Experimental Investigation of Liquid Film Stripping at a Sharp Corner

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Abstract
During port fuel injection in an internal combustion engine, a significant fraction of the injected fuel impinges on the back surface of the intake valve or on the intake runner walls and forms a thin film on the surface. When the intake valve opens, the thin film is sheared by the high speed gas flow and flows toward the intake port where it will reach a geometric discontinuity – the valve lip or the valve seat. At this point, the film may remain attached to the solid surface and flow around the discontinuity, or it may be stripped into droplets that are dispersed in the gas phase. In this study, an experimental apparatus has been designed and fabricated that generates a uniform, thin liquid film whose flow rate is controlled independently from an imposed high speed gas flow. With the current setup, liquid film encounters a sharp 45º angle. The gas flow rate is accurately determined using a 2-D PDPA system and ranges from about 50 to 200 m/s. The liquid film thickness before the sharp corner is measured using a non-intrusive optical technique, taking on values from 85 microns to partial dryout. The liquid flowing around the sharp corner and along the wall is captured and measured using a secondary pump and collection system. As expected, it was found that the liquid film thickness is a strong function of gas velocity with the liquid flow rate having a significant, though secondary effect. On the other hand, the percentage of liquid remaining adhered to the corner is a strong function of gas flow; the liquid flow rate has only a minor impact. These results show trends that are quite different than other recently published work on liquid film stripping, and strongly suggest the need for further work in this area.
Introduction

In port fuel injection engines, a significant fraction of the injected fuel impinges on the back surface of the intake valve or on the intake runner walls. Some of the fuel can splash from the surface and remain as suspended droplets, but the rest of the fuel forms a thin film on the surface. The injection period usually ends well before the next intake event, and during this period the film can partially vaporize. When the intake valve opens, the thin film is drawn towards the cylinder by the shear imposed by the high speed gas flow. Eventually, the film will reach a geometric discontinuity – the valve lip or the valve seat – where the liquid either successfully traverses the corner while attached to the wall, or is stripped into droplets that are dispersed in the gas phase. This configuration is common to many air-assisted atomization systems, but remains difficult to predict either analytically or computationally.

The liquid film stripping phenomena has been studied in a variety of simplified and engine-like geometries. Wang et al. [1] built a simulated intake port that held a stationary intake valve. Liquid fuel was introduced annularly about the port wall, and the mode of film stripping at the valve gap was investigated optically. At each valve lift, the air flow rate was modified to simulate an engine condition. The liquid film breakup was characterized as either gravitational, ligament or aerodynamic for different parts of the simulated intake valve event. The liquid film upstream of the valve was not characterized.

Maroteaux and co-workers [2,3] performed an instability analysis of a liquid film subjected to an angular change $\alpha$. They developed a dispersion relation for the growth rate, $\omega$, of a disturbance as a function of its spatial frequency, $k$, as

$$\omega = \sigma - \left( \frac{\Delta \rho a}{\mu h} k^2 \right) \left( \frac{k h \sinh (k h) \cosh (k h) - k^2 h^3}{\cosh^2 (k h) + k^2 h^2} \right)$$

(1)

where $h$ is the film thickness, $a$ is the acceleration that the film feels, $\Delta \rho$ is the density difference between the liquid and the gas, $\sigma$ is the surface tension, and $\mu$ is the liquid viscosity. The acceleration term was modeled as a centrifugal acceleration associated with turning the film through the angle $\alpha$ with a radius of curvature related to the turning angle and film thickness. Defining the Capillary and Reynolds numbers as

$$C_a \equiv \frac{\mu U_{film} h}{\sigma}$$

and

$$Re \equiv \frac{\Delta \rho U_{film} h}{\mu},$$

the dispersion relation can be rewritten as

$$\omega = \left( \frac{1}{2} \frac{1}{C_a} - \frac{Re}{k^2 h^2 (\sigma / \mu)^2 \alpha} \right) \left( \frac{k h \sinh (k h) \cosh (k h) - k^2 h^3}{\cosh^2 (k h) + k^2 h^2} \right).$$

(2)

The most unstable mode is found as the mode with the highest growth rate, $\omega$.

