Characterization of Shear-driven Liquid Film Separation and Break-up at a Sharp Expanding Corner

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

Abstract

The behavior of a shear-driven thin liquid film at a sharp expanding corner is of interest in many engineering applications. However, details of the interaction between inertial, surface tension, shear and gravitational forces on the film at the corner are not clear. An experimental facility is discussed which enables a controlled development of a thin shear driven film and subsequent analysis of the film at a sharp expanding corner. High speed imaging along with an interferometric film measurement technique is used to quantitatively characterize the propagation of the shear-driven film to and around the corner. Control variables include gas and film velocities, film flow rate, and film surface tension. Observables include film thickness and transient behavior of film separation and film break-up. A CFD model, developed to study the shear driven liquid film propagation along the bottom wall of the test section, is also discussed. The objective of the film model is prediction of film thickness and film velocity at the corner. Contribution of the results toward developing a comprehensive film separation model is discussed.

*Corresponding author
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 Figure 1), however, have received little attention. The films considered in this study can be classified as thin (~100 \text{ mm}), possibly evaporating, 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, refrigerant flows in evaporators, and film drag over wetted surfaces. Lack of understanding of film breakup at the sharp corners of a substrate is currently limiting the ability to accurately model film dynamics in engines and hence impeding improvements in the fuel and intake system designs for 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 is the prediction of film separation from the solid surface and its atomization as a function of gas phase velocity and wall angle. The lack of such understanding motivates the current work.

Figure 1. General geometry for shear-driven film at a corner

The general geometry for a shear driven liquid film with a separated gas flow at a corner is shown in Figure 1. A key objective of the program is the development of a comprehensive separation criterion for predicting the film behavior at the corner, i.e. whether it will separate from the corner and break up into droplets or negotiate the corner and stay attached [1]. This paper places emphasis on the development of a test facility to create and control a shear driven liquid film as well as quantitative determination of critical film characteristics just before separation. Included are measures of film thickness and predictions of film thickness and velocity with a film propagation model. Without accurate determination of these quantities at the corner, prediction of separation would be impossible. Observations using high speed imaging are also made of the film separation phenomena in the test section.

Experimental Facility

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. Flow rates through the test section are 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.

There are four parts to the rectangular test section, three of those parts are shown in Figure 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 plug on the bottom wall in the film introduction section. Simulations indicate that, with the entrance region, 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. As will be discussed in the results, due to surface tension effects, the film width in the span-wise direction does change with distance from the point of introduction. The flow of the liquid into the test section is quantified on a volumetric flow basis and measured using a rotometer with an uncertainty of 2.5%. Unless shown otherwise, for the results presented here, the liquid was water with the addition of a surfactant (Surfynol 465) at 0.1% which results in a surface tension of 0.042 N/m.

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.
Interferometric film thickness measurement

Knowing the film thickness before the corner is critical, not only for validating the film propagation model, but as a primary input to the film separation criterion. The technique needs to have good spatial resolution to determine uniformity of the film across the test section as well as good temporal resolution to account for any wave propagation along the film. It was decided to pursue an interferometer approach initially developed by Ohyama et al. [2]. Improvements have been made with the technique most recently by Kelly-Zion et al. [3] who measured film thickness of an evaporation film. As the published literature does not indicate any temporally and spatially resolved measurements of shear driven films made using this method, a secondary objective of this program is to advance the technique for such flows.

Briefly, the technique makes use of the phase shift between the reflection of incident light from the top and bottom surfaces of the film. When the light approaches the film over a small range of incident angles, a series of light and dark fringes appear in the reflected light. The number of these fringes which occur in a specified field of view is used to determine the film thickness. The field of view is defined by the focusing lens on the transmitting optics side and/or any aperture used in the receiving optics. The spatial resolution is determined based on the spot size of the incident light which, for the current configuration of the transmitting optics is approximately 10 microns. Temporal resolution is determined by the rate at which the fringe imaging takes place. For the results shown here, a high frame-rate camera, a Photon 1280 PCI, is used operating at 2000 frames per second.

