Parallel Doublet Liquid Fuel Injection in Supersonic Flow

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***Abstract*-The spray formation by impinging liquid jets introduced into supersonic flow of Mach number 1.7 from a backward step is experimentally studied. Two injectors of 0.8 mm diameter inclined 7.5 degree each towards the central axis are used. Due to angled injection the fuel streams coming from both injectors produce an elliptical liquid sheet perpendicular to the plane of impingement. The interaction of this sheet and supersonic airstream produce sized particles which was visualized using various laser based techniques like Laser Shadowgraphy and Particle Master Shadowgraphy. Mie Scattering visualization was also carried out to study the mixing characteristics. The results shows, high level of mixing and the formation of very fine droplets.**

Key words: Scramjet, Doublet liquid injection, backward step, Parallel injection, Supersonic flow

I. INTRODUCTION

The man's desire to travel in supersonic speed can be accomplished only by the Scramjet engines. But the small residence time available for mixing and combustion of fuel and air in Scramjets act as major stumbling block in the technological development. Hence for improved combustion the mixing efficiency should be increased. A large number of studies were done on mixing enhancement of gaseous fuels like Hydrogen because of its superiority in combustion performance. However the lower density of hydrogen results large storage volumes. Thus there is a need to use hydrocarbon fuels, especially Kerosene due to the ease of storage and availability. However the liquid fueled supersonic combustors are imparting many technical challenges compared to gaseous fuels. This include (1) a deeper fuel penetration into the air stream for better mixing; (2) generation of smaller liquid fuel droplets for faster evaporation; (3) appropriate flame stabilization mechanism for piloting and sustaining combustion; and (4) a substantial reduction in drag losses associated with processes of mixing and flame holding [1]. In order to minimize these technicalities a backward step parallel doublet liquid injection configuration was adopted. Parallel injection reduces the drag and formation of strong shocks as compared to transverse injection but penetration, formation of fine droplets and mixing will be relatively low in the case of parallel injection. Hence to increase the mixing performance doublet injection was selected. In doublet injection the impinging jets produces an elliptical liquid sheet perpendicular to the plane of impingement. This sheet increases the penetration height and the impact waves formed during impingement reduces the breakup length and accelerates the spray formation. The schematic of the doublet injection as shown in figure 1.

