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EXPERIMENTAL INVESTIGATION OF SPRAY CHARATERESTICS IN SUBSONIC CROSSFLOWS

By

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Abstract

The breakup of a liquid jet, in a crossflow leading to the evolution of the spray plume downstream is an important aspect that needs to be well understood for improving combustion efficiency and reduction of emissions for airbreathing propulsion engines. The drop size characteristics of a liquid jet in a non swirling crossflow of air were investigated experimentally at conditions relevant to ramjets and gas turbine afterburners. Experiments were done with a 1.0 mm diameter plain orifice nozzle which was flush mounted on the bottom plate of test section to provide normal injection. Laser diffraction using Malvern Spraytec particle analyzer was used to measure drops size and distributions in the near field of the jet. The momentum flux ratio was varied to address a reasonable range of liquid flow rates as in practical devices.

The sprays were characterized using the non dimensional parameters such as the Weber number and the momentum flux ratio and drop sizes were measured at an axial distance of 50 mm from the injector. Results indicate that as one goes from the bottom to the top of the spray plume, the drop size distribution becomes narrower. Further with increase in the momentum flux ratio the volume concentration across the plume becomes highly non uniform and depends on the measurement point in the expanding spray plume.

Nomenclature

d Orifice diameter, m
M Mach number
T Température, K
ρ Density, kg/m3
Cv Volume concentration ppm
σ Surface tension coefficient N/m

We Weber Number, ($\frac{\rho_a V_a^2 d}{\sigma}$)
J Momentum flux ratio, $J = \frac{\rho_l V_l^2}{\rho_a V_a^2}$

Subscripts

l liquid (distilled water)
a air

Introduction

Liquid jets in subsonic crossflows find varied applications in propulsion systems which include gas turbine combustors, aircraft afterburners and liquid fuelled ramjets. The fuel injection scheme is a critical aspect in the design of afterburners, ramjet, and scramjet combustors due to the very limited residence time available.

To understand the mixing characteristics better, knowledge of the breakup regime, the penetration and droplet size distribution in the fuel spray is of paramount importance which has motivated several investigations in this area with a focus on understanding the techniques and methods leading to the distribution of the right quantity of fuel at appropriate locations.

For these applications liquid fuel is typically injected from walls or bluff body flameholders into the air stream under various crossflow conditions. Therefore the liquid jet breakup processes leading to the development of the spray alongwith its ensuing droplet distribution must be reasonably well understood.

The resulting fuel/liquid distribution can be characterized by a variety of parameters like penetration, spray width and height, drop size distribution, volume flux, droplet velocity etc.

Over the years, extensive database for jet penetration (covering various liquid and flow parameters) has been generated through the various investigations carried out in this field[1-4]. Effect of momentum flux ratio at various Weber numbers on jet penetration has been well established. However only a few investigations have attempted to address the measurement of drop size distributions within the spray

Inamura and Nagai[5] investigated the spray characteristics of a liquid jet in a subsonic airstream using PDPA and measured dropsize distributions and velocities for a liquid jet.

Wu et al[6] conducted experiments in subsonic cross flows (0.2 M, 0.3 M, 0.4 M) and noted that smaller droplets were observed near the bottom wall. These droplets were generated from surface breakup and stripped away from the periphery of the liquid column by aerodynamic forces.

Oda et al[7] from their experimental studies at subsonic flows concluded that the mass flow rate increases along the spray height and decreases again after reaching a maximum whereas the SMD only shows an increase in spray height and does not decrease above the maximum mass flow rate location in the spray.

Kihm et al[8] noted that at low subsonic cross flow speeds, the peak of the SMD size distribution shifted to larger values as the distance from the injector wall was increased. The spray SMD was seen to monotonically increase with increasing distance from injector wall, because larger droplets penetrated farther into the air stream.

Tam et al[9] noted in their review paper that the droplet size distribution within the spray was non-uniform. The droplets were found to be concentrated in a small area of the plume. For cases with high jet/air momentum flux ratio, larger droplets are found in the upper portion of the spray plume while for cases with low jet/air momentum ratio, larger droplets are found predominantly in the spray core.

In spite of some amount of work done in this field it is seen that very few studies have been carried out near the injector at conditions typical of propulsion systems of practical interest. Accordingly this study was envisaged with a focus on measurements close to the injector at conditions relevant to ramjets and afterburners.

In this study water was injected into a high velocity cross flow air stream from a straight orifice with a length to diameter ratio of 10. Investigation of the spray was carried out at various momentum flux ratios and the spray was characterized in terms of the drop size distribution in the near field of the spray

(axial distance of 50 mm from injector)

Experimental Methods

The measurements were carried out in the Combustion and Gas dynamics laboratory at NAL. Air supply is from a 3600 m^3 10 bar storage reservoir which feeds to a 6" air supply line. Downstream of the supply line is a rig which is designed and fabricated to investigate the injection of liquid jet in subsonic cross flow. Fig 1 shows a schematic of the test rig used for the experiments.

