point of film introduction and up to the corner are 2 cm tall by 10 cm wide, giving an aspect ratio of 5. The liquid is introduced through a porous brass plug on the bottom wall in the film introduction section. Simulations indicate that with the entrance region previously specified, flow should be two-dimensional with this aspect ratio (i.e. limited wall effects) for the center 7.5 cm of the test section. It is over this center 7.5 cm width of the test section that the film is introduced. The liquid flow into the test section is quantified on a volumetric flow basis and measured using a rotometer with an uncertainty of 2.5%. For the results presented here, the liquid was water with the addition of a surfactant (Surfynol 465) at 0.1% and 1.0% by mass which results in a surface tension, \( \sigma \), of 0.042 N/m and 0.026 N/m, respectively. The surfactant had minimal effect on the fluid viscosity which was measured to be 0.983 x 10\(^{-3}\) Ns/m\(^2\) for the 0.1% solution and 1.027 x 10\(^{-3}\) Ns/m\(^2\) for the 1.0% solution, effectively the same as water at ambient conditions.

![Figure 2. Schematic of test section.](image)

The corner section is removable from the configuration such that the angle of the corner in the bottom wall may be changed. Currently a 60\(^{\circ}\) angle, measured from the horizontal, is being used. The length of the duct from the point of film introduction to the corner is 23 cm. After the corner, the duct has an aspect ratio of 1.429, wherein an exit section provides for a transition from the test section to the 10.2 cm diameter piping which runs to the liquid ring pump. Great care is taken to ensure the test section is horizontal to prevent biasing of the film flow.

Significant effort was expended in developing a test section which resulted in uniform gas phase velocities span-wise across the test section near the corner. Although the film is introduced uniformly over the center 7.5 cm width of the test section, the film width changes as it reaches the corner due to surface tension. Fig. 3 shows the typical variation in the width of the film, 5 mm from the corner, as a function of gas phase velocity for a surface tension of 0.042 N/m. The film width is measured based on imaging through a window in the top of the test section with an uncertainty of 3 % determined by parallax and scale resolution. Clearly increased gas velocity, and hence shear force, keeps the film spread over the test section lower wall, counteracting the surface tension forces. These same surface tension forces impact the film separation at the corner and will be discussed in the development of the separation criterion.
The liquid film flow condition is characterized by the use of a film Reynolds number, $Re_f$, based on the volumetric flow introduced to develop the film, $\dot{V}$, and the measured film width, $w_f$, at each flow condition:

$$Re_f = \frac{\dot{V} \rho_f}{w_f \mu_f}$$

Each flow condition can then be characterized by a gas phase velocity, $U_g$, and the film Reynolds number, $Re_f$. A range of experimental gas and liquid phase flow conditions were considered. Gas phase velocities ranged from 20 to 45 m/s and liquid flow rates varied from 6.5 to 41.5 cm$^3$/s. This resulted in a variation of film $Re_f$ from approximately 100 to 400.

4.2 High Speed Imaging System

The general characteristics of the liquid film, including the surface instabilities and interaction of the film with the separated gas phase at the corner, were characterized using high speed imaging. A Photron 1280 PCI high speed camera, with close-up lenses totaling +7 diopter, was used to capture 2000 frames per second at 640 X 256 resolution. A typical image from this system is shown in Fig. 4. The spatial resolution of these results was determined by the pixel resolution of the camera. At the current magnification, the spatial resolution shown in Fig. 4 is approximately 100 microns.

4.3 Film Separation Measurement

Measurement of the degree to which the liquid film is separated from the corner was made by pulling off the liquid which stayed attached to the downward sloping wall after the corner. A porous brass plug was placed in this lower wall as a means to extract the mass of the liquid film that stayed attached to the wall. As shown in Fig. 5, the porous plug (6 mm wide) extends across the span of the test section and is flush with the sloping wall to prevent any disturbance of the flow. The brass plug is located 6 mm from the corner, which was determined by flow visualization to be far enough from the corner as to not impact the film separation process and yet not low enough to capture liquid which may be pulled up the sloping wall by the recirculation flow region behind the step. Suction was applied below the porous plug to draw the liquid from the wall, which was then captured and the mass measured. Sufficient suction was applied behind the porous plug, adjusted at each flow condition, for complete removal of the liquid from the wall without pulling the gas through the porous surface. Imaging was used at each set point to ensure the liquid film was removed.

Film suction collection times were on the order of 1 minute in duration with an uncertainty of 1%. The captured volume was weighed to establish a mass flow of liquid attached to the wall, which, along with the meas-
ured liquid flow into the test section, provides the mass flow of liquid separated at the corner. Combined uncertainty in this measurement is 5%.