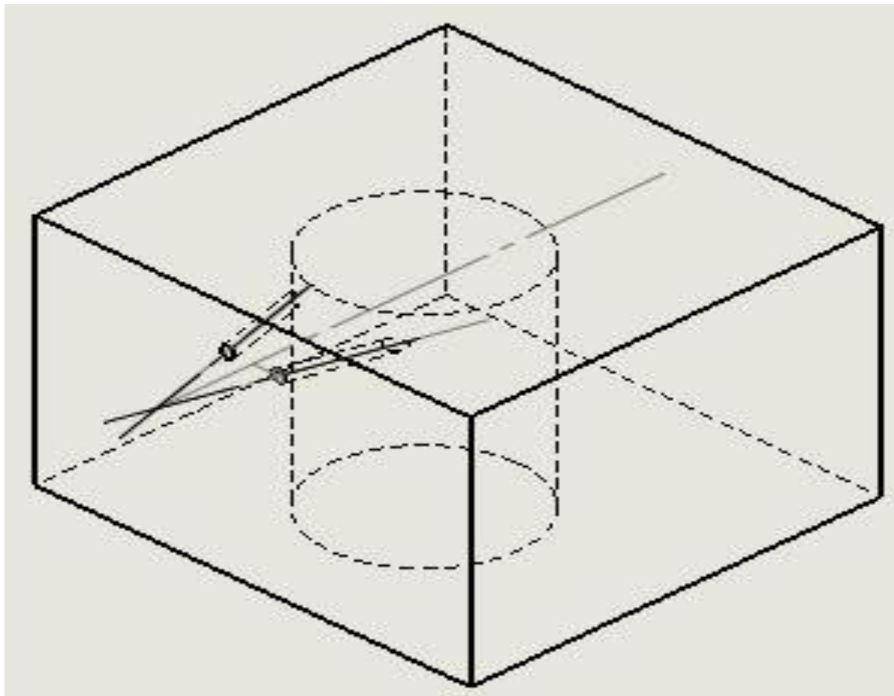

Figure 1 Configuration studied Impinging angle 15 degree

II. EXPERIMENTAL SETUP AND TEST CONDITIONS.

A. Test Facility

The experiment was conducted in a supersonic wind tunnel that produces a flow of Mach number 1.7. The stagnation temperature is assumed to be 300 K for all the test cases and the stagnation pressures were at 3 and 4 bar. The test section has an optical window of size 150x40 mm and the test setup is shown in figure 2.

Acetone was used for injection because its properties match with hydrocarbon fuels and its high volatile nature causes hardly any stains on the optical window. The simulant fluid (Acetone) was stored in a steel tank that is pressurized using compressed dry air and injected through two holes, each of 0.8mm diameter. The fluid was injected at an injection pressure of 2 bar in all test cases. A pulsed Nd-Yag Laser of energy 2.2mJ/pulse along with a diffuser was used as light source for both Laser Shadowgraphy and Particle master shadowgraphy..

A CCD (Charge-Coupled Device) camera (Imager pro X, LaVision Inc.) is synchronized with an illumination by a pulsed laser Diffuser. The PTU (programmable timing unit) commands this sequence and limits the exposure duration within 1micro seconds.The shadow-graphic technique employed using the above equipment capture instant images of spray at various primary (air) injection pressures say zero, three and four bar.

The particle master shadow-graphic technique was employed using the same laser diffuser, PTU and Imager Pro X CCD camera along with a microscope which zooms into an area of interest of 3.5 x3.5 mm. The camera and diffuser are installed on separate traverse which can be moved to desire locations for capture the images.

For Mie scattering experiments a continuous Helium Neon laser along with sheet optics to convert the round beam into laser sheet was used. Pixel fly CCD camera was installed at an angle of 45 degrees to the main flow for capturing the image. A system was developed for the simultaneous movement of laser and camera to different locations.