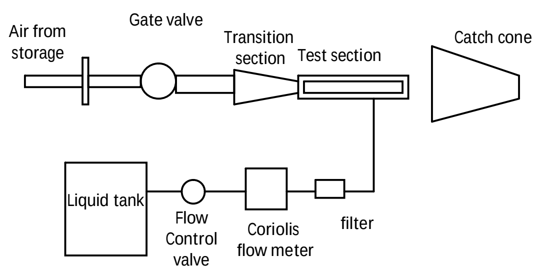

Fig 1: Schematic of the experimental test rig

It consists of a transition section 1200 mm long which provides the entrance conditions to the test section. The test section has a rectangular cross section of 50 mm x 70 mm and is 200 mm long. Two quartz windows about 3 mm thick are provided, one on each side for optical access. The windows are flush mounted with the test chamber’s flow surface. The fuel injector is flush with the bottom wall of the test section.

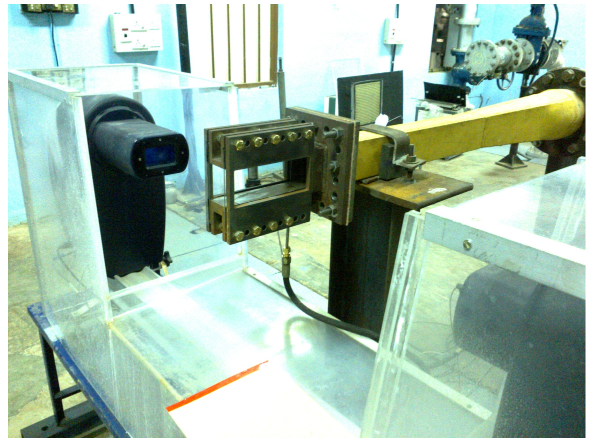

Fig 2: Experimental setup with the Malvern instrument.

Fig 2 shows the experimental set up for the investigation. Two pressure transducers are used to measure the total and static pressures and to estimate the Mach number. One pressure transducer (0 - 10 bar g with an accuracy of 0.2% FS) was placed far upstream in the rig to measure the total pressure and the second pressure transducer (0 – 115 psia with an accuracy of 0.1% BFSL) was used to measure the static pressure just before the entrance to the test section. Two sturdy clamped supports are provided to support the rig and arrest vibration during the test. A steady run time of 10 seconds for each test at various desired air flow rates corresponding to different fuel flow rates is maintained for experimental measurements.

b. LIQUID FUEL INJECTION SETUP

The fuel injector used for this study is a circular orifice of 1 mm diameter. Fig 3 shows the complete dimensions of the injector. A mounting bracket is used to attach the fuel injectors to the bottom part of the test section. The liquid is stored in small high pressure tank and pressurized with air for supplying it at the desired flow rate. A Coriolis flow meter (Micro motion CMF-010M with a 1700 Transmitter) is used to monitor and measure the liquid fuel flow rate. The liquid is passed through a filter before being injected into the flow. A pressure sensor UNIK 5000 system (0- 700 psig) is used to log and monitor the injection pressure.

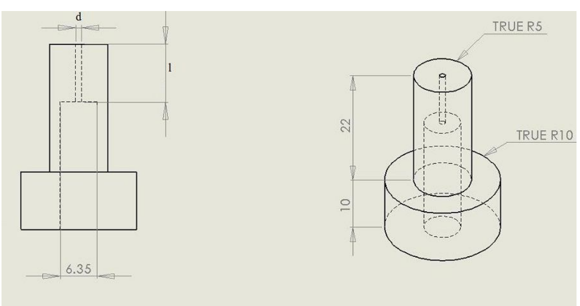

Fig 3: Injector used for the spray studies

c. DROP SIZE AND DISTRIBUTION MESUREMENTS

A Malvern Spraytec particle analyzer was used for the drop size and distribution measurements. This model is a widely used commercially available particle size analyzer. A low power He-Ne laser (5 mW) is expanded to 10 mm diameter beam which interrogates the spray .A 300 mm Fourier lens is used. This setup can provide measurement of drop sizes in the range from 5-600 microns. The main issue associated with an optical measurement of the drop size is the quality of optical access into the flow. The test section has a special window made of quartz with a IR coating to allow maximum transmission in the range.

Results and discussion

The non-dimensional parameters Weber number (We) and momentum flux ratio(J) were used to characterize the sprays. The various tests performed yielded J ratios in the range of 17 to 75 for two Weber number conditions namely 160 and 290 corresponding to Mach number of 0.3 and 0.4 respectively.

Drop size distribution measurements were performed at a distance of 50 mm from the injector and at two locations along the height of the jet. This axial distance was found to be close to the dense spray regime for most of the sprays investigated here by considering the transmission values reported from the instrument. The Malvern spraytec instrument used for this investigation includes a patented multiple scattering algorithm that allows successful measurements at extremely high droplet concentrations[10]. This option of enabling multiple scattering was used for the measurement and analysis of drop size distributions.

