Experimental Evaluation of a Film Separation Criterion

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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 liquid atomizer systems, refrigerant flows in evaporators, internal combustion engines, and demisters. 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. Recent work analyzed these forces to propose a film separation criterion in the form of a force ratio, which predicts the onset of film separation from the surface at the corner. The force ratio is calculated using the gas phase and liquid film flow conditions, including the average film thickness and velocity at the corner. In this study, the force ratio separation criterion is evaluated using experimental film separation measurements for a wide range of flow conditions. The experimental facility is described in detail, including the method for measuring the mass percent of separated film, and the laser focus displacement (LFD) instrument used for measuring film thickness. The advantages and limitations of using the LFD instrument are discussed, including the maximum measurable film surface angle when using this technique. Results are presented for film thickness and velocity, where film thickness is measured across the width of the film located at the corner, and average film velocities are inferred from liquid mass conservation. The force ratio is then calculated using the experimentally determined flow parameters, and the film separation criterion is evaluated by comparing the calculated force ratio to the measured mass fraction of film separation. In addition, the experiments are performed for several fluids in order to investigate the effects of viscosity and surface tension on the film separation process. The force ratio separation criterion successfully predicts the onset of separation and provides a good correlation to the fraction of film mass separated at higher separated fractions for fluids with varying surface tension and film viscosity.

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 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 internal combustion engines, atomizer design, flows in evaporators and condensers, and wave plate mist eliminators.

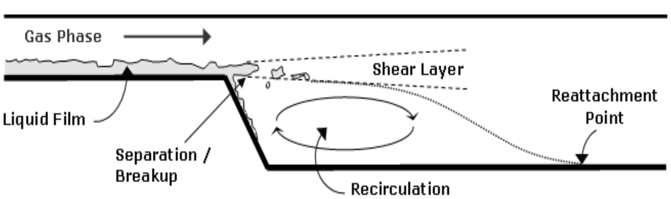

Figure 1. Schematic of shear driven film flow, resulting in partial film separation from the substrate at the corner.

To model these processes, a clearer understanding must be developed of the dynamics between the coupled gas phase (separated/reattached flow) and liquid phase. To date, most film propagation models which attempt to simulate these dynamics are two-dimensional. Equally important, most models are also time-averaged, prohibiting the simulation of dynamic wave structures and large disturbances. Consequently, to be used in conjuncture with such shear-driven film propagation models, a film separation model must be designed to accurately predict the separation process using two-dimensional, time-averaged initial conditions. 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 film properties.

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Background

Gas-liquid flows have application in a multitude of engineering problems. While a significant amount of work can be found for shear-driven films, such as annular flow [1] or prefilming atomizers [2-4], limited studies have considered film separation at a corner.

A few general theories have been proposed in the literature to predict film separation. An approach, put forth by O'Rourke and Amsden [5], 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. This model lacks experimental validation. The second approach is that of Maroteaux et al. [6,7] 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. The model was calibrated by a limited number of experiments. Other investigations have commented on the accuracy of this approach, including Gubaidullin [8] who points out several inconsistencies with the approach of Maroteaux et al. [6] including differences in the definition of the acceleration of the film at the corner. In addition, recent work by Steinhaus et al. [9] suggests the analysis of Maroteaux et al. [6] shows different trends than what is observed experimentally.

The literature also presents two separation models which consider a balance of liquid phase forces at the corner. In the work of Owen and Ryley [10], inertial, gravitational, and surface tension forces acting on the film are balanced in the form of tensile and compressive stresses at the corner. Separation is presumed to occur when inertial separating forces are balanced with restoring forces. The second force balance model was more recently proposed by Friedrich et al. [11], and although inertial, gravitational, and surface tension forces are included in a manner similar to Owen and Ryley [10], the film viscosity and the formation of separating ligaments at the corner were also considered. These factors were not considered by Owen and Ryley [10]. The analytical derivations of Friedrich et al. [11] resulted in a force ratio which was subject to experimental validation in the same study.

Scope

The key objective of this study is further experimental evaluation of the force ratio of Friedrich et al. [11] as a film separation criterion. The criterion must be able to capture to what degree the film will separate from the corner and break up into droplets or negotiate the corner and stay attached. To this end, the same test section as that used by Friedrich et al. [11] was utilized to create, control, and observe a shear-driven liquid film up to a sudden expansion (corner), and this facility 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, CFD predictions of the film thickness and average film velocity just before the corner were used as inputs to the separation criteria in the previous experimental work of Friedrich et al. [11]. But, for this study, these film flow conditions are obtained experimentally in order to avoid the uncertainties of a computational model. The focus of this study, then, is not the film propagation before the corner, but instead the examination of the force ratio using experimental techniques which will provide a more robust evaluation than previous experiments. A laser focus displacement instrument is used to measure film thickness at the corner. Average film velocity is then inferred from the measured film thickness and volumetric film flow rate, allowing the force ratio to be calculated using purely experimental flow parameters for each flow condition. Additionally, the strength of the experimental film separation measurements for validation is enhanced by using a broader array of more suitable fluids.

