Trajectory of a Liquid Jet in High Pressure and High Temperature Subsonic Air Crossflow

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Abstract

Atomization of a liquid jet by impaction of a crossflow air stream is a robust and versatile spray generation technique with applications in gas turbines and aerospace industry. Parameters such as jet penetration, trajectory and deflection are required prior to the design of the combustion chamber in these types of engines. In this paper, the breakup and atomization characteristics of a liquid (water) jet under atmospheric and elevated pressures and temperatures are studied at steady state conditions. Images for more than 220 test conditions were obtained, using pulsed laser sheet illumination technique. The obtained images were averaged and filtered and then the spray center and windward trajectories were calculated using an automated method. Using a regression analysis, two correlations were obtained for the trajectories of spray windward and center as a function of liquid to crossflow air momentum ratio, channel and liquid jet Re numbers. These correlations are reliable tools for design of atomization chambers.

Introduction

There are numerous papers available in the literature concerning the atomization of liquid jets in a crossflow air stream, owing to its wide applications in fuel injectors in aircraft engine afterburner sections, rockets, ramjets, scramjets and in stationary applications such as gas turbines. This is because jet and spray characteristics, such as jet penetration, trajectory and deflection, and spray characteristics such as droplet size and distribution, and droplet velocity directly affect the combustion process, and consequently the fuel consumption and the combustor performance. Leong et al. [1] reviewed the literature concerning spray and jet in crossflow under subsonic and supersonic conditions.

One of the important characteristics of jet and spray in crossflow is the jet penetration and spray trajectory which directly affects the chamber dimensions and design. There are several theoretical and experimental research works available in the literature, which address the jet breakup and trajectory. Wu et al. [2] experimentally and rather theoretically analyzed the breakup and atomization of a liquid jet injected into a subsonic crossflow air stream. They identified two breakup modes as the column breakup and shear breakup. They combined their experimental data of four liquids with a force analysis and correlated the jet trajectory with the liquid to air momentum flux ratios (q), (q ~ 4-185; D ~ 0.5, 1, 2 *mm*; V_j ~ 9-38 *m/s*; U_∞ ~ 70-141 *m/s*):

$$\left(\frac{y}{D}\right)=1.37\sqrt{q\frac{x}{D}} \qquad (1)$$

This is in general a valid conclusion that the spray trajectory is mostly controlled by the momentum ratio; however, as shown in this paper in many cases this ratio is not adequate in predicting the jet trajectory, particularly in elevated conditions. Tambe et al. [3] studied the jet and spray characteristics of jet in subsonic crossflow for three liquids (q ~ 1-10; D ~ 0.38, 0.76 *mm*; V_j ~ 3-26 *m/s*; U_∞ ~ 89-215 *m/s*). They correlated the jet trajectory with q, similar to Wu et al. [2], although they showed their correlation in a logarithmic form:

$$\left(\frac{y}{D}\right)=1.55q^{0.53}\ln\left(1+1.66\frac{x}{D}\right) \qquad (2)$$

Both correlations (1) and (2) were obtained at room temperature and atmospheric pressure. This is due to the difficulties associated with the design, constructing and operation of the apparatus and conducting experiments under

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more realistic conditions, i.e. elevated pressure and temperature that most of the research works have been limited to the atmospheric conditions or either elevated pressure or temperature. Becker and Hassa [4] studied the breakup and atomization of a kerosene jet in a crossflow at room temperature and elevated pressure of up to 15 bars (q ~ 1-40; D ~ 0.45 *mm*; U_∞ ~ 50-100 *m/s*, *We* ~ 90-2120). Using Mie scattering and shadowgraph techniques, they studied the effect of parameters such as the crossflow air velocity and the liquid to air momentum ratio (q) on breakup mode, jet penetration and trajectory. They constructed a map to correlate the breakup mode (column or surface) to the momentum ratio and the aerodynamic Weber number (based on air velocity and density, nozzle diameter and liquid surface tension). Their correlation for spray trajectory is as follows:

$$\left(\frac{y}{D}\right) = 1.48q^{0.42}\ln\left(1+3.56\frac{x}{D}\right) \tag{3}$$