Figure 3 shows the optical configuration of the film thickness measurement system. A 10 mW HeNe laser is collimated to approximately a 20 mm diameter. A 200 mm focal length lens is currently used to develop a spot size of less than 0.01 mm diameter on the film. The light reflected from the film, which forms the interference pattern, is imaged on a diffusing glass plate. A typical fringe pattern, as measured by the high speed camera, is shown in Figure 4.

Validation of the film thickness measurement system was performed using a sapphire disk of known thickness. The measurement of a nominal 508 µm thick sapphire disk was within the manufacturer’s uncertainty (10%).

Finally, it is important to note that this interferometric technique, as configured here, will only display fringes on the diffusing glass plate for film surfaces nearly parallel with the bottom surface of the test section. For example, measurements of a stationary drop placed on the test section bottom wall, indicated that the fringe pattern was only observable for film surfaces less than 2 degrees out of parallel with the bottom wall. Hence, for a film with traveling waves, this implies that the film thickness will only be recorded for wave peaks and troughs and not the continuous film profile. As will be shown in the results, a time series of film peak and trough thickness information is then used to obtain the average film thickness.
Shear Driven Film Model

A CFD model has been developed to study the shear driven liquid film propagation along the bottom wall of the test section. The objective of the model is to predict film thickness and film velocity at the wall corner, before the point of separation. A brief description of the model is given followed by a few predictions of film characteristics.

The two-dimensional rough wall model proposed by Sattelmayer and Wittig [4] for simulating shear driven liquid film flow is used. This model has been shown to provide good agreement with measured values for the average film thickness [5]. 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 shear driven liquid film in turbulent gas flow inside the experimental duct geometry.

Gas flow model:

The two-dimensional incompressible Reynolds-averaged Navier-Stokes equations, along with the continuity equation, were used to simulate the gas flow. The $k-\varepsilon$ turbulent model was utilized with wall functions (high-Reynolds-number model) applied to the rough wall (the film boundary), and low-Reynolds-number model applied to the other smooth wall of the duct. The general form for the governing equations can be represented by:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\nabla \cdot (\rho \phi \vec{V}) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi$$

Where, $\Gamma_\phi$ is an effective diffusion coefficient and $S_\phi$ denotes the source term [6]. The governing equations for the two velocity components ($u$ and $v$), the turbulent kinetic energy ($k$), and its dissipation ($\varepsilon$) can be represented by Equation (2), where $\phi$ is the corresponding variable and $\vec{V}$ is the velocity vector. These equations were discretized using a finite volume method in a staggered grid system, with SIMPLE algorithm. The discretized equations were solved by a line-by-line TDMA (Tri-Diagonal Matrix Algorithm) method. The computational domain is 0.8 m in length and 0.02032 m in height with the liquid film being injected at $x = 0.2$ m. Several grid densities and distributions were considered to insure a grid independent solution, and a grid of 120($X$) and 66($Y$) was selected for generating the final results. The use of higher grid densities (i.e. 1.5 and 2 times greater than the one sited above) did not alter the final results. The grid distribution was non-uniform. At least 5 grid points were set inside the laminar sublayer near the smooth wall where the low-Reynolds-number turbulence model was used; on the other hand, the first grid point for the gas flow near the rough wall (liquid film) is placed outside of viscous sublayer where $11.3 \leq y' \leq 40$ is satisfied. The grid for simulating the turbulent gas flow is distributed between the first grid point “p” near the rough wall and the smooth wall.