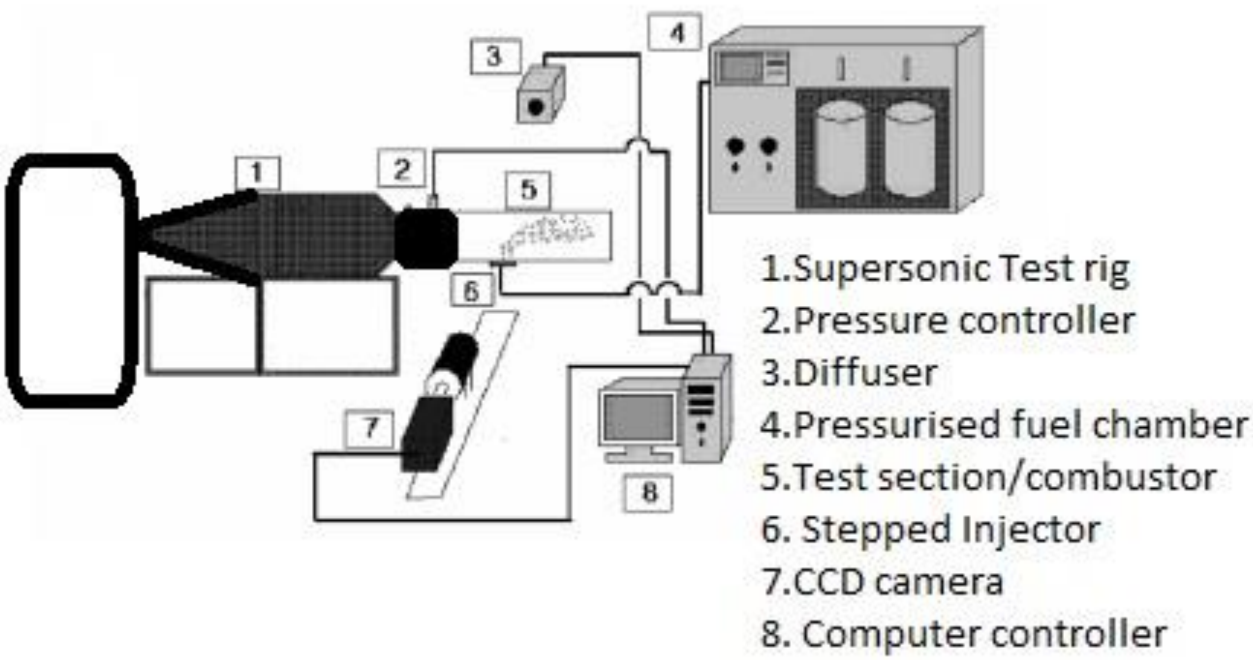

Figure 2 Test set up

III RESULTS AND DISCUSSION

A. Laser Shadowgraphy and Particle Master Shadowgraphy

The spray formation due to impinging jets in stagnant atmosphere was studied for deriving insights on the effects of supersonic flow on the atomization. The three (internal and external) forces which effect spray generation are hydrodynamic force before the jet collision, impact force due to the jet collision, and aerodynamic force. Figure 3 shows the breakup pattern of like impinging jets at an angle of 60 degrees at different pressures (or at different velocities) and it can be categorized into three patterns a) Closed rim b) Open rim c) Fully developed spray at different velocities [2]

