1 INTRODUCTION

As liquid fueled combustion systems continue to be improved in order to achieve improved emissions performance and operability, the generation and control of the fuel spray plays an increasingly significant role. One reason is that the emissions of pollutants in exhaust streams is, to a greater or lesser extent, a function of the spray quality (mean drop size, size distribution, spatial and temporal distributions) irrespective of the actual combustion system used [1,2,3]. When a particular system is being developed, for example a Lean Premixed Prevaporized (LPP) gas turbine combustor, certain characteristics may be more important than others. For example, it is reasonable to expect that a small mean drop size spray will achieve a greater degree of vaporization in a given premix time than will a spray of larger mean drop size and, therefore, achieve a higher degree of premix in a given fuel injector. Similarly, the degree of uniformity of the spray may have an impact on temperature uniformity. Both of these features influence pollutant formation.

Reaction temperature uniformity may also have an impact on flame stability which could result in, or suppress, resonant pressure fluctuations via Rayleigh coupling. Additionally, a “steady” flow of fuel may not produce a “steady,” time-invariant, spray whose spatial distribution is the same at successive instances in time. As a result, detailed understanding of the phenomena occurring is necessary to further evolve these systems.

A simple, yet effective strategy for preparing the fuel and air mixture is the injection of the liquid into a crossflow from a wall port. Substantial efforts have been directed at the injection of plain liquid jets into a fully developed crossflow that have focused on breakup [4,5,6,7], penetration [8,9,10,11,12,13,14,15], and spray structure [4,8,16]. With the large number of studies conducted, a wide range of expressions for the penetration of a plain liquid jet into a crossflow from a wall has been developed. A number of those expressions follow the basic form expressed in Eq. (1).

\[
\frac{y}{d_o} = A q^b \left( \frac{x}{d_o} \right)^c
\]

Eq. (1)

One specific example [10] is shown in Eq. (2):

\[
\frac{y}{d} = 2.0 q^{0.50} \left( \frac{x}{d} \right)^{0.27}
\]

Eq. (2)

A more complex form [13] which encapsulated different “zones” of the jet breakup process is shown in Eq. (3).

\[
\frac{y}{d_o} = 9.91 q^{0.44} \left[ 1 - \exp \left( \frac{-x}{13.1 d_o} \right) \right] \times 1 + 1.67 \exp \left( \frac{-x}{4.77 d_o} \right) \\
\times 1 + 1.06 \exp \left( \frac{-x}{0.86 d_o} \right)
\]

Eq. (3)

More recently (e.g., [8]) expressions for the penetration of the jet into the crossflow based on (1) shadowgraphs (Eq. (4)) and phase Doppler interferometry (PDI) (Eq. (5)).

\[
\frac{y}{d} = 4.3 \bar{q}^{0.33} \left( \frac{x}{d} \right)^{0.33}
\]

Eq. (4)
\[ \frac{y}{d} = 0.51 \bar{q}^{0.63} \left( \frac{x}{d} \right)^{0.41} \]  

Eq. (5)

Comparing Eq. (4) and Eq. (5) suggests that the apparent penetration is dependent upon the measurement methods used. This issue was addressed explicitly in recent work \[17\] which led to further expressions for penetration based on the type of data utilized in the analysis as shown in Eq. (6) and Eq. (7).

\[ \frac{y}{d} = 3.17 \bar{q}^{0.33} \left( \frac{x}{d} \right)^{0.40} \]  

(PDI)

Eq. (6)

\[ \frac{y}{d} = 2.42 \bar{q}^{0.48} \left( \frac{x}{d} \right)^{0.24} \]  

(Shadowgraph)

Eq. (7)

Relative to the analyses presented for the few studies based on distillate fuels at gas turbine-like conditions \[12\], Eq. (8) and Eq. (9) are available for two ranges of momentum flux ratios as indicated:

\[ \frac{y}{d_o} = 1.57q^{0.36} \ln \left[ 1 + 3.81 \left( \frac{x}{d} \right) \right] \quad (q = 1-12, \quad W_{e aero} = 90-2120, \quad x/d = 2-22) \]

Eq. (8)

\[ \frac{y}{d_o} = 1.48 q^{0.42} \ln \left[ 1 + 3.56 \left( \frac{x}{d_o} \right) \right] \quad (q = 1-40, \quad W_{e aero} = 90 - 2120, \quad x/d = 2-22) \]