Cavaliere and his coworkers e.g. [5] have performed jet in crossflow experiments at both elevated pressure and temperature. However, they produced the required air flow rate by pre-storing air in a tank and subsequent opening of a pneumatic valve. This operation may be able to simulate the actual process to some extent, but it is definitely different from the steady state conditions. In one study [5], water and Jet-A1 was used at pressures up to 2 MPa and temperatures upto 600 K (q ~ 5-280; D ~ 0.3, 0.5 *mm*; V_j ~ 10-55 *m/s*; U_∞ ~ 20-55 *m/s*). Their correlation is more sophisticated as it considers more parameters than the previous ones, i.e. Eqs. (1)-(3):

$$\left(\frac{y}{D}\right) = 2.28q^{0.422}We_{Vj}^{-0.015}\left(\frac{\mu}{\mu_{air,300K}}\right)^{0.186}\left(\frac{x}{D}\right)^{0.367} \tag{4}$$

Other correlations may be found in [6] where the authors have recently reviewed the literature on various types of spray trajectories viz. power-law, exponential and logarithmic at various conditions.

In this study, as a part of a comprehensive study on liquid jet in crossflow under elevated conditions, we report empirical correlations obtained to estimate the trajectory of upper bound and the center of a water jet injected into a crossflow subsonic air stream.

Materials and Methods

The experimental apparatus has been designed for jet in crossflow experiments under elevated pressures and temperatures at steady state conditions. It is comprised of three main parts: the high pressure, high temperature crossflow air supply system, the liquid fuel injection system, the test section (see Figure 1), and the exhaust gas system. A dual stage compressor (Broom & Wade 750C) capable of providing 750 scfm at 100 psig is used. Three large settling tanks are installed after the compressor to reduce the air fluctuations delivered to the test section. The high pressure air produced by the compressor enters a circulation heater (Watlow Hannibal, MO, USA) operating at 150 kW and 600 V. The high pressure, high temperature air passing through a 3" circular pipe enters a flow straightener, a ceramic honeycomb, and a screen and finally enters a pipe with a rectangular cross section of 25 *mm* × 35 *mm*, which is the same as the cross section of the test section. The crossflow air flow rate is controlled by two butterfly valves and is measured by an inline flow meter (Erdco Model Armor-Flo 1411, Evanston, IL, USA). The air flow pressure temperature and pressure are monitored at several locations of the pipeline.

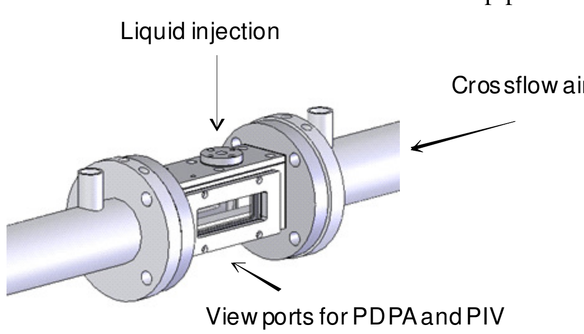


Figure 1. Schematic of the test section

The test section is equipped with high temperature and high pressure resistant quartz windows (Corning 7980) at the bottom and two sides for the optical measurements. The nozzle is mounted flush with the upper wall of the test section. The nozzle is mounted so as to provide optical access of 50 *mm* upstream and 100 *mm* downstream of the nozzle inlet. The test section is cooled by circulating water. The temperature and pressure are measured using type K thermocouples and a pressure gauge, respectively. The test liquid is stored in a tank, which is pressurized by high pressure nitrogen gas. Owing to the pressure of the gas, the liquid flows through a flow meter and then is injecting to the test section. The apparatus is equipped with emergency water spray to the test section.

Over 220 test conditions were considered with liquid to air momentum ratios varying from 10 to 80, air temperatures of 25, 200, and 300°C, absolute crossflow air pressures of 30, 55, and 75 psia. Table 1 shows the experimental conditions. For each test condition 400 images were obtained, using pulsed laser sheet illumination technique. The obtained images were averaged and filtered and then the spray center, windward and leeward trajectories were calculated using an automated method.