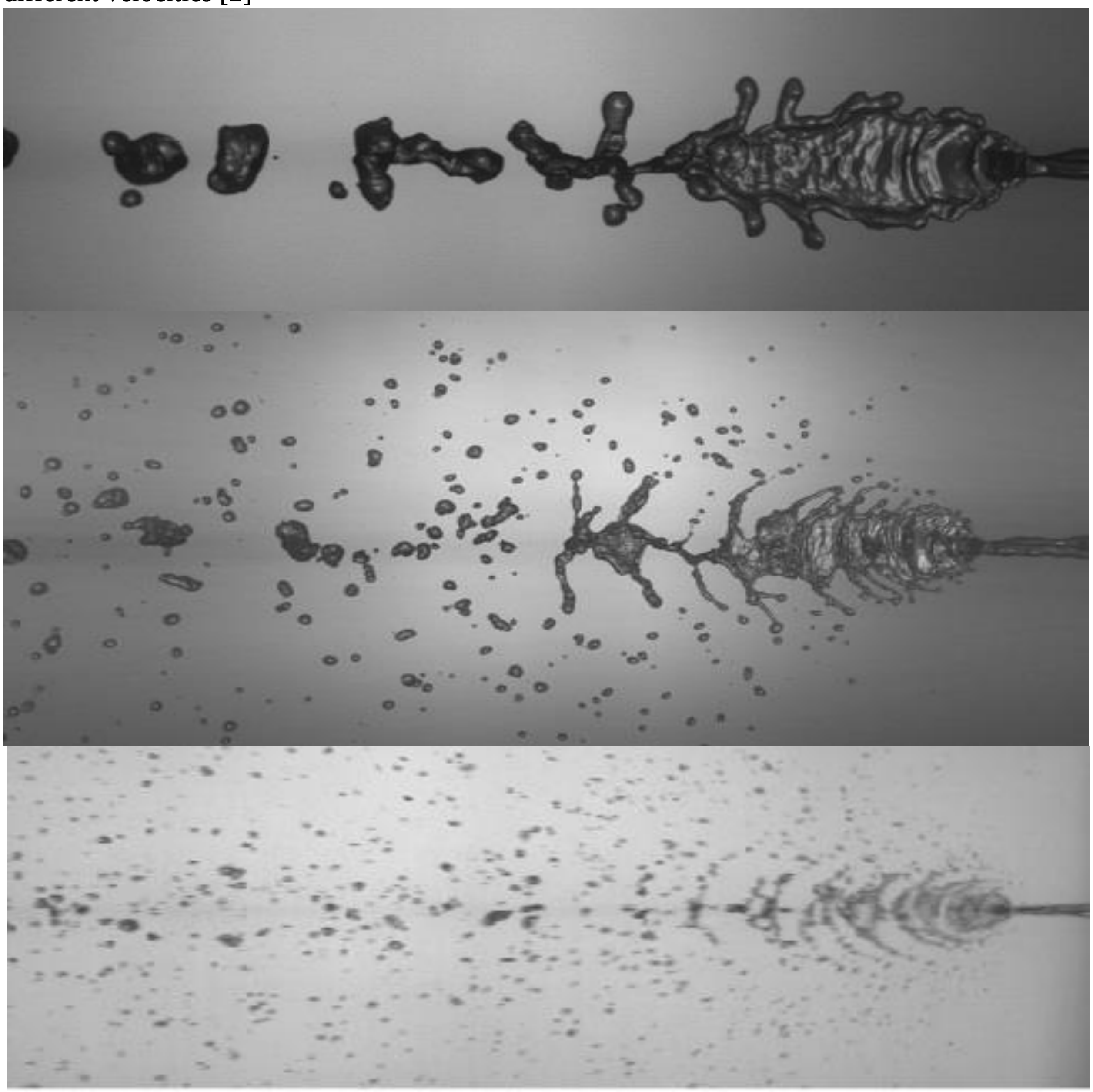

Figure 3 a) Closed rim b) Open rim c) Fully developed spray (flow is from right to left)

Further experiments were conducted at 15 degree impinging angle and the following results were obtained.

The image obtained from Laser shadow-graphic technique is presented in figure 4; from the above results it is evident that the flow pattern at 2 bar pressure and 15 degree angle represents a fully developed spray. Due to mass conservation the liquid jets after impingement are squeezed into thick bulk liquids and in order to conserve momentum the thick liquid jet is stretched out into lateral direction. Even in the absence of supersonic-flows the liquid stream produced from the impingement point exhibits highly dispersive fluid motion. The impingement of the jets at higher velocities induces strong impact waves leading to the disintegration of liquid sheet. The interaction of liquid sheet and atmospheric air also amplifies the spray formation. Still from the image it is clear that the breakup length is few millimeters.

Figure 4 shadowgraph image of doublet injection without supersonic flow.

Figure 5.1 and 5.2 represent the laser shadowgraph of impinging jets at two different momentum ratios

(q = gas jet momentum / liquid jet momentum) 35 and 45,which are under the influence of supersonic main flow.

Figure 5.1 shadowgraph image of doublet injection with supersonic flow @ q=35.