The wall roughness (or liquid film) effect, $k_f$ is incorporated into the logarithmic law of the rough wall through the following relations:

$$u_p^* = \frac{1}{k^*} \ln y_p^* + C(Re_{\varepsilon})$$

where,

$$u_p^* = \frac{u_p}{e^{1/4} \sqrt{k_p}}$$

$$y_p^* = \frac{y_p}{e^{1/4} \sqrt{k_p}}$$

$C(Re_{\varepsilon})$ is a function that is dependent on the roughness Reynolds number, $Re_{\varepsilon} = \frac{(c_p^1 k_{p}^{1/2})}{\nu}$. The functional relation for $C(Re_{\varepsilon})$ can be found in the literature [7]. The term $y_p$ is the distance of the first grid point in the computational domain for the gas flow from the rough wall. The shear stress $\tau_p$ is given by [6]:

$$\tau_p = \frac{\rho c k_{p}^{1/2} u_p}{y_p e_{p}}$$

To start the gas flow simulations, initial values for all of dependent variables need to be assumed, in the code as $u = u_{in}$, $v = 0$, $k = 0.005 u_{in}^2$, $\varepsilon = 0.1 k^2$. In addition, for a given liquid film volume flow rate ($V_f / B$), the average film thickness ($\bar{h}_f$) needs to be assumed at the start of the simulation. This provides a means for calculating the average film velocity and the wall shear stress from the following relations:

$$\bar{h}_f \cdot \vec{u}_f = \frac{V_f}{B}$$

$$\tau_f = \frac{2 \mu_{water} u_f}{\bar{h}_f}$$

Note that the velocity distribution of shear driven liquid film is assumed to be linear (i.e. $u_p = 2u_f$). The wall roughness is evaluated by using the following relations [7]:

$$k_f = \psi_f \bar{h}_f$$

$$\psi_f = 1.47 + 0.01851 r_{f}$$

The boundary conditions for the low-Reynolds-number turbulent model are $u = v = k = 0$, $\varepsilon = 2 \psi f / y_f$ at the wall.
In the high-Reynolds-number turbulent model, the boundary conditions that are applied at \( y_p \) consisted of \( u_p \) that is computed from the logarithmic law of the wall (Equation (3)), and 
\[ \varepsilon_p = \frac{c_{f_p} \kappa^2}{\kappa y_p^2}, \]
boundary conditions for \( v \) and \( k \) are applied at the wall as \( \frac{\partial v}{\partial y} = 0, \frac{\partial k}{\partial y} = 0 \). The inlet velocity distribution of the gas flow was equivalent to fully developed turbulent flow and the exit conditions were taken as fully developed. The shear stress at “p”, which is considered to be constant between “p” and the rough wall, is evaluated using Equation (4) and the simulated gas flow results.

Film flow model:
The liquid film flow is simulated by using the laminar boundary layer flow approximation that is governed by the following simplified Navier-Stokes equation:
\[ \rho (\frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}) = \frac{\partial}{\partial y} (\frac{3}{2} \rho \tau_p - \frac{3}{2} \rho \tau_w) \]
Assuming a linear velocity distribution through the film, and using the integral method (i.e. integrating the above momentum equation together with continuity equation (Equation (1)) in the \( y \) direction from 0 to \( h(x) \)), yields the following ordinary differential equation for the surface film velocity:
\[ \frac{du(x)}{dx} = \frac{3}{2} \rho \tau_p - \frac{3}{2} \rho \tau_w \]
where \( \tau_p \) is evaluated from Equation 4, and \( \tau_w \) is evaluated from Equation (5). A fourth-order Runge-Kutta integration scheme with adaptive step-size control is used to determine the local surface film velocity from Equation (9), and from these results the local film thickness over the length of the calculation domain. The resulting average film thickness is used to update the effective wall roughness, and this new wall roughness is used to start a new gas flow simulation. This iterative procedure is repeated until the difference between the evaluated shear stress at the first grid point “p” for two iterations, \( (\tau_p^n - \tau_p^{n+1}) \), is smaller than \( 10^{-6} \).

At that state \( \tau_p \) becomes equal to \( \tau_w \) for most of the simulated domain downstream except for the injection region of the liquid film. A starting film thickness is needed to initiate the computation of the film flow, and that film thickness is updated after every iteration during the coupling iteration process.

