Response of Spray Formed by Liquid Jet Injected into Oscillating Air Crossflow

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Abstract
Experimental results on the characteristics of near-field (up to x/D=8) spray formed by a liquid jet injected into an oscillating air crossflow are presented. The modulation frequency is varied from 90 Hz to 450 Hz and the crossflow velocity (25-100 m/sec) and ambient pressure (2-3 atm) are systematically changed to investigate the spray response to modulated crossflow velocity over a range of crossflow Weber number (18, 60 and 175). Shadowgraph is used to visualize near field spray. The response of spray to modulated crossflow is characterized quantitatively in terms of upper penetration boundary and the corresponding change of momentum flux ratio is calculated based on an empirical correlation for upper penetration boundary. Spray response to modulated crossflow is found to depend on Weber number as well as modulation frequency.
Introduction

Liquid jet injection into steady crossflow air which is used frequently for fuel injection in many practical combustion devices has been a topic of numerous studies [1-4 and references therein]. Under unstable combustion caused by combustion dynamics, the resulting acoustics can also affect crossflow velocity as well as the fuel injection process and the subsequent fuel/air mixing and heat release may cause either favorable or unfavorable effect on combustion dynamics. Few reports [5-8] have been made on how spray responds to modulating crossflow. However, the spray response is described mainly in qualitative manner and the spray characteristics of liquid jet in oscillating air flow are not well understood yet. Hence, more quantitative understanding of the spray response to oscillating air crossflow is warranted.

The objective of this study is to characterize the near-field spray formed by a liquid jet injected into oscillating air crossflow in quantitative manner. The response of spray to modulated crossflow is characterized in terms of upper penetration boundary and the corresponding change of momentum flux ratio is calculated based on an empirical correlation for upper penetration boundary.

Experimental Methods

The experimental apparatus used in this paper is a horizontal test rig which consists of four major systems: an air supply system, a modulation device, a test section and a liquid fuel supply system.

A main feature of the setup is the use of a modulating device (siren) to impose a periodic modulation of cross flow rate at the frequency up to 500 Hz. It consists of a stator and a rotor and the amount of crossflow velocity fluctuation at the injector location can be adjusted by varying the amount of air passing through the siren and bypass air which does not go through the siren while maintaining the total air flow rate constant.

The test section (shown in Figure 1) is made from stainless steel plates with interior dimensions 31.8mm in height and 25.4mm in width. On the sides and on top, fused silica windows are used to provide optical access up to the axial distance of 200d from the injector plane. The fluctuating crossflow velocity is measured using the two-microphone method: two dynamic piezoelectric pressure transducers (Model 112A22 PCB Electronics) are mounted so that the velocity fluctuation at the injector location is measured.

The test fuel is water which is dispensed from pressurized tank by nitrogen. The flow rate of the test fuel is monitored by a rotameter calibrated at over a range of pressure drop. The metered water is then passed through a 60µm filter and injected into the test section through a simple-orifice injector which has a diameter of 0.508mm (0.02 inches). The injector is divided into three sections namely an inlet section of 1.4mm diameter, a tapered transition section (90° angle) and an exit section whose aspect ratio (l₀/d₀) is 5.5. The injector tip is flush mounted with the floor of the test section.

Table 1 lists the operating condition used.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
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<tbody>
<tr>
<td>Mean Crossflow velocity (u_a)</td>
<td>25-102 m/sec</td>
</tr>
<tr>
<td>Liquid jet velocity (u_j)</td>
<td>5-22 m/sec</td>
</tr>
<tr>
<td>Liquid momentum flux ratio (q)</td>
<td>10 and 18</td>
</tr>
<tr>
<td>Weber number (ρ_ju_j²/ρ_au_a²)</td>
<td>18, 60 and 175</td>
</tr>
<tr>
<td>Mean crossflow temperature (T_c)</td>
<td>293 K</td>
</tr>
<tr>
<td>Chamber pressure (P_c)</td>
<td>2 and 3 atm</td>
</tr>
<tr>
<td>Liquid (water) density</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Crossflow modulation level (u_a'/u_a)</td>
<td>5-20 %</td>
</tr>
</tbody>
</table>

The near-field spray around injector location is characterized using a high-speed shadowgraph. A solid state lamp (HPLS-30-04, Thorlabs) is used as a light source and the shadowgraph is recorded by a high speed camera (Phantom V411, Vision Research) whose frame rate is fixed at 10000 frames/sec.