Experimental Facility

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 average 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 gas flow rate.

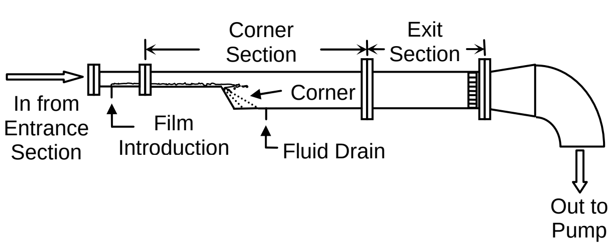

Figure 2. Schematic of test section.

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 2-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, three different fluids are used. The first, aqueous acetic acid, has a surface tension of 51 mN/m and a viscosity of 1.00 cP. The second fluid is a solution of glycerol, acetic acid, and water, which also has a surface tension of 51 mN/m and a viscosity of 1.42 cP. The third fluid is a lightweight mineral oil with a surface tension of 27 mN/m and viscosity of 1.42 cP. Thus, both surface tension and film viscosity can be isolated to investigate their effect on the separation process.

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° 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. 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.

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, $\dot{\forall}_f$, and the measured film width, w_f, at each flow condition:

$$Re_f = \frac{\dot{\forall}_f \rho_f}{w_f \mu_f} \quad (1)$$

Each flow condition can then be characterized by a mean 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 40 m/s and liquid flow rates varied from 6.5 to 25.0 cm^3/s. This resulted in a variation of film Re_f from approximately 100 to 300.

Film Separation Measurement

Measurement of the degree to which the liquid film is separated from the corner is made by pulling off the liquid which stayed attached to the downward sloping wall after the corner. A porous brass plug is placed in this lower wall as a means to extract the mass of the liquid film that stays attached to the wall. As shown in Fig. 3, the porous plug (6 mm wide) spans across 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 is applied below the porous plug to draw the liquid from the wall, and the mass of this liquid is measured. Sufficient suction is applied behind the porous plug, adjusted at each flow condition, for removal of the liquid from the wall without pulling the gas through the porous surface. 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 measured liquid flow into the test section, provides the mass flow of liquid separated at the corner. Combined uncertainty in this measurement is 5 %.

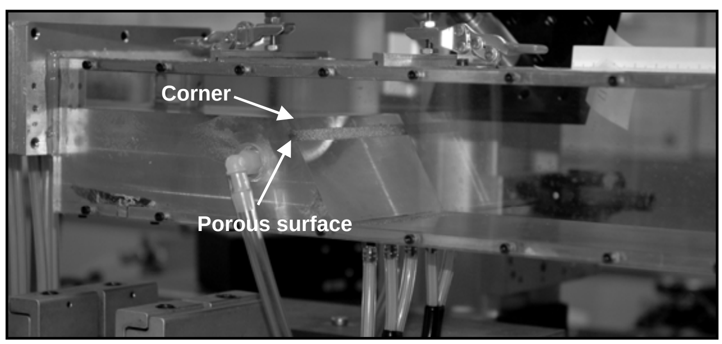

Figure 3. Picture of test section showing porous surface where film which remains attached after the corner is removed.

This approach works well for separated mass fractions greater than approximately 10%. However, at very small separated fractions, the wall suction has difficulty removing all of the film from the wall, particularly for cases with high liquid flow rates. Hence, uncertainties in the mass fraction separated for values less than 10% were greater than for highly separated conditions. For these cases, imaging was used in conjunction with the wall suction measurements to confirm cases of no film separation.

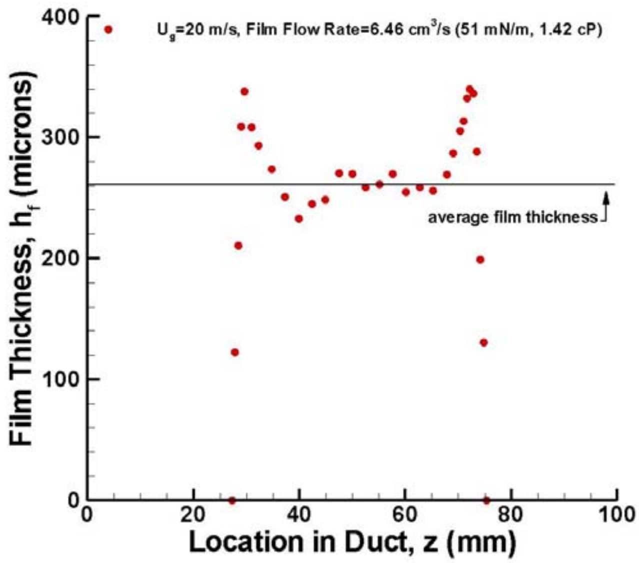

Figure 4. Film thickness measured across the width of the test section using a laser focus displacement instrument.