Numerical Results:
Results from the above simulation for the average film thickness and average film velocity are presented respectively in Figures 5 and 6 for different liquid film volume flow rates and average inlet gas velocities. As expected, the average film thickness decreases with increasing gas velocity while the average film velocity increases. The results will be compared below with measured values.

Film characterization
Critical to the prediction of the shear driven film separation and breakup at a corner is measurement of the film thickness. Measurements of film thickness were made under several flow conditions, with average gas velocities, \( u \), ranging between 20 and 45 m/s and liquid flow rates, \( \dot{V}_f \), between approximately 6 and 20 \( \text{cm}^3/\text{s} \). For each set of gas and liquid phase flow parameters, the film thickness was measured over a period of approximately 1000 ms. All measurements were made at 5 mm upstream from the corner edge. The corner edge is located 23 cm downstream from the film.
introduction point. A time-average thickness was then obtained from the time series at each location.

Figure 7 shows a typical measured film thickness at the center of the test section, 5 mm upstream of the corner as measured using the interferometric technique. Each point represents the results from one fringe pattern imaged at 2000 frames per second. The erratic behavior in the film thickness is a result of the instabilities located on top of the film and the nature of the measurement technique which only provides results for wave peaks and troughs. Hence, not all frames contain a fringe pattern. The horizontal line represents the mean, averaged over the time window shown. Clearly, establishing the appropriate window length over which to determine a mean is critical to reducing the uncertainty in the mean.

Figure 7. Time series of film thickness at \( u = 45 \) m/s, \( \dot{V}_l = 13 \) cm\(^3\)/s.

Great care was taken in developing a test section which resulted in uniform gas phase velocities span-wise across the test section near the corner. However, variation in film thickness still occurs over the width of the test section. Figure 8 shows typical variation in time-averaged film thickness at five locations, span-wise across the test section, 5 mm from the edge. The zero location corresponds to the centerline of the 10 cm wide test section. The non-uniformity of the film thickness is a strong function of the surface tension of the liquid. Although the film is introduced uniformly over the center 7.5 cm width of the test section, the film narrows as it reaches the corner due to surface tension. Figure 9 shows the variation in the width of the film, 5 mm from the corner, as a function of gas phase velocity. Clearly, increased gas velocity and, hence shear force, keeps the film spread over the test section lower wall, counteracting the surface tension forces. A reduction in film surface tension, results in a wider film near the corner due to lower surface tension forces pulling the film together. These same surface tension forces impact the film separation at the corner.

Figure 8. Typical average film thickness over the width of the test section (\( u = 40 \) m/s, \( \dot{V}_l = 16.34 \) cm\(^3\)/s).

Figure 9. Film width near the test section corner versus gas phase velocity

Finally, Figure 10 illustrates the variation in time-averaged film thickness measured at the test section centerline for a constant film flow rate per unit width. The liquid flow rate is normalized by the film width to account for the varying film width as discussed. Other than the discrepancy in the values at low gas phase velocities, the measured results in Figure 10, shown with the predicted results from Figure 5, are within 20\%.
Figure 10. Centerline film thickness at test section edge versus gas phase velocity
\( \dot{V}_f / B \approx 2.5 \text{ cm}^2/\text{s} \)

Film separation and breakup observations

The film separation and breakup process was captured using high speed imaging for several test cases. Imaging was performed at 2000 frames per second for a test section corner angle of 60° from the horizontal. A few of the images have been selected for presentation from the range of gas velocities (20-45 m/s) and liquid flow rates (6-20 cm³/s). They were chosen to illustrate three distinct observed modes: Complete film separation from the wall, partial separation and no separation. Note that not all modes could be observed for a fixed gas velocity or liquid flow rate. Hence the test conditions vary for the figures shown. Results shown are all for a liquid surface tension of 0.042 N/m.