The liquid film is expected to become unstable when the amplitude of an initial perturbation (at the spatial frequency corresponding to the maximum growth rate) reaches a critical size. The disturbance growth was integrated for the time it takes to rotate through the angle $\alpha$. The critical angle then becomes

$$\alpha_{cri} = C \frac{U_{film}}{\omega_{max} h}$$

(3)

where $C$ is a scaling constant that depends on the critical amplitude. Maroteaux et al. suggest a value of $C = \ln(20) \equiv 3$. The simultaneous maximization of (2) with the angle $\alpha$ defined by (3) allows the critical turning angle to be determined. Above this critical turning angle, the liquid is more likely to strip off rather than flow around the step.

The results of the model were verified by steady flow experiments performed in a wind tunnel [2]. A step was placed on the lower surface of the test section, and liquid fuel was introduced through a hole in the step. The resulting fuel film was pulled by the gas flow to the edge of the step. Downstream of the step the nature of the fuel film was investigated optically. The film thickness was measured using a laser-induced fluorescence technique. Different step geometries and flow rates were investigated. The critical angle from (3), which varied across the step width due to the two-dimensional nature of the film, was found to correlate with the conditions that visually shows film separation.

The multi-dimensional KIVA code uses another approach for identifying the critical turning angle of a fuel film [4]. The approach uses a linear momentum analysis to assess the gas pressure needed to turn the liquid flow around a corner, and an argument is made that surface tension effects are negligible. The film separation criteria is given in terms of film pressure

$$p_{film} = C_t \frac{\rho U_{film}^2 \sin (\alpha)}{1 + \cos (\alpha)}$$

(4)

where the film is considered to separate from the corner when $p_{film} > p_{amb}$, and the recommended value of $C_t$ is 3, although no experimental data is cited in the establishment of the constant value.

The objective of this paper is to present initial measurements of fuel film separation at a geometric discontinuity made in a simplified one-dimensional apparatus. It was initially believed that under the conditions to be investigated, a significant fraction of the liquid would be stripped, and initial efforts were focused on drop size measurements. This proved to be
difficult due to the collection, and subsequent re-entrainment, of liquid in the test section. During the process of designing a system to eliminate this problem it became clear that the collection of liquid was associated with a majority of the liquid adhering to the surface. Therefore, the droplet size measurements will not be discussed, and the remainder of the paper will be focused on the adhered liquid volume measurements, and their implications on the models discussed above.

**Experimental Apparatus**

A schematic of the experimental setup is shown in Fig. 1. The gas flow system is analogous to a blow-down-type wind tunnel. The driver gas (air) is charged in a 0.45 m$^3$ reservoir, and the gas flow is actuated manually using a ball valve. When the ball valve is opened, the gas flows through two high capacity pressure regulators, placed in series, that regulate the upstream pressure of a critical flow orifice that meters the gas flow rate. Multiple orifices are used to prevent acoustic disturbances in the system.

After the orifice, the gas flows through a gradual cross-sectional area change from a 3.81 cm diameter circle into a 3.81 × 3.81 cm square. The total length of this section, including the mounting flanges, is 9 cm. The gas then flows into a flow straightener section consisting of a tube bundle and two perforated metal screens. The straightener section is made of a 3.81 × 3.81 cm inside dimension square tube fitted with 144 stainless steel tubes (12 × 12), each having an inner diameter of 0.29 cm and outside diameter of 0.32 cm. To ensure fully developed flow leaving each tube, the tube bundle section length is 10 cm. Two perforated metal screens were also installed in this section at a distance of 2 and 4 cm from the exit of the tube bundle. The nozzle reduces the flow to a 3 × 1.5 cm cross section over a length of 9 cm.