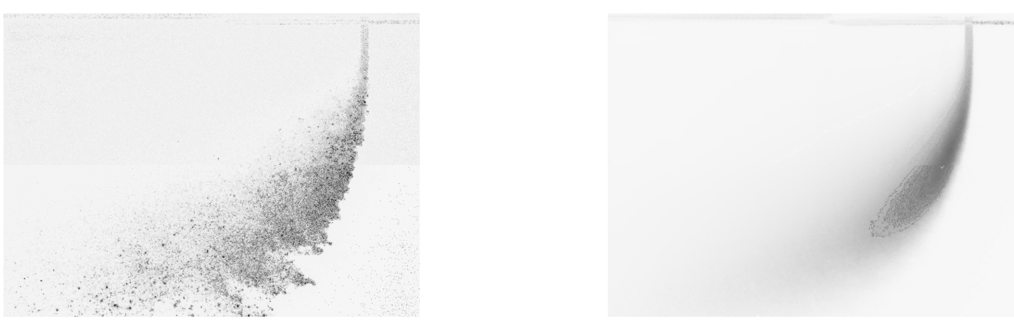
Table 1. Experimental conditions; liquid used: water

Q	10, 20, 50, 80	V_j *(m/s)*	6.8-54
T (K)	298, 473, 573	U_∞ *(m/s)*	22-156
P (psia)	30, 55, 75	*D (mm)*	0.40, 0.50
We	20-487	Re_j	7600-47000
Re_{ch}	18000-168000	ρ_g (kg/m^3)	1.26-4.46

Results and Discussion

Figure 2 shows the color-inverted snapshot and time-averaged image of a typical jet in crossflow experiment taken at q = 80 and *We* = 145, using the pulsed laser illumination technique. The laser light intensity is proportional to droplet size and droplet number density in spray and therefore to mass concentration. At the exit of the nozzle the jet is still intact which hinders the light transmission and therefore the light intensity is reduced. Nevertheless this does not affect the procedure that was followed to determine the boundary of the spray. Furthermore, it is rational to assume that the highest mass concentration within the spray occurs on the axis of deflection of the jet/spray. As a result, it has been assumed that the spray center-line is the loci of the points with the highest light intensity in each row of the captured image. On the other hand, the windward spray boundary are the defined as the loci of the points with the lowest light intensity after a light cut-off threshold of 25% has been applied. This threshold was used to reduce the noise without significantly affecting the analysis of the jet trajectory.

Analysis of the images showed two types of spray patterns. At higher values of momentum ration and/or Weber number, the spray looks steady with minimum fluctuations (see Figure 2). This mode has been previously observed and identified as the shear breakup mode [4]. On the other hand, at low values of momentum ratio and *We* number, the column breakup mode prevails and the spray trajectory and boundaries has an unsteady behavior (Figure 3).



(a) (b)

Figure 2. A Color-inverted pulsed laser sheet-illuminated images of, (a) a typical steady snapshot; (b) a time-averaged image of 400 individual snapshots taken at q = 80 and *We* = 145.

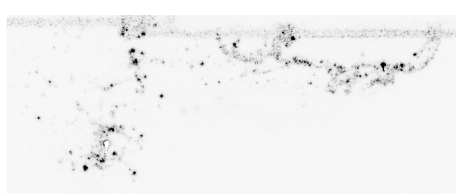


Figure 3. A-color inverted snapshot of an unsteady case (q = 10 and *We* = 36). The nozzle inlet is close to the upper-right hand corner and the air is flowing from right to left.

A map is produced which shows all tests conditions in a coordinate system with abscissa showing the Weber number and the ordinate the momentum ratio (Figure 4). This map is similar to that of Becker-Hassa [4] column breakup versus shear breakup map, although our criterion in rating each case was the steadiness of the spray. Figure 4 shows this map in conjunction with the estimated borderline between steady and unsteady cases and the borderline proposed by Becker and Hassa [4]. Higher momentum ratios and Weber numbers favor a better atomization and a steady spray. For momentum ratios greater than 20, all spray boundaries are steady. Since the trajectory of unsteady sprays was rather randomly, only those test conditions that produced steady trajectories were considered towards finding the final correlations.