Figure 11 shows the film becoming completely separated from the wall at the corner. Instabilities on the film surface are clearly visible before the corner. Once reaching the corner, the inertia of the film carries the liquid, separating it from the surface. Careful study of the time-resolved film behavior at the corner seems to suggest that, as proposed earlier [1, 8], surface tension and film inertia strongly influence film separation.

Figure 12 shows the case of partial separation at the corner. A portion of the film separates as in Figure 11, but a portion of the bulk flow also remains attached to the surface and continues around the corner. This partial separation condition can develop over time from the fully separated condition. In other words, beginning with a dry test section surface, the film may start as fully separated. Over time, a meniscus of fluid is stretched between the separated film and the sloped surface. This meniscus stretches further down the sloped wall, slowly pulling more fluid with, until a partially separated condition exists as shown in Figure 12. The time scale involved in this transition is on the order of 10 to 100 ms. The development and growth of this meniscus appears to be related to the corner wall angle.

Figure 13 shows the case where the film remains attached to the wall around the corner. The film thickness grows significantly around the corner due to the reversal of the gas phase interfacial shear on the film in the separated gas flow region. Interestingly, breakup downstream of the corner of some of the bulk liquid from the surface into ligaments appears to be instability driven. Large instabilities propagate around the corner and separate from the bulk fluid, pulling into long ligaments as shown in Figure 13. This behavior suggests that to predict the breakup process, the behavior of both the bulk liquid as well as the instabilities will need to be captured.

Figure 11. Image captured at 2000 fps showing liquid fully separated from test section surface \((u = 45 \text{ m/s, } \dot{V}_f = 19.76 \text{ cm}^3/\text{s})\)

Figure 12. Image captured at 2000 fps showing liquid partially separated from test section surface \((u = 40 \text{ m/s, } \dot{V}_f = 6.46 \text{ cm}^3/\text{s})\)

Figure 13. Image captured at 2000 fps showing liquid remaining attached to the test section surface \((u = 20 \text{ m/s, } \dot{V}_f = 19.76 \text{ cm}^3/\text{s})\)
Summary and future work

A test facility has been designed and constructed to study shear-driven film behavior at a sudden expansion. An interferometric system is used to measure film thickness and high-speed imaging is applied to consider the time-resolved behavior of the film at the corner. In support of the experimental work, a numerical model has been applied to predict the development of the film along the bottom surface of the test section to the corner. 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.

Quantitative measurements of film characteristics as well as high-speed imaging (2000 frames per second) of the film behavior at the corner reveal a very complex film separation process. As suggested in earlier work [1, 8], the separation process appears to be controlled by film inertia and surface tension forces. However, time-resolved imaging indicates that starting with a dry surface, what is initially a separated film condition can transition into an attached film with the growth of a meniscus region below the film attached to the lower wall. Even for a film attached to the surface around the corner, breakup can occur with large instabilities pulling into long ligaments from the surface. This behavior suggests that the behavior of both the bulk liquid as well as the instabilities will need to be captured to predict the downstream atomization.

Acknowledgements

This work was supported in part by NSF Grant No. CTS-352135.

Nomenclature

- $c_p$: Constant in $k-\epsilon$ model, 0.09
- $\overline{h_f}$: Average film thickness
- $k$: Turbulent kinetic energy
- $p$: Pressure
- $u$: Velocity component in x-direction
- $v$: Velocity component in y-direction
- $\vec{V}$: Velocity vector
- $V_{f}/B$: Film volume flow rate per unit width
- $x$: Coordinate in main flow direction
- $y$: Coordinate in the axes normal to x-direction
- $\kappa$: Von-Karman coefficient
- $\rho$: Density
- $\mu_t$: Turbulence viscosity
- $\nu$: Kinematics viscosity
- $\epsilon$: Turbulent dissipation rate
- $\tau$: Shear stress

Subscripts

- $f$: Film
- $g$: Gas
- $i$: Interface
- $p$: First inner grid point
- $s$: Film surface
- $W$: Wall

References