Film Thickness Measurement

The time-averaged film thickness values are needed as initial conditions of the film separation criterion, and this need is met by measuring film thickness using a laser focus displacement instrument (LFD). A laser focus displacement instrument utilizes the confocal principle with laser light to determine the location of an interface between two media. By moving the focal point of a converging laser beam, the LFD locates a surface by sensing peaks in reflected light intensity when the laser's focal point is at the interface of two media. Few other experimentalists have utilized this instrument for measuring shear-driven liquid films [12,13], and consequently, this study was preceded by an examination of the LFD technique [14]. The LFD used in this study (Keyence Co., Model LT-9030) was found to have a maximum measurable surface angle of approximately 6˚ from the horizontal. Thus, the LFD measures the peaks and valleys of the wavy film surface, and time-averaged film thickness values were determined from these measurements.

The LFD is mounted on the outside of the top wall of the flow duct, where a window allowed for optical access from above the film. Measurements are taken across the width of the film at a location 5 mm upstream from the corner, which limited effects caused by the corner to influence thickness at the point of measurement. For each flow condition, thickness is measured at evenly spaced locations beginning at one side of the film and extending to the opposite side. Measuring thickness at many locations across the width of the film provides valuable cross sectional profile information that is not available in many film studies. The film thickness is averaged in the spanwise direction, providing a time-averaged, width-averaged film thickness value for each flow condition to be used as initial conditions of the film separation criterion. An example is shown in Fig. 4, where a horizontal line represents the average film thickness. The uncertainty of this measurement is ±11.1 μm.

The volumetric film flow rate and the cross sectional area of the film can be related to estimate the average film velocity, which is also needed as an initial condition of the film separation criterion. More specifically,

$$u_f = \frac{\dot{\forall}_f}{A_f} \qquad (2)$$

where u_f is the average film velocity, $\dot{\forall}_f$ is the volumetric film flow rate, and the cross sectional area, A_f, is calculated as the product of film width and average film thickness. This method allowed film velocity to be inferred from experimental film thickness measurements coupled with the controlled film flow rate and the measured film width. Ultimately, the experimental techniques described here permitted a two-dimensional film separation criterion to be evaluated using purely experimental measurements.

Film Separation Criterion

Friedrich et al. [11] established a criterion for predicting the onset of film separation for a shear-driven film at a sharp corner. A force balance approach was used to compare forces causing separation with forces acting to prevent separation. This force balance approach considered the film at the point of separation, when separating forces and restoring forces are equal. A control volume was drawn around the film at the corner, which was presumed to form a suspended ligament. The forces of inertia, gravity, and surface tension were included in a balance of forces acting on the control volume, where the separating force was caused by the inertia of liquid flowing through the control volume. The surface tension and gravitational forces acted to prevent film separation. Hereafter, Friedrich et al. [11] formed a force ratio

$$Force\,Ratio = \left\{ \frac{\rho_f u_f^2 h_f \sin\theta}{\sigma \sin\theta + \sigma + \rho_f g h_f L_b \cos\theta} \right\} \qquad (3)$$

where θ is the angle of the sharp corner, σ is surface tension, ρ_f is film density, u_f is average film velocity, h_f is film thickness, and L_b is the ligament length as calculated by an empirical equation created by Arai and Hashimoto [15] for thin sheet breakup length. The angle of the sharp corner, θ, is independent of the corner radius, which was assumed to be zero. Although a truly sharp corner can never be achieved experimentally, the small corner radius achieved in the current test section was presumed to have a negligible effect on the force ratio. Conclusively, the numerator represents the inertial separating force and the denominator represents the restoring forces of surface tension and gravity. Consequently, a force ratio value of one occurs when restoring forces are balanced by the inertial separating force. Thus, Friedrich et al. [11] predicted the onset of film separation, or the point at which the film begins to separate, to occur at the critical force ratio value of one.

Results and Discussion

The percent of separated mass is measured for 48 flow conditions, including 3 gas phase velocities, 6 film flow rates, and 3 different fluids. The measured film thickness and velocity, volumetric film flow rate, gas phase velocity, and fluid properties allows for calculation of the force ratio per Eq. 3 for each flow condition. A comparison between measured film separation and the calculated force ratio is shown in Fig. 5 for each flow condition.

As shown by Fig. 5, a small force ratio value results in a small amount of film separation if not zero separation. But, as the force ratio increases to near one, the onset of film separation is observed. This agrees with the conjectures of Friedrich et al. [11], and reveals that varying film viscosity by more then 40% does not cause significant deviation of the critical force ratio.