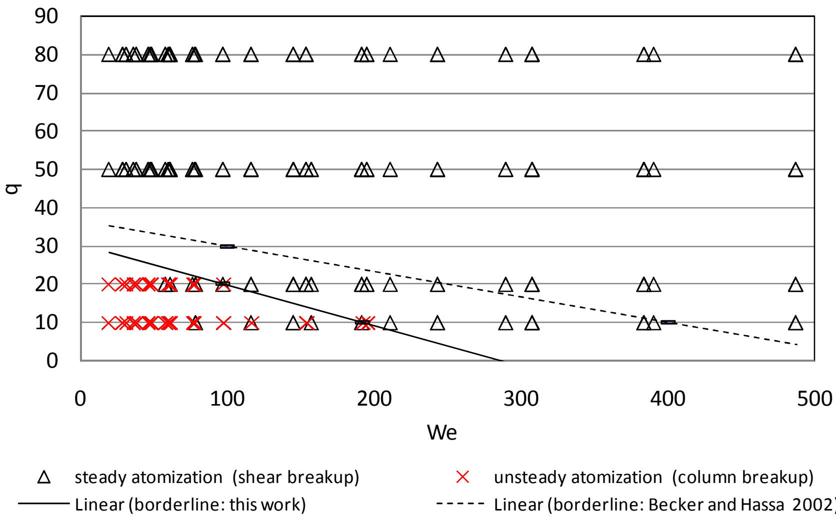


Figure 4. Breakup and atomization map: unsteady atomization (column breakup) versus steady atomization (shear breakup)

A preliminary analysis was performed to investigate the approximate correlation between the spray trajectory and principal variables such as nozzle diameter, crossflow air velocity and liquid injection velocity. That correlation revealed that the liquid jet velocity has a greater effect on spray trajectory than the crossflow velocity. As a result, correlating the spray trajectory merely with the momentum ratio q, which ascribes equal (but reverse) contributions to crossflow and jet velocities, is inadequate. Therefore, we propose to correlate the jet trajectories with Re_{ch}, which is the Reynolds number based on crossflow air velocity properties and the hydraulic diameter of the channel and also Re_j, which is based on liquid properties and nozzle diameter. Re_{ch} is important as it is a measure of the turbulence intensity in the channel that has a direct effect on wave growth and liquid breakup and atomization. Re_j has a similar effect on jet breakup and atomization. Spray trajectory is directly dependent upon parameters that affect the jet deflection such as the momentum ratio; however, the affect of parameters which control the liquid atomization and droplet dispersion, such as Re_{ch} and Re_j should not be overlooked. The crossflow air viscosity was obtained at the crossflow air temperature, while the liquid viscosity and surface tension was assumed to be the average of those properties at room temperature and at the crossflow air temperature.

Among the employed types of correlations used in the literature, the power law is utilized here owing to its simplicity and popularity. A nonlinear regression analysis was performed to obtain the spray center-line and windward trajectories.

$$\left(\frac{y}{D}\right)_{Center-Line} = 0.191\left(\frac{x}{D}\right)^{0.43} q^{0.30}\,\mathrm{Re}_{ch}^{0.12}\,\mathrm{Re}_j^{0.14} \quad (5)$$

$$\left(\frac{y}{D}\right)_{Windward} = 0.167\left(\frac{x}{D}\right)^{0.37} q^{0.31}\,\mathrm{Re}_{ch}^{0.11}\,\mathrm{Re}_j^{0.15} \quad (6)$$

The coefficients of determination (R^2) of the center-line and windward correlations are 0.83 and 0.8, respectively. The standard error of the center-line correlation is 0.39 and that of the windward correlation is 0.44. These correlations are most reliable within the range of the parameters of this study given in Table 1.