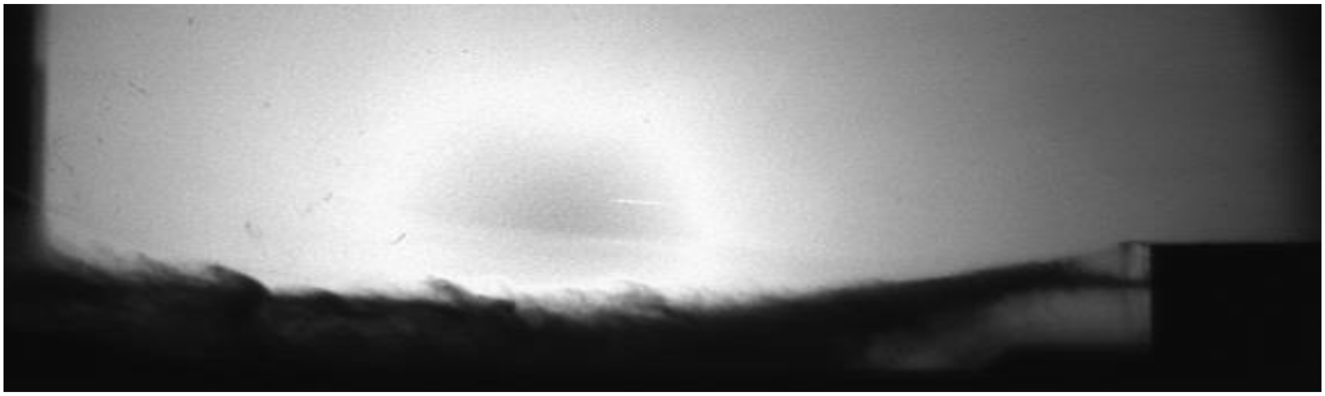

Figure 5.2 shadowgraph image of doublet injection with supersonic flow @ q=45.

From Figure 5.1 and 5.2, it is clear that the liquid jets after impingement are thouroghly mixed with the supersonic main flow. The impingement of the jets at higher velocities induces strong impact waves leading to the disintegration of liquid sheet. The interaction of liquid sheet and atmospheric air also amplifies the suface wave. The wavelength and amplitude depend only on the relative velocity in stagnant atmospheric conditon, whereas in the presence of supersonic main flow it also depends on the shear layer oscilations.When the amplitudes of the wave reaches maximum, the sheet tends to breakdown at the crests and troughs in the magnitude of the half-wavelength [2]. The slow motion video clearly indicated this trend. Here the aerodynamic forces dominate the impact force which was vice versa in stagnant conditon.The interaction of shear layer formed from the step and the liquid sheet causes further disintegration of the spray formed. The recirculation zone formed immediately behind the step helps in thorough belnding of the spray and leads to the formation of fine sized droplets. Since due to higher air momentum the drops find it difficult to peneterate at the injection location whereas the penetration is higher at dowsntream distances; this could be attributed to the interaction of the plume with the shear layer that is hitting the floor.

Further investigation at stagnant atmospheric condition(absence of supersonic main stream flow) using particle master shadowgraphy shows that the Sautter mean diameter (SMD) at a location 40mm from the injecting point without supersonic flow is 28μm. While at the same location under supersonic environment for the same injection pressure the high magnified image (figure 6) shows no clear drops which indicates the formation of mist at that location. The high momentum ratio imparts high aerodynamic forces, along with the impact force

,recirculation and the shear layer interaction causes the formation of mist which is very much favourable for combustion.

