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Breakup of volatile liquid jet in hot cross flow

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Abstract

Liquid jet in cross flow has been a widely studied subject although most of the experimental work has been carried out at ambient conditions. The present study involves the investigation of the behavior of an ethanol jet injected into a cross flowing air at elevated temperatures up to 418 K. Spray parameters such as the trajectory and drop size distributions are measured and compared for cold and hot flow conditions. Experiments are conducted for a range of liquid-to-air momentum ratios (Q) ~ 4 – 13 and for Aerodynamic Weber numbers (We) ~ 15. Though most of the existing literature attributes the effect of elevated temperature on the effective change in Q due to density variation, the present study shows interesting observations where the results vary in spite of maintaining similar magnitudes of Q between cold and hot flow conditions. It is observed that a higher trajectory is consistently manifested by the ethanol jet at elevated temperatures as compared to that found at ambient temperatures. It is proposed that the physical parameter, density ratio, needs to be considered as an additional parameter to account for these differences. Therefore, a new trajectory correlation is proposed which is observed to match experimental data at different temperatures. The drop size measurements indicate considerable amount of evaporation of the fine droplets formed at the leeward portion of the resultant spray of ethanol jet in cross flow.

Keywords:

1. Introduction

Liquid jet injected into gaseous cross flow finds direct relevance predominantly in aerospace applications – combustors of gas turbine engines, lean premixed prevaporizer (LPP) chambers, afterburners, ramjet engines being the most important ones. The topic has regained prominence in the recent past due to rising costs of the fuel and the necessity to improve the efficiency of fuel consumption. The behavior of liquid jet subjected to gaseous cross flow has been studied by various experimental groups. While most of the studies have been conducted in ambient...
conditions [1, 2], a few of them have been carried out at elevated pressure [3] and temperatures [4]. The most relevant non-dimensional numbers associated with the physics related to this problem are aerodynamic Weber number (We) and the liquid-to-air momentum ratio (Q) [1-3]. The experimental investigations of the influence of elevated pressure and temperature have primarily attributed the behavior of the liquid jet to the change in density of the gaseous medium; however, this effect was thought to be accounted for by the momentum ratio parameter. There is a general consensus in the previous literature that the trajectory followed by a liquid jet in cross flow is primarily dependent on the momentum ratio. However, one of the recent studies [5, 6] has also reported that the correlation for trajectory at elevated pressures and temperatures not only depends on the effective magnitudes of Q but also on We and Reynolds numbers of the two fluids.

The present study is an attempt to investigate the effect of cross flow at elevated temperatures on the breakup process of the volatile liquid jet with the objective of verifying the dependence on the above stated non-dimensional numbers. Ethanol being one of the more volatile liquid fuels, is used in the present study. The experiments are conducted for ambient conditions and at two higher temperatures, T ~ 373K and 418K. The liquid-to-air momentum ratios are maintained constant for different temperatures. The trajectory of the jet in cross flow is known to strongly depend on the momentum ratio [1] and by maintaining it constant, the variability effect of Q is negated. The other non-dimensional number, We, is known to dictate the transition between the different regimes of jet breakup [1] and does not have a direct effect on the jet trajectory. It is to be noted that the experiments are carried out at the lower range of Q (4-13) and We (4-13) so as to allow greater residence times for the ethanol droplets in the hot environment before exiting the test section. The following sections describe the experimental setup used to carry out this work and discuss the results obtained.

2. Experimental Setup

The schematic of the experimental setup employed for the current study is shown in Fig. 1. The source of air is a receiver tank kept pressurized by a positive displacement compressor. High mass flow rate regulator aids in
controlling the air flow to the test section. An electrical heater is installed in-line ahead of the test section to heat the incoming air. The test section has a square cross section of 54mm X 50mm. The peak heater capacity gives a flow rate of 29 m/s in the test section at 418K. The source of liquid is again a pressurized liquid tank and a mass flow controller is used for liquid injection. The properties of ethanol, the liquid used in the experiments, are listed in Table 1. The injector has an orifice diameter (d) of 0.5mm having an L/D ratio of 100, so as to promote a faster breakup of the cylindrical liquid jet.

Flow visualization is carried out with the aid of shadowgraph imaging which involves using a fluorescent diffuser illuminated by a Nd:YAG laser for background illumination. These high quality images are processed to obtain data on spray trajectory. Drop size measurements are also carried out using PDA technique [7], by zooming into a smaller area (15mm x15mm) with lower camera exposure time to avoid streaking of droplets. A laser pulse width of around 4-ns provides background illumination of the order of 20-ns to produce instantaneous near-frozen images without producing any streaking of high velocity droplets. A schematic of the arrangement is shown in Fig. 2. More details of the setup can be found elsewhere [8].