Figures 5 and 6 may be used to investigate the prediction ability of our correlations with respect to the experimental data and other correlations. Figure 5 shows the experimental data and estimates of the windward trajectories at momentum ratio of 50 and constant pressure of 30 psia and at various temperatures. It should be noted that for each given temperature for a given q there exists more than one combination of air and liquid jet velocities; therefore Figure 5 shows more than one trajectory for each case. The penetration increases with increase of crossflow air temperature. This is because with increase of temperature, the crossflow gas density decreases, and to keep the momentum ratio constant, the crossflow air velocity has to increase. Also note that with temperature rise, the Weber number increases owing to a decrease in liquid surface tension, while the term $\rho_g U_\infty^2$ is constant. As a result of an increase in crossflow velocity and Weber number, the liquid jet atomization is enhanced, leading to the production of smaller droplets which penetrate and disperse more. The Tambe et al.[3] correlation (Eq. 2) is only a function of momentum ratio and therefore cannot capture the effect of temperature on spray trajectory. This correlation also overestimates the spray windward trajectory, particularly at room temperature where it has been designed for. The Ragucci et al. [5] correlation (Eq. 4) can predict the increase of jet penetration with temperature rise; however, it fails to predict the trajectory of each data series at constant temperature. This is because Eq. (4) is a weak function of Weber number based on the liquid jet velocity (We_{Vj}) and therefore cannot effectively spread to predict the experimental data. The presented correlation (Eq. 6), on the other hand, shows the most flexibility in all temperatures and particularly at higher temperatures. It slightly overestimates the experimental data, though.

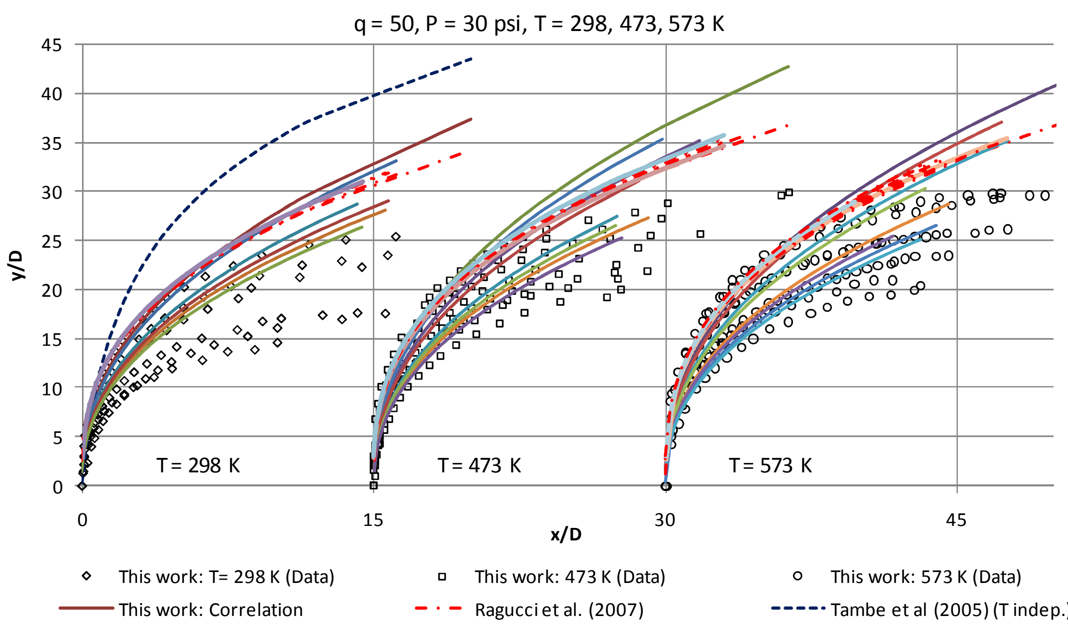


Figure 5. Jet windward trajectories at various temperatures at constant momentum ratio and pressure: Experimental data and various correlations.

Figure 6 displays the experimental data and the predicted jet windward trajectories at various absolute pressures at constant temperature of 573 K. Since temperature and momentum ratio are constant, $\rho_g U_\infty^2$ and surface tension remain constant. Therefore, the Weber number is constant at all pressures. With increase of pressure, the density of crossflow air increases while the crossflow velocity decreases. Physically, an increase in gas density results in a decrease in jet penetration, while a decrease in the crossflow velocity is accompanied with an increase in jet penetration. Overall, the shown experimental data do not show any perceptible change in penetration with pressure change, while the correlations predict a slight decrease in penetration with increase of pressure.