After exiting the nozzle, the gas flows into the main test section, shown in Fig. 2. The first part of the test section has a rectangular 3 × 1.5 cm cross section. Windows are installed on all sides of the test section. Fuel is introduced into a fuel well through a 2 × 2 cm porous metal plate installed in the bottom wall of the test section. The fuel well is covered by a thin metal plate that forms a thin, ~0.2 mm gap on the downstream side. The cover plate prevents the interaction of the relatively thick fuel in the fuel well and the high speed gas flow. The fuel is delivered to the test section through the gap, and uniformly across ~90% of the test section width. The trailing edge of the cover plate was made as thin as possible to avoid wake effects in the gas stream. The result is a relatively uniform fuel film thickness across the entire test section width.

The fuel was delivered to the test section by a positive-displacement, multi-headed peristaltic pump that provided repeatable, well-characterized, stable flow. A thin BK7 glass window (1 mm thickness) was installed in the bottom test section wall downstream of the fuel supply section to allow for measurement of the fuel film thickness. Thus, the fuel film is well characterized prior to the change of geometry.

The second part of the test section consisted of a 45° sloped piece where the fuel droplets form. The angled piece is removable and can be replaced with different geometries as necessary. From the test section, the gas and fuel mixture flow to a liquid separator before venting into the building exhaust system.

Liquid fuel was found to accumulate at the end of the ramped section, and was then, on a relatively long time scale, driven back into main gas flow stream by the recirculation flow. To eliminate this bias to the droplet measurements, a system was devised to drain this accumulated liquid. A thin plate was mounted parallel to the lower wall of the test section. Liquid that flows under the plate is directed to a drain that was maintained under slight suction by a second peristaltic pump. In this manner, the liquid fuel was drained with minimal perturbation to the gas flow, especially in the region near the separation corner.

The liquid used for all of these experiments was low aromatic mineral spirits, having a dynamic viscosity of 9.97×10$^{-4}$ Pa·s, a density of 745 kg/m$^3$, and a surface tension of 0.024 N/m.

**Instrumentation**

The film thickness upstream of the separation point was measured using an optical sensor developed previously [5]. The sensor utilizes the total internal reflection of a diffuse point light source from the free surface of the film to determine the film thickness. The technique has been validated over the range of film thickness from 30 µm to 5 mm and has been widely used to measure shear-driven films in internal gas/liquid flows as well as the films formed by spray impingement on a flat surface [6-8].

Laser light is scattered from a light diffuser affixed to the bottom of the window. When the scattered light hits the film/air interface, most of the light is transmitted and a small part is reflected. At the critical angle, or angle of total internal reflection, all of the light is reflected. This light bounces back to the outer wall surface and hits the diffusive material, forming a light ring around the source. The diameter of the light ring is linearly proportional to the total distance that the light travels and can therefore be used to determine the film thickness. As shown in Shedd and Newell [5], assuming that the liquid surface is flat and parallel to the glass substrate, the film thickness $h$ can be calculated using the measured light ring ($d_{meas}$) and the diameter of the light ring without liquid present ($d_{dry}$).

$$h = \frac{d_{meas} - d_{dry}}{4}$$
\[ h = \frac{(d_{\text{max}} - d_{\text{dry}})}{4 \tan(\theta)} \]  

where \( \theta \) is the critical angle for total internal reflection between the liquid and the gas. In reality, the surface of the film is not flat and parallel at any given instant, but it has been verified that the mean of at least 70 measurements of a wavy thin film accurately represents the mean film thickness [9].

In this work, one hundred images of the resulting light ring were collected for each set of flow conditions at a frequency of approximately 50 fps. A typical light ring image is shown in Fig. 3. Thirty six data points were then obtained from each image, as shown on Fig. 3, resulting in 3600 values of the ring thickness per trial. These 3600 values were averaged and used to obtain a final film thickness.

A 2-component TSI Phase Doppler Particle Analyzer (PDPA) was employed for measurement of the droplet velocities and size distributions downstream of the step. The drop size measurements will be presented in a future publication, but in the current study only velocity data will be discussed.