Eq. (9)

It is also worth noting an expression for penetration, presented as Eq. (10), which includes liquid properties and the aerodynamic Weber number, both of which reflect an effort to bring in the effects of atomization on the penetration \[9\].

\[ \frac{y}{d_o} = 2.63 q^{0.442} \left( \frac{x}{d_o} \right)^{0.39} We^{-0.086} \left( \frac{\mu_l}{\mu_{H_2O}} \right)^{-0.027} \]

Eq. (10)

With the large number of expressions, it is both helpful and insightful to compare the results. An example is shown in Figure 1 for a typical momentum flux ratio and crossflow velocity. Interestingly, the results vary substantially and fall into two general groupings. Since Eq. (8)-Eq. (10) were developed using conditions more representative of gas turbines, it is encouraging to see that Eq. (8) and Eq. (10) give similar trends.

In addition to the dependence on the measurement method (Eq. (6) vs Eq. (7)), another possible reason for discrepancies might be due to assumptions made in defining terms in the momentum flux ratio. In nearly all cases, the liquid jet velocity is determined by dividing the volumetric liquid flow by the physical liquid jet cross section. The squared dependency of the momentum flux causes small differences in the actual velocity of the liquid jet to significantly impact the predicted penetration. In previous work, the liquid jet discharge coefficient, which is directly related to the velocity of the jet for a given flow rate, has been assumed to be 1.0 To illustrate how this assumption might affects the results, Figure 2 shows the jet penetration using several of the correlations but with a 20% variation in discharge coefficient.

![Figure 1. Penetration of Various Correlations for water/air, q=10, U_cross=100 m/s.](image1)

![Figure 2. Comparison of Penetration with Variation in Discharge Coefficient.](image2)

Relative to practical gas turbine applications, injection from an injector exit flush to the wall may lead to issues with fouling. As a result, in practice, it may be preferred to recess the physical exit of the liquid injector from the wall surface. This recess yields a comparable geometry with ALR = 0.0 in previous work \[14\].

In summary, only a handful of studies have been conducted using distillate fuels at practical conditions and no studies have been reported that examine how recessing the jet influences the behavior. As a result, the objectives of the current study are:

- Collect data on the jet produced by a “recessed” liquid jet injector using high speed videography
for a distillate fuel under elevated pressure and temperature conditions

- Establish a model describing the penetration and behavior of the jet and examine the sensitivity of the results to the analysis protocols and assumptions made regarding velocities
- Compare the current results to existing correlations based on pure wall jet configurations

2 EXPERIMENT

2.1 Test Facility.

The test facility used in the study is shown in Figure 3 and is described in more detail elsewhere [14]. The pressure vessel and window arrangement used is designed to withstand 17 atm at 1200 °F. The test section is mounted within the main pressure vessel as shown and issues downward at a plane where various optical ports are available as shown in Figure 3b.

For the present study, the liquid flow rate was monitored using a coriolis meter (Micromotions®). MIL-PRF-7024 Type II, a distillate similar to Jet-A, but with tighter specifications for use in research, was used as the test liquid and the key properties are summarized in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Tension</td>
<td>24 dyne/cm, T = 298 K</td>
</tr>
<tr>
<td>Density, specific</td>
<td>0.770, T = 289 K</td>
</tr>
<tr>
<td>Viscosity, cSt</td>
<td>1.20, T = 298 K</td>
</tr>
</tbody>
</table>

Air flow is metered using a Sierra Instruments mass flow meter and is controlled using a Fischer Proportional Integral Differential (PID) controller and a pneumatically actuated valve. PID controllers utilize three calculus operations as feedback to minimize error. As shown in Figure 3, the air to the crossflow is fed from a plenum. A window purge system was utilized to minimize fouling of the windows.

2.2 Test Section.

The test section, shown in Figure 4, is a straight 2-D duct. A liquid jet is formed by passing fuel through an orifice located in one wall of the test section. The test section flow area was 1500 mm². The injector is a plain orifice, 0.029" (0.74 mm) diameter. The orifice is located at the entrance to a short tube, 0.3" (7.6 mm) long by 0.09" (2.29 mm) internal diameter, which shields the jet as it passes through the test section wall.