![Figure 1: Schematic of the arrangement of laser diagnostcis used for flow visualization.](image)

### 3. Results and Discussion

The liquid mass flow rate was varied between 0.3 – 0.5 g/s to analyze the variation of trajectory of the liquid jet at different Q values at each air-temperature setting. The velocity of the air stream is adjusted so as to maintain a constant momentum ratio. The aerodynamic Weber, We, also remains a constant as the numerator \( \rho v^2 \) remains the same. There is no variation in surface tension (\( \sigma \)) since the liquid is injected at room temperature.

<table>
<thead>
<tr>
<th>Properties of Ethanol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>790 kg / m³</td>
</tr>
<tr>
<td>Viscosity</td>
<td>( 1.03 \times 10^{-3} ) Pa.s</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>0.022 Nm</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>78.4 °C</td>
</tr>
<tr>
<td>Diffusivity in air</td>
<td>( 1.03 \times 10^5 ) m²/s</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>46</td>
</tr>
</tbody>
</table>
3.1. Jet Trajectory

It is observed from the experimental investigation that there is an increase in jet penetration at elevated temperatures. This behaviour may be observed in Figs. 3 and 4 for different temperature conditions. While instantaneous images are shown in Fig. 3, Fig. 4 shows the time-averaged processed images. Here it is clear that the liquid jet consistently tends to have higher penetration at elevated temperatures. What is interesting is that this is manifested in spite of maintaining similar momentum ratios. This indicates that the assumption of dependence of jet penetration solely on momentum ratio may not be correct. It is clear that the density ratio of the two fluids is playing a role on the jet trajectory. The time-averaged images also indicate the presence of spatial fluctuations of the jet when seen in comparison with instantaneous images. The processed images are also utilized to extract the windward trajectory of the resultant spray on the same lines as is prevailing in the literature which is of the form

\[ (y/d) = a \cdot (x/d)^b \cdot Q^c \]  

(1)

Since the standard expression only accounts for the effective momentum ratio, we obtain different exponential values of \( b \) and \( c \) for different temperatures. The corresponding expressions are as mentioned below:

\[ (y/d) = 1.01 \cdot (x/d)^0.49 \cdot Q^{0.50} \]  

at Ambient conditions (\( T = 298 \) K) \hspace{1cm} (2)

\[ (y/d) = 1.05 \cdot (x/d)^0.53 \cdot Q^{0.49} \]  

at \( T = 373 \) K \hspace{1cm} (3)

\[ (y/d) = 1.07 \cdot (x/d)^0.56 \cdot Q^{0.48} \]  

at \( T = 418 \) K \hspace{1cm} (4)

Figure 3: Trajectory of the liquid jet observed to vary with increasing temperatures at different values of \( Q \). The jet penetrates further at higher temperatures.
Figure 4: Processed images obtained by time-averaging the instantaneous images shown in Fig. 3.

Figure 5: Comparison of trajectory correlation with experimental data. The variable parameters for the shown cases are – (a) $a = 1.01$, $b = 0.49$, $c = 0.50$; (b) $a = 1.05$, $b = 0.53$, $c = 0.49$; (c) $a = 1.07$, $b = 0.56$, $c = 0.48$. Thus, it is seen that the exponents vary for different temperatures.

Figure 5 also shows that different expressions are needed to match the experimentally obtained trajectories at different temperatures. It may be evident from these observations that the standard expression alone is inadequate to represent the trajectories at different air temperatures which result in changes to the effective density ratio between the two fluids. While the exponents of $Q$ do remain fairly constant, the change in trajectory is reflected in the exponent of $(x/d)$. However, it is to be recognized that $(x/d)$ is not the dictating factor when there is a change in operating flow conditions. Thus, it is clear that Equations 1-3 cannot be effective correlations for the trajectory, and there is clearly a need to derive a universal correlation which can work at different temperatures and also pressures. One strategy to overcome this problem is to account for the effect of density ratio on trajectory. Therefore, an
additional term representing the density ratio of the two fluids \( D = \rho_f / \rho_g \) is included in the correlation for trajectory. The new expression now reads as follows:

\[
(y/d) = a \cdot (x/d)^{0.5} \cdot Q^d \cdot D^e
\]  
(5)

Experimentally obtained trajectories are utilized to derive the exponents for momentum and density ratios. It may be noted that the exponent of \((x/d)\) is retained from the previous studies. These new exponents \(d\) and \(e\) are found to maintain constant values for different temperatures. The magnitudes of \(d\) and \(e\) are calculated to be 0.45 and 0.05, respectively. The derived trajectories from the modified expression are compared with experimental data points and are shown in Fig 6. Thus, the new expression effectively reads as follows:

\[
(y/d) = 1.1 \cdot (x/d)^{0.5} \cdot Q^{0.45} \cdot D^{0.05}
\]  
(6)

![Image of graphs](image)

Figure 6: Comparison of experimental penetration data with the proposed correlation.

