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Liquid jet in crossflow – Effect of liquid entry conditions

R. Surya Prakash, Anubhav Sinha, Gaurav Tomar, R.V. Ravikrishna*

Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

The focus of the present article is to study the effect of liquid jet injection entry conditions on the structure of liquid jet in crossflow (JICF). The experiments are conducted over a range of liquid-to-air momentum ratios (Q ~ 3–100) and aerodynamic Weber numbers (*We* = 17–89). Control over the exit conditions of the injected liquid is achieved through the usage of different L/D ratios of the nozzle of the plain-orifice atomizer. The geometrical parameter L/D is varied between 10 and 100 in order to obtain fully-developed laminar flow, transition and turbulent flow. High-speed imaging and Shadowgraphy are used to study the trajectory, drop-sizing and transient behaviour of the resultant spray. It is observed that the dependence of trajectory of the spray is not just limited to the momentum ratio, Q, but also requires correction factors with respect to the injection entry conditions, which are in turn related to L/D. The trajectory of the turbulent jet is found to be lower at all times when compared to that of a laminar jet for the corresponding conditions. This behaviour may be attributed to the inherent instabilities present in a turbulent jet as opposed to a perfectly laminar jet. Turbulent jets also observed atomize better, producing smaller droplets when compared to their laminar counterparts. Further, we also investigate the transient phenomena of the liquid jet breakup at different conditions with the aid of Proper Orthogonal Decomposition (POD) analysis. Distinct modes of breakup are captured for the laminar and turbulent cases.

1. Introduction

Jet in crossflow (JICF) has been a topic of much interest owing to its applicability in various processes of engineering interest, particularly in fuel injection for gas turbine combustors. The significance of this injection strategy is also enhanced by its applicability in low emission combustors, especially the lean premixed, pre-vaporized combustors. The performance of combustors depends critically on the liquid jet breakup, droplet dispersion, droplet evaporation and mixing. Thus, it becomes important to understand the physical processes involved in jet breakup and techniques to control or modify them to suit combustor requirements. Jet in crossflow has been the subject of various investigations, both experimental and computational. Moreover, prediction of the jet trajectory is a valuable input for combustor design, and hence there is a large body of literature focusing on formulating correlations for the spray trajectory.

Wu et al. [1–3] have extensively studied the injection of liquid jet in uniform crossflow of air and proposed correlations for the windward spray trajectory. A regime map for the breakup processes for JICF was generated based on the study of liquid jets formed using pure water, and aqueous solutions of ethanol and glycerol [1,2]. The column breakup was also studied and a correlation was proposed for the column fracture point. To further investigate the spray structure and droplet dispersion, an experimental study was carried out on water jets in subsonic crossflow [3]. Droplet sizes, volume and axial velocity were measured using PDPA technique across the spray plume, and the droplet distributions at various axial locations for different momentum ratios were discussed.

Lee et al. [4] carried out an experimental study of turbulent jet of water and ethanol in crossflow. Experimentally obtained spray trajectories were compared with the correlation proposed by Wu et al. [1] and the agreement was found to be reasonable. It is noteworthy that the *L/D* for the injector used in this work was maintained to be greater than 100 in all the experiments. It was observed that the column breakup length (CBL) of the turbulent jets was shorter than the CBL of the non-turbulent jets in crossflow, for the same Weber number. Sallam et al. [5] experimentally studied non-turbulent liquid jets in crossflow, investigating jet deformation, deflection and breakup of liquid jets. The formation of ligaments and droplets was also analysed. The spray trajectory was compared with the correlation of Wu et al. [1]. The transition between breakup regimes was observed to be fairly independent of liquid viscosities for low Ohnesorge numbers and liquid exit velocity for momentum ratios smaller than 8000. Mazallon et al. [6] carried out experiments to investigate non-turbulent liquid jet breakup in

* Corresponding author.
E-mail address: ravikris@mecheng.iisc.ernet.in (R.V. Ravikrishna).

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crossflow. It was found that the liquid column deformed into a disc shape with frontal diameter equal to twice the initial diameter of the liquid jet, at the onset of breakup. It was also observed that the bag and bag/shear breakup involved both liquid and column waves, while only surface waves were observed in the case of shear breakup. Aalburg et al. [7] investigated the physics of JICF using both experimental and computational methods. Computational studies were conducted on jet deformation with time for various Weber numbers and Ohnesorge numbers. These predictions were then compared with experimentally observed jet deformation. This study covered a wide range of parametric space of Reynolds number, Weber number, Ohnesorge number, liquid to gas density ratio, and liquid-to-gas viscosity ratio.

Inamura and Nagai [8] conducted experimental studies on the JICF configuration. Droplet sizes and velocities were measured using PDPA technique, and droplet mass flux measurements were carried out using iso-kinetic sampling probes. Droplet diameters are found to reach peak values at the periphery for lower crossflow air velocities, while larger diameters were found in the core regions for higher crossflow air velocities. Theoretical studies on jet in crossflow were undertaken by Inamura [9], focusing on the drag coefficients and spray trajectory. The jet penetration predictions were also compared with the experimentally observed trajectories in previous studies. Shetz and Padhye [10] studied jet in crossflow experimentally and derived correlations on the jet trajectory. Droplet sizes after the breakup were also measured. In this work, a small exposure time was employed to study breakup behaviour and large exposure time to generate streak pictures for penetration studies. Sinha et al. [11] undertook an experimental investigation on JICF. Various breakup regimes were observed with specific emphasis on bag and column breakup behaviour of liquid jets. Ng et al. [12] carried out an experimental investigation primarily focused on bag breakup of non-turbulent liquid jets in crossflow. The wavelength of column and surface waves, number of bags formed and drop sizes and velocities were measured. Behzad et al. [13] carried out theoretical studies on the azimuthal shear instability of a liquid jet in crossflow. Similar work was carried out by Behzad et al. [14] to investigate the surface breakup of non-turbulent liquid jet in crossflow.