5 Shear-Driven Film, Rough Wall Model
A CFD model was used to study the shear-driven liquid film propagation along the bottom wall of the test section. The focus of the current work is the development of a separation model for use in the context of a comprehensive numerical film model, hence, the film propagation model, chosen from the literature, is used to predict film thickness and film velocity on the wall at the corner, before the point of separation.

The two-dimensional rough wall model proposed by Sattelmayer and Wittig [6] for simulating shear-driven liquid film flow was used. This model has been shown to provide good agreement with measured values for the average film thickness [7, 8]. The model treats the liquid film as an equivalent rough wall interacting with the turbulent gas flow, with the wall roughness being a function of the interfacial shear stress and the average film thickness. The interfacial shear stress provides the coupling between the liquid and the gas flows, and an iterative procedure is developed to arrive at a converged solution. This scheme was implemented in a computational code to numerically simulate the development of the shear-driven liquid film in the turbulent gas flow using the same duct geometry used in the film separation experiments. Fig. 6 shows results of the 2-D rough wall model for the average film thickness and average film velocity versus the liquid Reynolds number at various gas phase velocities.

6 Separation Prediction by Analytical Force Balance
When the liquid film flow reaches the sharp corner, the bulk of the liquid may separate from the wall and then breakup into droplets by the aerodynamic force of the gas, or turn the corner and remain attached to the inclined wall, depending on the flow conditions of both the gas and liquid phase. To determine the behavior of the bulk film at the corner, an appropriate separation criterion needs to be established. For the analysis here, the forces considered are film inertia, surface tension, and body forces.

To consider this balance of forces at the corner, an approach similar to that of Hartley and Murgatroyd [16], Murgatroyd [17], and Penn et al. [18] for the analysis of dry patches on flat surfaces is used. A 2-dimensional control volume is drawn around the liquid film, in this case at the point of separation, and a linear momentum conservation law is written for the control volume.

Figure 6. Typical results from the rough wall model used to predict film characteristics before the corner in the test section.

Figure 7. Momentum analysis for a control volume.

As shown in Fig. 7, a control volume, represented by dashed lines, is chosen perpendicular to the film flow at the corner and surrounding the presumed separated film after the corner at an angle of $\beta$ from the ho-
rizontal. The bottom surface expands at an angle θ with the horizontal. The force balance is made perpendicular to the film, in the p-direction, to ascertain the equilibrium position of the separated film by balancing the perpendicular forces on the film. External forces considered are the surface tension force at the top of the film, \( F_s \), the surface tension force at the bottom of the film, \( F_c \), as well as a gravitational force, \( W \). The surface tension force at the bottom of the film, \( F_c \), is presumed to act perpendicular to the control surface, in the negative p-direction, at the meniscus between the separated liquid and the film that remains on the wall.

When the film approaches the corner, the effect of its momentum is to drive the film to separate from the corner which is balanced by the two surface tension forces as well as the gravitational force. This balance is established by considering conservation of linear momentum for steady conditions for the p-direction. Beginning with

\[
\int_{cs} \rho_f u_f (\bar{V} - \bar{n}) dA = \rho \ddot{\gamma} + \bar{F}_{ce}
\]  
(2)

the momentum flux entering the control volume in the p-direction, assuming uniform flow at the mean film velocity, \( u_f \), is given by

\[-\rho_f \ddot{\gamma} u_f \sin \beta.
\]  
(3)

There is no momentum flux in the p-direction exiting the control volume. For the external forces, \( F_{ce} \), acting on the control volume, the surface tension force on the upper surface, \( F_s \), is

\[-\sigma w_f \sin \beta
\]  
(4)

while for the lower surface, the surface tension force, \( F_c \), acts in the negative p-direction and is given by

\[-\sigma w_f
\]  
(5)

To consider the magnitude of the gravitational force, a characteristic length of the film after the corner, \( L_b \), must be established. Using the experimental correlations of Arai and Hashimoto [19] for thin sheet breakup, a characteristic breakup length is given by

\[ L_b = 0.0388 h_f^{0.5} R e_f^{0.6} W e_{rel}^{0.5}. \]  
(6)

For this correlation, the Reynolds number of the film is defined as

\[ R e_f = \frac{h_f u_f \rho_f}{\mu_f} \]  
(7)

and the Weber number is based on the relative velocity between the gas phase and the liquid film

\[ W e_{rel} = \frac{h_f \rho (U_e - u_f)^2}{2 \sigma} \]  
(8)

where \( \rho \) is the gas phase density. Given that the film volumetric flow is

\[ \dot{V}_f = u_f w_f h_f, \]  
(9)

and combining the external forces, the p-direction linear momentum balance, per unit width, results in

\[ \rho_f u_f^2 h_f \sin \beta = \sigma \sin \beta + \sigma + \rho_f \gamma h_f L_b \cos \beta. \]  
(10)