Figure 3. Schematic of Elevated Pressure Facility.

Figure 4. Test Section.
2.3 Diagnostics.

Imaging of the jet was accomplished using a variety of video resources. Two video cameras, a single speed (30 fps) Toshiba 1KM41A, fitted with a telephoto lens (Fujinon), and a high speed camera (Redlake MotionScope PCI) fitted with a Nikon 35-70 mm zoom lens captured backlit images either to tape or to digital media, respectively.

Figure 5 illustrates the setup for the imaging work.

3 RESULTS

Images were obtained at 500 frames per second with an exposure time of 1/10,000 second. For the present work, time averaged results were sought in order to compare penetration expressions. Time averaged images were obtained by extracting individual frames of the *.avi file and generating *.tif files. The 100 tif files were then averaged using image-processing software. In order to determine the penetration, an algorithm based on pixel intensity was used. Figure 7 illustrates the orientation.

Figure 6. Relation Between Expected Breakup Mode and Conditions Studied.

2.4 Test Conditions.

Results were obtained for a number of conditions for the range shown in Table 2. Liquid flows were varied to span typical operating conditions. In addition, cases that over- and under-penetrated were included to facilitate development of correlations describing penetration.

Figure 6 shows the relationship between the expected breakup mode [8] (shear or column) and the current conditions. The majority of the conditions are predicted to result in shear mode breakup.

Table 2. Summary of Parameter Ranges.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, K</td>
<td>350</td>
<td>475</td>
</tr>
<tr>
<td>Pressure, bar</td>
<td>3.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Crossflow, m/s</td>
<td>85</td>
<td>112</td>
</tr>
<tr>
<td>Momentum Flux Ratio</td>
<td>2.2</td>
<td>75</td>
</tr>
<tr>
<td>We</td>
<td>700</td>
<td>1580</td>
</tr>
</tbody>
</table>

Because of the dependency of the results upon the nature of the diagnostics [17], the approach for determining penetration in the present study is explained here in detail. Above the edge of the spray plume, the background intensity is relatively uniform in the y direction. The maximum intensity at any given \( x_i \) is \( I_{\text{max}, x_i} \). The minimum intensity within the spray plume is \( I_{\text{min}, x_i} \). The difference between these two intensities is then noted. A threshold, “THRESH,” is taken as a percentage of this difference. The intensities along the y-axis at each \( x_i \) position are noted until the y coordinate corresponding to the “edge” is found for that particular \( x_i \), according to Eq. (11).

\[
y_{\text{edge}, x_i} = \text{THRESH} \times \left( I_{\text{max}, x_i} - I_{\text{min}, x_i} \right)
\]

Eq. (11)

Sensitivity to the value THRESH was carried out by repeating the calculations from Eq. (11) for different values ranging from 20 to 80%. The variation in \( y/d \) is about ±1. This variation is taken as the general uncertainty in the \( y/d \) values for the subsequent analysis.

3.1 Comparison with Previous Results.

Penetration results for a range of momentum flux values for the present study are compared with existing correlations in Figure 8.

The correlations used for comparison are based on imaging and/or reflect those based on most relevant conditions and liquids. The results reveal two principal observations. First, significant variations in the predictions are again seen. Second, the current results are not well predicted by the correlations. This may not be surprising given the recessed jet. If the recess of \( y/d = 10.3 \) is added to the measured penetration (effectively moving the jet exit to the wall), the results approach those predicted by Eq. (7) and Eq. (9) for the higher momentum.
flux ratios (Figure 8c,d), but not for lower momentum flux ratios (Figure 8a,b).

Figure 8. Comparison of Current Results with Previous Penetration Expressions

To provide a more detailed comparison of a recent correlation,

Figure 9 presents the predicted penetration from Eq. (7) to the current study. Some of the results appear grouped (momentum flux ratios less than 50) but the agreement is poor.

Next the data were compared to Eq. (10) in which the Weber number and fluid properties are taken into consideration. The results Figure 10 show better grouping than those in Figure 9, suggesting that Eq. (10) may be able to predict the penetration up to a momentum flux ratio of approximately 50. However, the actual one-to-one predictions are not accurate.

Figure 9. Comparison of Eq. (7) with

Figure 10. Comparison of Experimental Data with Eq. (10) Correlation. Current Study.