Most of the earlier investigations have primarily focused on jet trajectory and droplet size measurements. However, there are a few recent studies which have also focused on the column breakup behaviour, its characterization, and the effect of injector geometry. Lubarsky et al. [15] investigated the effect of injector geometry by using sharp-edged and round-edged injectors. A novel technique has been devised to measure jet fracture point by using the total internal reflection of light by the liquid jet. In this work, correlations for spray penetration are also proposed. Surya Prakash et al. [16] carried out an experimental study of JICF using injectors with varying L/D ratios. The difference in trajectories for the various injectors was presented. Wang et al. [17] conducted experimental studies on JICF focusing on obtaining the column break point, which was found by image processing of jet images. It was observed that the location of breakup point varies with time for a configuration owing to the unsteady physics of jet breakup processes. Zheng and Marshall [18] also focused on column breakup in an experimental study. A probability-based approach was adopted to determine the column breakup point, and they concluded that the breakup distance in the crossflow direction remains constant for each breakup mode. Ahn et al. [19] investigated the effect of injector internal flow on the liquid jet and its trajectory in the presence of cross flow. In this work, round and sharp-edged orifices were used. Chang et al. [20] studied the effect of inlet surface roughness and nozzle material on cavitation and hydraulic flip for a liquid jet in a quiescent ambient.

Brown and McDonnell [21] investigated the near-field behaviour of the liquid jets injected into cross flows. They pointed out that, though the trajectory correlations appear to agree well, it is mostly due to the similar injector geometries used in those studies. Hence, they also suggested a need for a systematic investigation on this front. Osta and Sallam [22] studied the nozzle-geometry effects on upwind-surface properties of turbulent liquid jets in gaseous crossflow. They observed that the injector passage length does play a role in determining the breakup length and the breakup time. However, their study involved only turbulent jets. Broumand et al. [23] studied the effect of nozzle exit turbulence on the column trajectory and breakup location. They proposed two modified correlations for predicting a liquid jet trajectory and column breakup height which taking into account the discharge coefficient of different nozzles. Broumand and Birouk [24] also studied the effect of nozzle-exit conditions on the near-field characteristics by using sharp-edged and tapered internal geometry injectors. In their study, they have also accounted for the hydraulic flip that occurs in the sharp-edged injector at higher flow rates. While contemplating on the influence of injector geometry it may also be noted that Birouk and Lekic [25] have reviewed the effect of internal construction on liquid jet breakup in detail, albeit in quiescent conditions.

There is also a significant amount of experimental and computational effort on the JICF configuration at high pressure and temperature [26–31], which resemble practical gas turbine combustor conditions more closely. Overall, studies on the effect of liquid jet entry conditions still provide scope for further investigations. Moreover, a large number of spray trajectory correlations are present in the literature [32,33] but all correlations differ from each other, and sometimes there is a significant mismatch, even up to the extent of 100% between the two correlations for the same conditions. The reasons for this mismatch can be attributed to the following factors: (i) Difference in crossflow air entry conditions, (ii) Measurement techniques, and (iii) Liquid inflow conditions. Regarding the first point, the crossflow air conditions, viz., incoming velocity profile and turbulence intensity are rarely measured/reported. A difference in these incoming parameters is expected to affect the jet breakup and resulting spray trajectory. Regarding the second point, it is important to note that not all imaging techniques give the same results. This discrepancy becomes more apparent near the upper trajectory of the resulting spray, where large droplets are present in sparse numbers. Insufficient resolution of images may result in under-predicting the trajectory curve. The third aspect has been addressed by very few researchers mostly limited by the range of conditions – either laminar or turbulent. The inflow conditions in the liquid line are expected to affect the jet characteristics and hence the spray trajectory. Investigating this aspect with a wider range of variation is the primary focus of the present study. The next few sections describe the experimental setup, results obtained, discussion of the results and important conclusions.

2. Experimental setup and imaging techniques

2.1. Experimental setup

The schematic of the experimental setup employed for the current study is shown in Fig. 1a. The source of air is a receiver tank kept pressurized by a positive displacement compressor. A high mass flow rate regulator aids in controlling the air flow to the test section. The test section has a square cross-section of 50 mm × 50 mm. The source of liquid is again a pressurized liquid tank and a mass flow controller is used to measure the amount of liquid injected. The injector has a circular orifice of diameter 0.5 mm. The length of the orifice is varied between 5 mm and 50 mm in order to obtain different L/D values between 10 and 100, respectively. These values are obtained through analytical calculations to produce fully developed smooth laminar jet for $L/D = 10$ and turbulent flow at $L/D = 100$, with the transition from laminar to turbulent flow occurring in between 10 and 100. These nozzles make use of pre-fabricated surgical SS tubes (Mfr: Sigma-Aldrich) in order to ensure smooth and consistent inner surface finish. Care is taken to maintain similarity in the internal geometries of all injectors. The velocities of liquid jet and cross flow air are varied to obtain various experimental conditions in terms of liquid-to-air