Fig 4 and 5 show spray drop size distribution for two different heights from the injector base (27 and 33 mm) at x=50 mm downstream for a Weber number of 290 and Momentum flux ratio of 55. As the height of the drop size measurement increases the size distribution becomes narrower with a large proportion of high diameter drops. For the drop size measurement at the lower height condition a long tail is seen for the drop size distribution result at the beginning. This is consistent with the fact that the high inertia to drag ratios for the larger drops results in their deeper penetration along the jet height axis

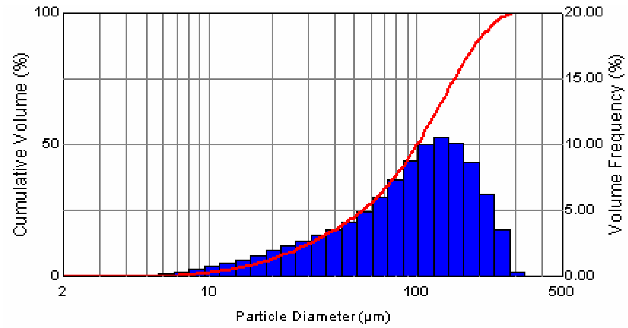

Fig 4: Drop size distribution at a height of 27 mm from orifice for Mach no= 0.4 and J ratio=55

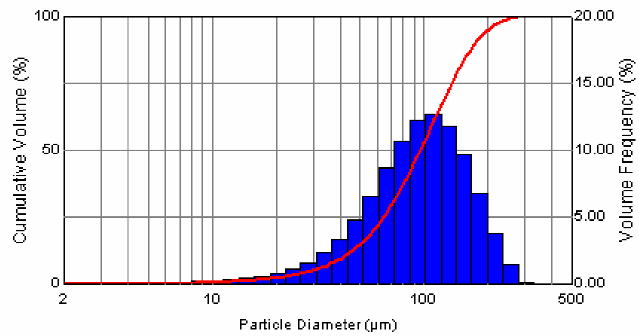

Fig 5: Drop size distribution at a height of 33 mm from orifice for Mach no=0.4 and J ratio=55

Further the concentration volume data for each of the runs was examined to get an idea about the spray density at these locations. The concentration volume data is obtained in parts per million and gives an indication of the liquid content in the measurement volume with a value of 1 Cv signifying that an amount of 1 cubic centimeter of liquid content is present per cubic meter of air (dispersed phase). Considering the weber number of 290, for the lower jet momentum case a higher liquid volume concentration was noted at 27 mm and a drop in the volume concentration was observed at 33 mm possible indicating an approach towards the outer boundary of the spray. for the same Weber number as one moves towards the higher momentum flux ratios the volume concentration values become significantly higher. Further the volume concentration at 33 mm is higher to that observed at 27 mm as the spray width is expanding and one is moving towards the core of the spray towards the region of higher volume concentration.

Conclusion

An attempt was made to partially characterize the near field structure of a spray formed by the penetration of a liquid water jet in a high speed crossflow environment. This was done by examining the droplet size distribution and droplet volume concentration across the spray plume at a particular axial location near the injector using a Malvern spraytec instrument. It is seen that as one goes from the bottom to the top of the spray plume, the drop size distribution becomes narrower. The droplet volume concentration gets significantly redistributed across the spray plume with increasing jet to air momentum flux ratios alongwith the increasing spray plume size.

Acknowledgements

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References

1.Schetz and Padhye "Penetration and breakup of liquids in subsonic airstreams" AIAA Journal, Vol 15,9,1977

2. Wu, P., Kirkendall K.A., Fuller R.P., Nejad A.S., “Breakup process of liquid jets in subsonic crossflows,” JPP 13 (1), 1997,pp 64-73

3. Stenzler, J.N., Lee ,J.G., and Santavicca D.M., "Penetration of liquid jets in a crossflow" AIAA 2003-1327

4.Tambe, S. B., Jeng, S. -M., Mongia, H., and Hsiao, G., “Liquid Jets in Subsonic Crossflow,” AIAA 2005-731, *43rd AIAA*

5. Inamura and Nagai " Spray characteristics of liquid

jets traversing subsonic airstreams" JPP 13 (2), 1997,pp 250-256

6. Wu, P., Kirkendall K.A., Fuller R.P., Nejad A.S., “Spray structures of liquid jets atomized in subsonic crossflows,” JPP 13 (1), 1997,pp 64-73.

7. Oda, T., Hiroyasu, H., Nishida, K., and Arai, M. "Characterization of liquid jet atomization across a high-speed airstream" JSME International Journal, Series B: Fluids & Thermal Engineering 37(4):937-944 1994

8. Kihm, K. D., Lyn, G. M., and Son, S. Y., “Atomization of Cross-Injecting Sprays into Convective Air Stream,” *Atomization and Sprays*, Vol. 5, 1995, pp. 417-433.

9. Tam, C. J., Stouffer, C. S., Lin, K.C., Gruber M., and Jackson, T., “Gaseous and liquid injection into high speed cross flows". AIAA 2005-0301

10. Triballier K.,Damouchel C., and Cousin J., “A technical study on the Spraytec performances: influence of multiple light scattering and multi-modal drop-size distribution measurements" Experiments in Fluids 35 (2003) 347–356