A second observation involves the trends in film separation which occurs for higher force ratio values. A common trend is revealed for a viscosity of 1.00 cP, and a different slope results for 1.42 cP. Although a force ratio of near one manifests the onset of separation for all fluids in this study, a further increase in the force ratio causes a more rapid increase in the percent of separated mass for 1.00 cP than for 1.42 cP. The higher fluid viscosity tends to slow the rate of increasing mass separation with increasing force ratio. The lower viscosity fluid shows an abrupt change from no separation to significant separation over very small changes in force ratio. This indicates that for flow conditions which are dominated by inertial forces, film viscosity influences the physics of film separation in a way such that the existing force ratio is unable to collapse all the results to a common trend.

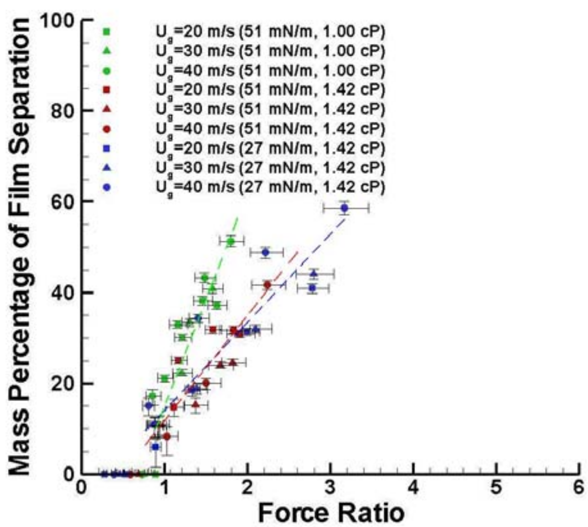

Figure 5. Experimentally measured film separation by mass correlated to the calculated force ratio for various gas phase and liquid phase flow conditions. Surface tension and film viscosity is shown in parenthesis.

Conclusions

Validation of a simple force balance method to predict film separation under shear driven conditions has been conducted over a range of flow conditions and liquid phase properties. Given the three dimensional and unsteady nature of film separation in such shear driven flows, the force balance approach appears to provide a reasonable means to predict film separation at a corner. However, a slightly different trend in the separated fraction relative to the force ratio exits with varying liquid phase viscosity which warrants further study.

Acknowledgements

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Nomenclature

A_f cross sectional area of the film
g gravitational constant
h_f film thickness
L_b length of film after corner
Re_f film Reynolds number
U_g gas phase velocity
u_f film velocity
w_f film width
θ surface corner angle
μ_f film viscosity
ρ_f film density
σ surface tension
$\dot{\forall}_f$ volumetric film flow rate

References

1. Hanratty, T.J., and Theofanous, T. (editors), *Colloquium, University of Illinois at Urbana-Champaign*, November 5-6, (1994).
2. Sattelmayer, T., and Wittig, S., *J. of Engineering for Gas Turbines and Power* 108:465-472 (1986).
3. Wittig, S., Himmelsbach, J., Noll, B., Feld, H.J., and Samenfink, W., *J. of Engineering for Gas Turbines and Power* 114:395-400 (1992).
4. Himmelsbach, J., Noll, B., and Wittig, S., *International J. of Heat and Mass Transfer* 37:1217-1226 (1994).
5. O'Rourke, P.J., and Amsden, A.A., *SAE Technical Paper* No. 961961 (1996).
6. Maroteaux, F., Llory, D., Le Coz, J-F., and Habchi, C., *J. of Fluids Engineering* 124:565-575 (2002).
7. Maroteaux, F., Llory, D., Le Coz, J-F., and Habchi, C., *International J. of Engine Research* 4:11-26 (2003).
8. Gubaidullin, A, *J. of Fluids Engineering* 129:665-666 (2007).
9. Steinhaus, B.C., Ghandhi, J.B., and Shedd, T.A., *Twentieth Annual Conference on Liquid Atomization and Spray Systems*, Chicago, Illinois, May 2007.
10. Owen, I. and Ryley, D.J., *International J. of Multiphase Flow*, 11, 1:51-62 (1985).
11. Friedrich, M.A., Lan, H., Wegener, J.L., Drallmeier, J.A., and Armaly B.F., *J. of Fluids Engineering* 130:051301 (2008).
12. Takamasa, T., and Kobayashi, K., *International J. of Multiphase Flow* 26:1493-1507 (2000).
13. Busam, S., Ebner, J., and Wittig, S., *International Gas Turbine and Aeroengine Congress and Exhibition*, New Orleans, Louisiana, 2001.
14. Wegener, J.L., "Experiments and Modeling of Shear-driven Film Separation," *A Thesis, Missouri University of Science and Technology,* (2009).
15. Arai, T., and Hashimoto, H., *Third International Conference on Liquid Atomization and Spray Systems*, London, 1985.