Results and Discussion

Figure 2 shows a sequence of typical instantaneous shadowgraph images during one period of crossflow modulation at 90 Hz, exhibiting the liquid column trajectory varies in response to modulating crossflow.

However, if the modulation frequency changes to 450 Hz by keeping flow condition the same, it can be qualitatively seen that the variation of column trajectory is not as much as shown in Figure 3.

Figure 2 A sequence of instantaneous shadowgraph images for crossflow modulation at 90 Hz (P_c= 30 psi, Wc=18, q=18 and u'/u=10%).
Figure 3 A sequence of instantaneous shadowgraph images for crossflow modulation at 450 Hz (Pc=30 psi, We=18, q=18 and u’/u=10%).

Figure 4 A sequence of instantaneous shadowgraph images for crossflow modulation at 90 Hz (Pc=30 psi, We=175, q=18 and u’/u=10%).

Figure 5 Typical predicted trajectory (in line) of upper boundary of spray overlaid on shadowgraph images for We=18 (left) and We=175 (right).

Figure 6 Time trace of calculated momentum flux ratio for f=90 Hz (top) and f=450 Hz (bottom).

Figure 7 FFT of amplitude of calculated momentum flux ratio.

The correlation is used to calculate the corresponding momentum flux ratio for instantaneous shadowgraph image: an upper spray trajectory is extracted from an instantaneous shadowgraph image and curve-fitted to the correlation to calculate the corresponding momentum flux ratio. Figure 6 shows typical time traces of calculated momentum flux ratio for the mean momentum flux ratio of 18, clearly indicating that the near-field spray penetration changes with respect to crossflow Weber number as well as modulation frequency.
Also, it should be noted that the modulating crossflow contains frequency components at higher harmonics as well as fundamental frequency. As a result, the calculated momentum flux ratio also exhibits responses at higher frequency (e.g. \( We=18 \) and \( f=90 \) Hz).

Figure 7 shows results of Fast Fourier Transform of deduced momentum flux ratio for the modulation frequencies of 90 and 450 Hz at the Weber number of 18. For the case of modulation frequency of 90 Hz, the amplitude of calculated momentum flux ratio is about 6.5 with smaller amplitude at higher harmonic frequencies. However, for the modulation frequency of 450 Hz, the amplitude of momentum flux ratio is very low (less than 0.5).

Another interesting question regarding the effect of modulation frequency on the near-field spray is if the upper penetration boundary would response quasi-steadily to the crossflow modulation. In order to quantify the degree of quasi-steadiness of spray response, the measured amplitude of spray upper penetration change for modulated flow is normalized by the corresponding calculated amplitude of momentum flux ratio to the modulated velocity at given frequency. Figure 8 shows its results. At the modulation frequency of 90 Hz (450 Hz) the measured amplitude of fluctuating momentum flux ratio is greater (smaller) than the calculated momentum flux ratio.

**Summary and Conclusion**

Experimental results on the characteristics of near-field (up to \( x/D=8 \)) spray formed by a liquid jet injected into an oscillating air crossflow are presented. The response of spray to modulated crossflow is quantified in terms of the amplitude of fluctuating upper penetration boundary and the corresponding change of momentum flux ratio is calculated based on an empirical correlation for upper penetration boundary.

Spray response to modulated crossflow is found to depend on Weber number as well as modulation frequency. The amplitude of upper penetration boundary fluctuation of liquid column decreases as the Weber number increases. Also, for a fixed weber number the amplitude of upper penetration boundary’s fluctuation decreases as the crossflow modulation frequency increases.

**References**