The above relation provides a means by which the film angle, \( \beta \), can be determined which balances the film momentum flux with the external forces of surface tension and gravity. This “equilibrium” film angle should provide a measure, when compared to the corner angle, \( \theta \), of whether the bulk of the liquid film will separate. However, measuring this “equilibrium” film angle is very difficult experimentally due to the characteristic unsteadiness in the flow.

If film separation is considered to exist for any \( \beta \) less than \( \theta \), then a critical force ratio can be obtained by setting \( \beta = \theta \). Doing so in Eq. 10 and normalizing by the surface tension, one finds the following ratio of the inertial force to the surface tension and gravitational forces:

\[ \text{Force Ratio} = \frac{\rho_f u_f^2 h_f \sin \theta}{\sigma \sin \theta + \sigma + \rho_f \gamma h_f L_b \cos \theta} \]  
(11)

or nondimensionalizing gives

\[ \text{Force Ratio} = \left( \frac{W e_f}{1 + \frac{1}{\sin \theta} + F r_{nh} W e_{rel} \left( \frac{L_b}{h_f} \right) \left( \frac{1}{\tan \theta} \right)} \right) \]  
(12)

where

\[ W e_f = \frac{\rho_f u_f^2 h_f}{\sigma}, \quad F r_{nh} = \frac{\gamma h_f}{u_f^2} \]  
and \( R e_f = \frac{\rho u_f h_f}{\mu} \).

This force balance is effectively a Weber number modified by the wall angle due to the surface tension at the lower surface and a gravitational force effect. This
differs from previous Weber number models [20] in the inclusion of the effects of the wall angle as well as body forces on the separation process. It differs from the force analysis of Owen and Ryley [14] by the inclusion of additional surface tension forces which provide the wall angle dependence seen experimentally. Arguably, when the Force Ratio becomes greater than one, the inertial force becomes great enough for the film to begin to separate from the wall. Hence, a Force Ratio of one can be used as a criterion for the onset of film separation. Clearly, since the unsteady nature of the film surface has not been considered, as displayed in Fig. 4, one could not expect all of the liquid film to separate at this point. If however, the appropriate forces have been captured, for Force Ratios greater than one some measurable film mass should be separated since sufficient film inertia exists, whereas below one all the film mass should remain attached to the wall.

Finally, the Force Ratio defined in Eq. 12 is shown as a function of the $Re_f$ for various gas phase velocities in Fig. 8. The rather significant difference in the Force Ratio for different gas phase velocities at higher $Re_f$ seems to be driven by the gravitational term, which becomes significant at these higher $Re_f$. If the above force balance is capturing the appropriate physics, then the film should begin to separate from the wall when the Force Ratio in Eq. 12 becomes greater than one. Looking at Fig. 8, then, one can conclude that films with lower $Re_f$ would be more likely to stay attached to the wall. Similarly, films driven by lower gas phase velocities would also tend to stay attached. Based on Figs. 6 and 8, films would need to be quite thick at lower gas phase velocities (leading to higher relative film velocities) to begin to separate from the wall. To test the viability of the above force balance to predict the onset of film separation, film separation experiments were conducted.

### 7 Experimental Results

#### 7.1 Validation of Film Separation Criterion

Film separation experiments were made for gas phase velocities between 20 and 45 m/s and $Re_f$ between 100 and 400. Validation of the separation criterion was performed by measuring the percent of liquid mass that remained attached to the wall after the corner. For each experimentally determined gas phase velocity and $Re_f$, as established by the liquid flow rate and film width, the rough wall model was used to predict the film velocity, $u_f$, and average film thickness, $h_f$. This provided sufficient information for calculating the Force Ratio, as per Eq. 12.

![Figure 8](image)

**Figure 8.** Dimensionless Force Ratio as a function of $Re_f$.

![Figure 9](image)

**Figure 9.** Experimentally measured film separation by mass correlated to the calculated Force Ratio for various gas phase and liquid phase flow conditions. Surface tension is shown in parenthesis.