The static and stagnation pressure upstream of the nozzle, and the test-section static pressure were measured in order to accurately determine the test section gas velocity. The pressure taps were made using modified 18 gauge needles affixed to the walls of the system. The pressure was measured with Omega PX138 differential pressure transducers coupled to a data acquisition card and LabView. A one-dimensional compressible, isentropic flow relation was used to estimate the test section gas velocity, which is defined to be the free stream gas velocity in the 3 x 1.5 cm section upstream of the film separation corner. Table 1 shows a comparison of the velocity obtained with the 1-D compressible flow relation and the droplet velocity measured 3 cm downstream of and 1 cm above the separation corner. Good agreement is seen between the two velocities. The air mass flow rates that were investigated led to high test section velocities (in excess of 200 m/s) and test section static pressures that were noticeably greater than atmospheric.

In order to directly investigate the phenomena of the liquid fuel film adhering to the step, a system was developed to measure the liquid that was drained from underneath the flap at the bottom of the test section. A programmable delay generator was used to externally trigger the peristaltic pump that delivers fuel to the test section. The gas flow was allowed to reach a steady state, and then the pump was activated for a programmed time, delivering a known mass of liquid into the test section. The process was repeated multiple times to allow a statistically meaningful sample to be collected. The system was also run with no gas flow to provide a direct measure of the volume of fuel delivered and collected in this system. The reported value of fuel fraction adhered is the ratio of the mass collected with the gas flowing to that acquired with no gas flowing.

**Results – Film Thickness**

The measured fuel film thickness is shown in Fig. 4 as a function of the air mass flow rate (see Table 1 to convert to test section velocity). Two trials were conducted at each condition to verify the repeatability of the system, which is seen to be quite good. The data in Fig. 4 show that the fuel film thickness is a function of both the liquid and gas flow rates. The film thickness is found to decrease with either an increase in the gas flow rate, or a decrease in the liquid flow rate. These trends can be easily understood with a simple mass conservation argument. Consider first a fixed liquid flow rate. As the gas flow rate is increased, the film feels a higher shear stress and accelerates, which must be balanced by a reduction in film height. Similarly, at a constant gas flow rate the shear stress on the film is nearly constant, but the mass flow rate is higher giving rise to a thicker film.

There are two important features that bear mention. First, the fuel film thickness is a dependent parameter in this geometry, i.e., is established by the dynamic force balance in the film. Second, the film thickness is independent of the gap through which the liquid is introduced provided that the film does not experience dry out. In part, it is believed that at low liquid flow rates, the gap height is not fully flooded with liquid, which leads to spatial variations in the film thickness and dry out.

**Results – Adhered Flow**

Figure 5 shows the adhered fuel fraction for three different liquid flow rates and a range of gas flow rates. The data are seen to be a strong function of the gas flow rate, but only a weak function of the liquid flow rate over the conditions tested. At low flow rates, the majority of the liquid is seen to remain adhered to the step, and only at the highest gas flow rates, which correspond to a velocity in excess of 200 m/s, does the liquid preferentially strip.

**Discussion**

In order to put the results of Fig. 5 in context, it is useful to compare with the models given by eqs. (3) and (4), but the calculation of the \( \text{Re} \) and \( \text{Ca} \) requires the film velocity. One-dimensional incompressible flow was assumed in the liquid to estimate the film velocity. Using this, the measured film thickness and the liquid volume flow rate define a mass-averaged film velocity. It is worth noting that the \( \text{Re} \) depends on the product \( \bar{U}_{\text{film}}h \), which under these assumptions only depends on the mass flow rate of liquid. This is a common assump-
tion in the treatment of shear-driven thin film flows that has been found to be useful in predicting other interfacial phenomena, such as the stripping of droplets from the film and the generation of waves [10].

Figure 6 shows contours of the critical turning angle for the separation of the liquid from the surface as function of Re and Ca using the recommended C=3. The step angle for the current experiments was 45°, but it can be seen in Fig. 6 that, at the highest Re and Ca shown, the critical turning angle is ~80°, indicating that under no conditions of the experiment would separation be observed. Thus, the approach of Maroteaux et al. does not quantitatively represent the present data well. Some improvement in the quantitative comparison can be achieved by reducing C, but there is a limit due to the physical interpretation of C.