3.2 Correlation Refinement.

Because of the inability of the existing correlations to describe penetration in the present study, further analysis was conducted to improve the performance. As a first step, the form of Eq. (7) was maintained, but the coefficients were modified. Since the behavior of the cases with momentum flux ratios above 30 fell away from the rest of the data, these were excluded. The best correlation coefficients ($R^2 = 0.986$) were obtained with the following formulation:

$$\frac{Y}{d} = 0.92 \bar{q}^{0.33} \left( \frac{X}{d} \right)^{0.33} \quad (2 < q < 30)$$

Eq. (12)
The relatively low value of 0.92 vs. 2.42 found previously (Eq. (7)) may be associated with the recessed nature of the liquid jet exit in the present case. However, the exponent values are similar to those found previously (Eq. (7)) despite differences in liquid properties and conditions [17]. The predicted vs. measured penetration results shown in Figure 11 show excellent agreement.

A similar analysis was carried out with the form of Eq. (10). Because the q = 75 data fall away from the rest of the data, they were excluded in the analysis. A nonlinear multivariate regression analysis was conducted and the following optimized formulation was obtained:

\[
\left( \frac{y}{d_o} \right) = 15.0 q^{0.7} \left( \frac{x}{d_o} \right)^{0.33} W e^{-0.41} \left( \frac{\mu_t}{\mu_{H_2,0}} \right)^{-0.027} \quad (2 < q < 50)
\]

Eq. (13)

The comparison is shown in Figure 12. The agreement between the predicted and measured values is not as satisfactory as it is for Eq. (12) (R^2 = 0.944), but the results of Eq. (13) are still good. It also allows higher values of q to be considered. The coefficients for momentum flux ratio and downstream distance are the same as for Eq. (12), but much greater values of constant and the Weber number exponent were found necessary. This again is attributed to the recessed jet. Because the jet is sheltered for y/d of ~10, the Weber number of the jet (once it reaches the crossflow) is an “effective” number since the column diameter differs from the injector diameter.

The penetration of a distillate liquid fuel jet, injected from a recess into a crossflow at elevated temperature and pressure, has been characterized experimentally, quantified, and modeled. The results show that while previous correlations do not describe the behavior adequately, modified forms of two expressions are found to work well. In particular, the inclusion of the Weber number increases the range of momentum flux ratios that can be described.

\[
\frac{y_j}{d} = 0.92 q^{0.58} \left( \frac{x}{d} \right)^{0.33} \quad (2<q<30)
\]

\[
\frac{y_j}{d_o} = 15.0 q^{0.5} \left( \frac{x}{d_o} \right)^{0.33} W e^{-0.41} \left( \frac{\mu_t}{\mu_{H_2,0}} \right)^{-0.027} \quad (2<q<50)
\]

These equations serve as models that can be used by a designer to predict liquid fuel penetration from either flush wall or recessed jets in advanced combustors. Jet injection from a recessed jet allows higher momentum flux ratios to be used with moderate penetration. This provides a strategy to improve fuel turndown without (1) sacrificing penetration, (2) increasing the potential for fouling, and (3) degrading pollutant emission.

5 NOMENCLATURE

- \(A\) constant
- \(B\) constant
- \(C\) constant
- \(d\) jet diameter [m]
- \(I\) intensity [A.U.]
- \(y\) distance from wall [m]
- \(x\) downstream distance from centerline of wall jet [m]
- \(q\) momentum flux ratio \(\frac{\rho U_j^2}{\rho U_c^2}\)
- \(U\) average velocity [m/s]
- \(We\) Weber Number \(\frac{\rho U_j^2 d}{\sigma}\)
- \(\rho\) density [kg/m^3]
\[ \mu \text{ viscosity} \quad [\text{cSt}] \]

\[ \sigma \text{ surface tension} \quad [\text{dyne/cm}] \]

Subscripts

\[ c \text{ crossflow} \]

\[ i \text{ index} \]

\[ j \text{ jet} \]

\[ L \text{ liquid} \]

\[ m \text{ maximum flux} \]

\[ \min \text{ minimum} \]

\[ \max \text{ maximum value} \]

\[ o \text{ initial} \]

\[ t \text{ top edge} \]

6. ACKNOWLEDGMENTS

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7. REFERENCES