It may be observed from Fig. 6 that this equation for trajectory matches reasonably well with experimental data at different temperatures. Though the magnitude of \(e\) appears to be small, it is to be noted that \(D\) happens to be a large number and thus, this term tends to have an appreciable effect on the trajectory. The present approach is promising enough to warrant further comparisons with data at higher temperatures and pressures.

3.2. Droplet Sizing

The drop sizes measurement is carried out at two downstream locations – 50 mm and 150 mm – translating to 100 and 300 diameters of the injector orifice as depicted in Figure 7. Table 2 lists the drop size variation at these locations at room temperature and at an elevated temperature of 145ºC. Even though there are no visible differences in the breakup structures under hot flow conditions when compared to ambient conditions, there seems to be an effect on the extent of atomization as indicated by drop size measurements.

While the drop sizes are higher for hot flow condition at 100 diameters downstream, they are lower at the bottom of the spray (station-b) at 300 diameters downstream location. It is to be noted that there are fine droplets formed at the leeward (lower) periphery of the spray due to the shear stripping mechanism. Therefore, these droplets tend to evaporate as they travel from \(X=100\) diameters location to the next measurement station downstream. It is observed that the number of droplets at location-b (in Fig. 7) reduces by 55% when compared to number of droplets at location-a, under ambient temperature conditions. This reduction in number of droplets increases to 84% for an elevated temperature of 418 K. This indicates that there is significant evaporation of droplets at the elevated temperature case. The higher percentage of droplet-count at the lower station (station-b) of the ambient case indicates that the smaller drops may not have undergone evaporation because of the lower temperature. The PDF of
the drop sizes measured for the hot condition is shown in Fig. 8. It may be observed that the distribution shifts toward the lower drop sizes as we move downstream from the point of injection. This behaviour also indicates that the drops are undergoing evaporation and reduce in size. The preferential evaporation of droplets in terms of their size and spatial location (mostly happening at the bottom periphery) gives rise to a possible situation of non-uniform spatial distribution of differently sized droplets. This may be the reason for the higher SMD value observed at location-c for hot flow conditions.

Table 2. Droplet diameter variation in stream-wise direction for cold and hot flows.

<table>
<thead>
<tr>
<th>Location (axial distance)</th>
<th>X=50mm (Location ‘a’ in Fig. 7)</th>
<th>X=150 mm (Location ‘b’ in Fig. 7)</th>
<th>X=150 mm (Location ‘c’ in Fig. 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMD in microns (T=298K)</td>
<td>308</td>
<td>335</td>
<td>437</td>
</tr>
<tr>
<td>SMD in microns (T=418K)</td>
<td>422</td>
<td>308</td>
<td>470</td>
</tr>
</tbody>
</table>
4. Conclusions

The breakup of an ethanol liquid jet in cross flow is studied under ambient and elevated cross flow temperatures. Important spray parameters such as the spray trajectory and drop size distributions are measured and analyzed. The experimental data is then utilized to obtain trajectory correlations for cold and hot flow conditions. It is observed that the conventional form of the trajectory equation requires corrections to its coefficients and exponents in order to accurately predict the trajectories at higher temperatures. It is recognized that the momentum ratio (Q) by itself is not able to account for spray trajectory variation. The need to derive a universal correlation which is applicable at different temperatures is shown and addressed. A new expression for spray trajectory is proposed to capture the effect density ratio by including it as an additional term. The trajectory correlation thus derived is observed to satisfactorily predict spray trajectories for different temperatures. The proposed trajectory correlation shows sufficient potential to warrant further experimental validations over a wider range of temperatures and pressures. Drop sizes measurements are carried out at two downstream locations, 50-mm and 150-mm corresponding to 100 and 300 injector orifice diameters, respectively. The data shows evidence of significant evaporation, particularly at the leeward side. This causes a shift in drop size PDF towards lower drop values as we move downstream and also causes spatial variations in SMD of droplets as compared to the ambient condition.

References