Conclusions

Experiments were performed to study the breakup, atomization and trajectories of water jets injected into high pressure, high temperature steady crossflow air stream. The jet center-line and windward boundary is correlated with liquid jet to crossflow momentum ratio, channel and jet Reynolds numbers. Compared to the very few correlations available in the literature for spray trajectories in high pressure and temperature conditions, our correlations are more sensitive to the variation of test conditions and satisfactorily estimate the jet trajectories at various conditions.

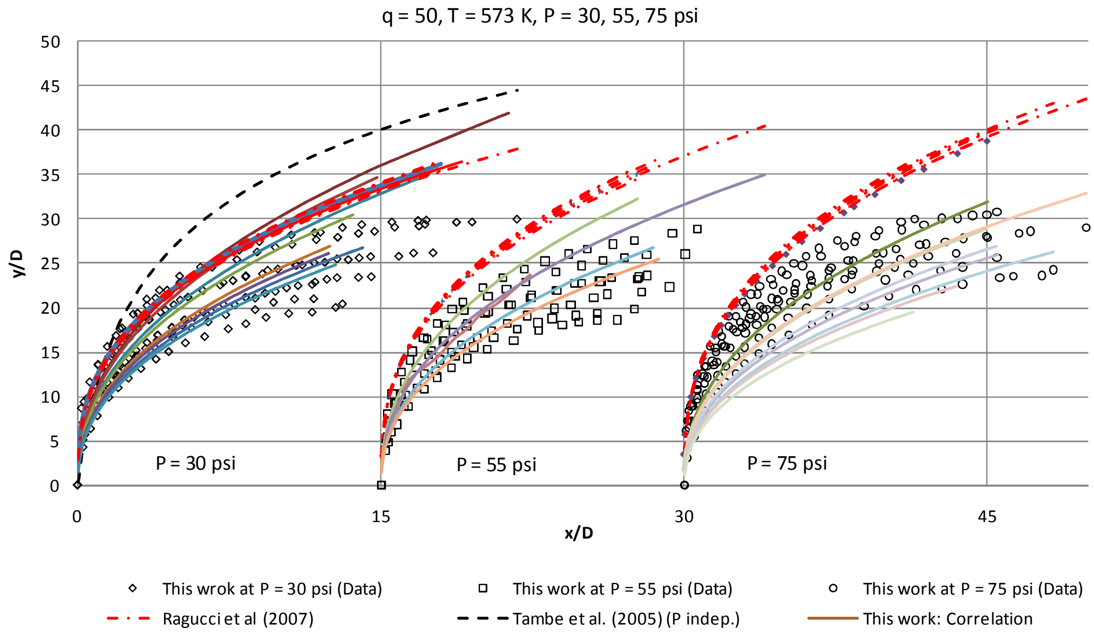


Figure 6. Jet windward trajectories at various absolute pressures at constant temperature and momentum ratio: Experimental data and various correlations.

Nomenclature

D	nozzle diameter
q	liquid jet to crossflow air momentum ratio ($= \rho_j V_j^2 / \rho_\infty U_\infty^2$)
Re_{ch}	Reynolds number based on the channel hydraulic diameter and velocity and properties of crossflow air
Re_j	Reynolds number based on the nozzle diameter and velocity and properties of liquid
V_j	liquid jet velocity at injection point
U_∞	crossflow air velocity
We	Weber number based on crossflow air velocity and density, nozzle diameter, and liquid surface tension
We_{Vj}	Weber number based on liquid jet velocity, air density, nozzle diameter, and liquid surface tension
x	coordinate along the channel and direction of the crossflow air
y	coordinate showing the jet and spray penetration
μ	crossflow air viscosity
ρ_j	liquid density
ρ_∞	crossflow air density

Subscripts

ch	channel
j	jet
∞	crossflow air

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