Results for 68 different flow conditions are shown in Fig. 9. For each gas phase velocity, several liquid film flow rates were established; with the film width and liquid mass attached to the wall measured for each set point. Two water-surfactant mixtures were used to study the effect of surface tension. Two important features should be noted from these results. First, the Force Ratio appears to reduce the results from a wide range of experimental conditions into a common trend. The results varied from cases where no liquid was separated from the wall (i.e. the film remained attached) to approximately 90% of the liquid mass separated from the wall near the corner. The second important observation is that the force balance performed for this analysis appears to capture quite well the onset of the film separation process. For the range of conditions examined, the start of the film separation process begins when the inertial film force is greater than the restoring forces, i.e. at a Force Ratio of one. As the Force Ratio
increases from one, a continual increase in the mass of the film separated from the corner was observed. A determination of when the film is “separated” versus “not separated” is not made here as this determination is a bit arbitrary. In fact the results show that under many flow conditions a “partial separation” occurs where a fraction of the liquid mass separates with the remainder staying attached to the wall. However, as can be seen in Fig. 8, the Force Ratio model predicts quite well the onset of film separation from the corner at a force ratio of near one, with approximately 50% of the liquid mass separating at a force ratio of two for most flow conditions.

The ability of a force balance at the corner to capture the onset of the film separation process suggests that the appropriate forces are being included, at least over the range of flow conditions studied. This suggests that the model established by O’Rourke et al. [9] is inconsistent with this work in that it argues the importance of the gas phase pressure on either side of the film and does not include surface tension effects. Clearly, the nature of the gas phase shear, particularly the shear layer and recirculation zones as depicted in Fig. 1, will impact the breakup process. However, the separation process only appears to be affected by the gas phase field through the film inertia, established by the shear driven boundary condition.

Although the flow conditions and fluid properties were quite different than those considered in this study, a few comments can be made in regard to the force balance developed here and the experimental observations of Steinhaus et al. [13]. Steinhaus et al. [13] observed that higher film flow rates (i.e. Re_f) generally resulted in more film separation, which agrees with the trends shown in Fig. 8. However, they commented that the film flow rate seemed to have a relatively small effect. This may be due to the fact that their study considered only very high gas phase velocities (between roughly 70 and 200 m/s) which resulted in very thin films (less than 100 microns) for the liquid considered. With Re_f well less than 100 in their experiments, the decreasing slope shown in the Force Ratio at low Re_f in Fig. 8 would suggest a lessening dependence on Re_f. Steinhaus et al. [13] also noted that very high gas phase velocities (greater than 200 m/s) were necessary to “preferentially strip” the liquid film for low liquid flow rates (Re_f < 10) for a 45° wall angle. Again, this observation fits well with the trend in the Force Ratio of Fig. 8, which suggests gas phase velocities would need to far exceed the 45 m/s considered here for the onset of separation (Force Ratio = 1) at a wall angle of 60°.

7.2 Comparison with Radial Stress Model

A comparison is made of the current analysis to the work of Owen and Ryley [14], where a radial stress model is used to determine the onset of film separation. The three principle forces used in the current Force Ratio are similar to the principle forces included in the radial stress model, where film inertia, surface tension, and body forces are used to estimate the radial stress of a film traveling on a rounded corner. The film is attached to the rounded corner with a specific radius and film thickness as shown in Fig 10. A positive radial stress in this case represents a compressive stress acting to keep the film attached to the wall. A negative stress is a tensile stress causing the film to separate from the wall. In each of the two force balance methods the principle forces included are the same, but further investigation shows significant differences within the terms of each method. These differences and their effects are investigated further.
tio model. In the radial stress model of Owen and Ryley [14], the particle of fluid of interest has surface tension forces acting in the direction of flow and against the direction of flow. In this case, both of these are slightly compressive forces due to the shape of the rounded corner. For the current Force Ratio model, the force diagram in Fig. 7 shows four surface tension forces, but two force vectors are shown at the downstream end of the ligament and do not possess a component in the p-direction. Therefore the only two surface tension forces used in the Force Ratio include the force at the top surface of the film at the corner, and the force at the lower meniscus. Both of these forces act in the negative p-direction to resist film separation. The force at the lower meniscus is not included in the radial stress model because the film is not viewed as a unique ligament. Like the gravitational term, the surface tension terms create significant differences between each separation criterion.

The radial stress model provides a criterion that greatly depends on film inertia. Fig. 11 shows the relative influence of each term by plotting the percentage of the sum of all three terms for inertia, gravity, and surface tension. Over the flow conditions investigated here, film inertia is a large portion of the overall force, especially in the radial stress model, where the influence of gravity and surface tension becomes negligible at high Re. The Force Ratio gives a more evenly distributed force balance. In fact, Fig. 11 shows at Re = 100 the surface tension force is more than twice the magnitude of the inertial force. These results clearly reveal the balance of forces that determine the onset of film separation differ for each force balance method.