The symbols shown on Fig. 6 are the data points calculated from the measurement conditions of the 45° step in our laboratory, i.e., the data shown in Fig. 5. As stated above, the liquid mass flow rate uniquely defines the Re, thus the vertical groupings observed in Fig. 6. The Ca scales with the film velocity, which increases with gas flow rate as indicated at the low liquid mass flow rate data points. Referring to Fig. 5, the lowest Ca points in any sequence were not found to separate from the step.

A more significant issue with the results of the Maroteaux instability analysis applied to the current data is that the scaling observed in the critical turning angle contours does not directly follow the experimental observations of Fig. 5. As discussed above, the mass flow rate of the liquid defines the Re, i.e., the Re does not depend on the gas flow conditions. The Ca depends on the gas flow conditions indirectly through the use of the measured film thickness in the determination of the film velocity (the film thickness does depend on the gas flow rate, Fig. 4). Based on the results of Fig. 5, one would therefore expect a weak Re dependence and a strong Ca dependence on the critical turning angle. However, the stability analysis approach shows a moderately strong dependence on both Re and Ca.

The film pressure calculated from (4) for the data acquired with the 45° step are shown in Fig. 7. The test section operates at or above ambient pressure, so (4) indicates that separation would never be predicted for these conditions, which is inconsistent with the results of Fig. 6. Increasing C, by a factor of ~20 would help the prediction ability.

There are, however, some features of the experiment that are captured by the scaling of the separation criterion of eq. (4). There is a strong dependence on the air mass flow rate when the two data points at the highest mass flow rate are considered. The lower liquid flow rates do not allow such high gas flow rates because the film is seen to dry out under those conditions. The dependence on the liquid flow rate appears to be over-estimated by (4). At the low gas flow rates, there is a significant difference in the film pressure, but the adhered film fractions in Fig. 5 were comparable.

Conclusion

This study has addressed the behavior of a thin liquid film encountering a geometric discontinuity, or sharp corner. This is an issue that is important to the modeling of many processes, including port fuel injection for internal combustion engines, but it has received relatively little attention in the open literature. An experimental apparatus was designed and fabricated to establish a well-controlled, uniform liquid film so that the mechanics of the film flow at the discontinuity could be isolated from other issues regarding the development of the liquid film flow. The results from this experiment and subsequent analysis show that the amount of liquid adhered to the wall after the discontinuity is a strong function of the shearing gas flow, and only a weak function of the liquid flow rate, contrary to other published findings. Thus, it is clear that further careful studies are required to identify the key physical mechanisms that control the flow of a thin liquid film at a sharp corner.

Nomenclature

Ca Capillary number
d light ring diameter
µ viscosity
Re Reynolds number
ρ density
θ critical angle for total internal reflection
U_film Average film velocity

References

Table 1. Air mass flow rate and velocities calculated based on 1-D compressible flow relation and measured using the LDV apparatus (3 cm downstream of and 1 cm above the step with a fuel flow of 0.98 g/s).

<table>
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<th>Mass flow rate (g/s)</th>
<th>$V_{1-D}$ (m/s)</th>
<th>$V_{LDV}$ (m/s)</th>
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<tr>
<td>384</td>
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Figure 1. Test apparatus. The flow cross section is shown above the figure at the indicated locations.

Figure 2. Close up view of the test section including the fuel delivery system and liquid trap design.
**Figure 3.** Representative light ring image with the determined ring locations shown.

**Figure 4.** Film thickness measurements as a function of gas velocity for the two highest liquid flow-rates. Partial film dry-out was observed for the lowest fuel flow.
Figure 5. Fraction of liquid fuel that remains adhered to the step for the 45° step.

Figure 6. Critical turning angle (marked on the contour, in degrees) for separation for the case where \( C = 3 \). The symbols are the data points collected with the 45° step.