Similar to Fig. 9, Fig. 12 shows a plot of mass of separated film versus the radial stress of the Owen and Ryley model for each of the 68 different flow conditions. Comparing Fig. 9 and Fig. 12 confirms the significant differences that appear due to changing surface tension of the fluid. Fig. 12 shows a different trend for a surface tension of 0.026 N/m when compared to a surface tension of 0.042 N/m. However, the Force Ratio model results in Fig. 9, show films with different surface tension values follow the same trend. The Owen and Ryley model in Fig. 12 shows greater differences between gas phase velocities, while the current Force Ratio model appears to collapse the results into a single trend. The different representation of gas phase velocity in each separation criteria may be caused by the gas phase velocity on the ligament length. With the exception of its influence on ligament length, both force methods utilize gas phase velocity to determine the mean film velocity in the inertial term only.

**Figure 12.** Experimentally measured film separation by mass correlated to the calculated Owen and Ryley radial stress for various gas phase and liquid phase flow conditions. Surface tension is shown in parenthesis.

### 7.3 Prediction of Wall Angle Effects

It is important to note that the ability of the Force Ratio to capture the onset of film separation leads to a predictive capability. For example, using the rough wall film model, the Force Ratio can be calculated for a given set of gas phase velocity, liquid flow rate and wall angle. Considering those conditions which provide a unity Force Ratio for a chosen wall angle, prediction of the onset of film separation can be established, as shown in Fig. 13. As indicated on the figure, to the right of the curves are flow conditions which result in a Force Ratio larger than one for the given wall angle and would suggest the occurrence of some degree of film separation; to the left of the curves are Force Ratios less than one which would imply no separation.

**Figure 11.** Comparison of force balance contribution for the radial stress model (1) and the current Force Ratio model (2) at Ug = 20 m/s.
The results suggest that the wall angle has a lesser effect on film separation for steeper wall angles. Additionally, the impact of wall angle on the separation process is more significant for lower gas phase velocities and of lesser importance for higher gas phase velocities.

Figure 13. Predicted effects of wall angle of the onset of film separation for various gas phase and liquid phase flow conditions.

8 Summary and Conclusions

An experimental test facility to study the development of a shear-driven liquid film and its subsequent separation at an expanding corner has been developed. Built into the test section is the ability to measure the liquid mass which stays attached to the wall after the corner. An analytical force balance was developed to serve in a predictive sense as a criterion for the onset of film separation. Required for the force balance is knowledge of the film thickness and velocity at the corner, which for this study, were determined using a simple rough wall film propagation model.

The force balance of the major liquid phase forces acting at the corner, including surface tension, film inertia, and gravity, correlated well to the onset of film separation as measured in the experiment. Unlike previous Weber number models, effects of the wall angle on film separation are included. Also, the use of a characteristic ligament length to describe the film after the corner provides a better correlation than previous force balance methods. This correlation of Force Ratio with mass fraction of liquid film which separates from the wall occurred over a wide range of experimental test conditions. The correlation of the separated mass to the liquid film force balance suggests the gas phase impacts the separation process only through its effect on the liquid film momentum. It is surmised, however, the inclusion of gas phase effects in the shear layer and recirculation zone will be necessary to consider the breakup of the film.

Acknowledgements

This work was supported in part by NSF grant CTS-0352135.

Nomenclature

\[ A \]  area
\[ CS \]  control surface
\[ F_c \]  surface tension force at bottom of film
\[ F_{e x} \]  external force
\[ Fr_{bf} \]  film Froude number
\[ F_s \]  surface tension force at top of film
\[ g \]  gravitational constant
\[ h_f \]  film thickness
\[ L_b \]  characteristic length of film after corner
\[ \Pi \]  normal vector
\[ Re_f \]  film Reynolds number
\[ U_g \]  gas phase velocity
\[ u_f \]  film velocity
\[ u \]  fluid velocity component
\[ v \]  fluid velocity component
\[ \vec{V} \]  velocity vector
\[ \dot{V}_f \]  film volumetric flow rate
\[ W \]  gravitational force
\[ We_f \]  film Weber number
\[ We_{rel} \]  relative Weber number
\[ w_f \]  film width
\[ \beta \]  separated film angle from the horizontal
\[ \theta \]  surface corner angle from the horizontal
\[ \mu_f \]  film viscosity
\[ \rho_f \]  film density
\[ \sigma \]  surface tension
\[ \tau \]  shear stress
\[ \nabla \]  gradient
\[ \forall \]  volume

References