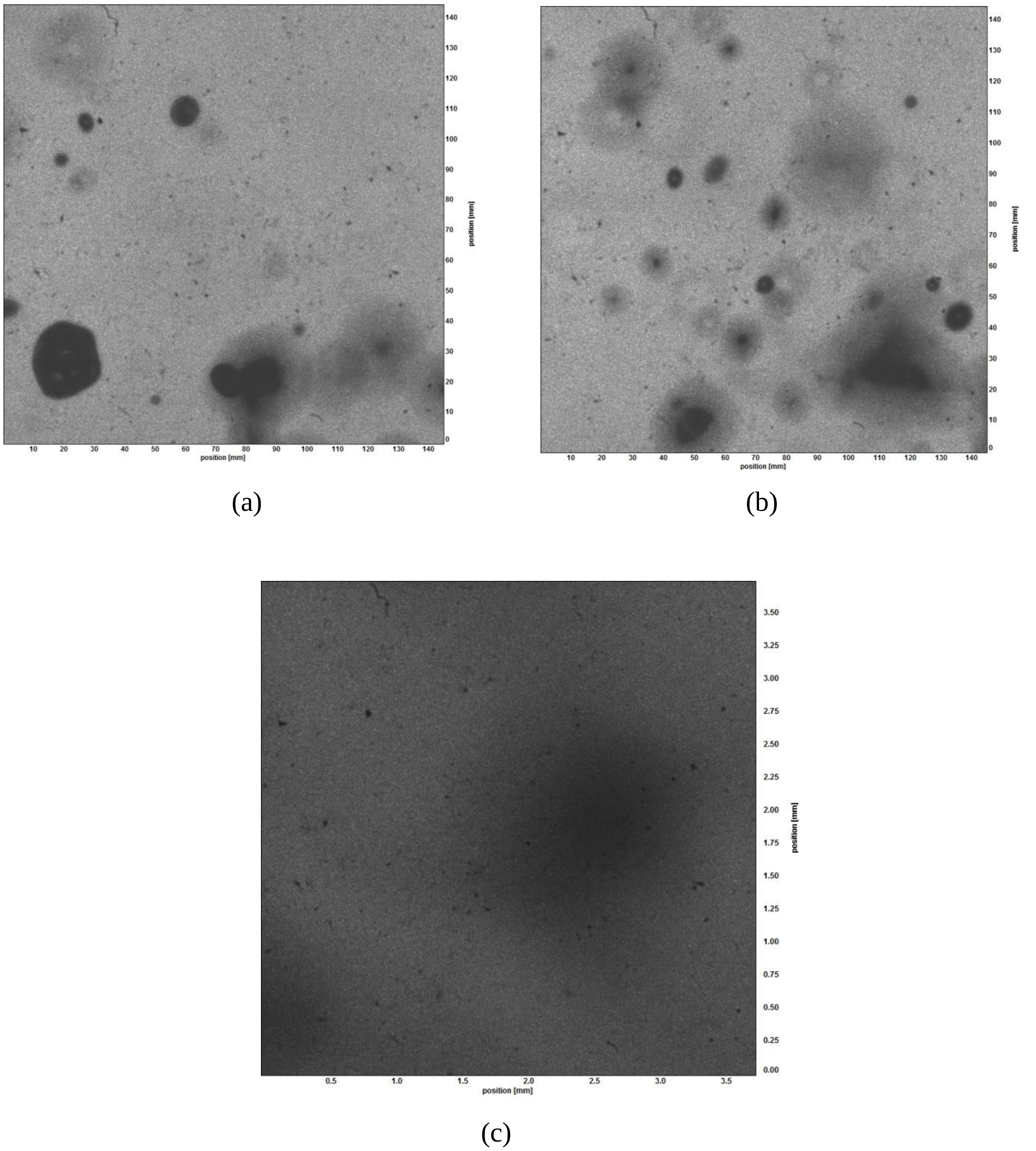

Figure 6 Microscopic image at a location of 40mm from injection point. a)&b) without supersonic main flow and c) with supersonic main flow

B. Mie scatering results

Mie scatering visulaization was performed across the test set up cross section at various locations for both mometum ratios. The results obtained is in conjucntion with the results obtained from the Particle master shadowgraphic technique. Figure 7a shows the Mie scatering at 13 mm from the injection point with and without supersonic flow. In the image without supersonic flow at 13 mm shows a white core which indicates small liquid sheet because the impinging point is at 6 mm from the injection point (this is by geometry). This clearly indicates that sheet breakup is not yet achieved. However the Mie scattering image at the two momentum ratios at the same location of 13 mm indicates the formation of fine droplets with central centre core for a momentum ratio of 35; however for q=45 case, there is enahced mixing with the absence of centrela core. Experiments were conducted with non impinging injection to demonstrate that impingement of jest in supersonic flow yields more mixing than the later. Figure 8a shows the Mie scattering image of non impinging parallel jet without supersonic flow. The presence of two core regions are readily percived. As there is no supersonic flow there is no intensity spread across the section which indicates unmixedness. Figure 8b shows the Mie scattering image of non impinging parallel flow with supersonic flow at q=45. The two cores can be still seen with high intensity with minimum mixing. The intensity is still higher in the cores than in the case of impinging case. Therefore impinging the flow yields better mixing in supersonic flow.

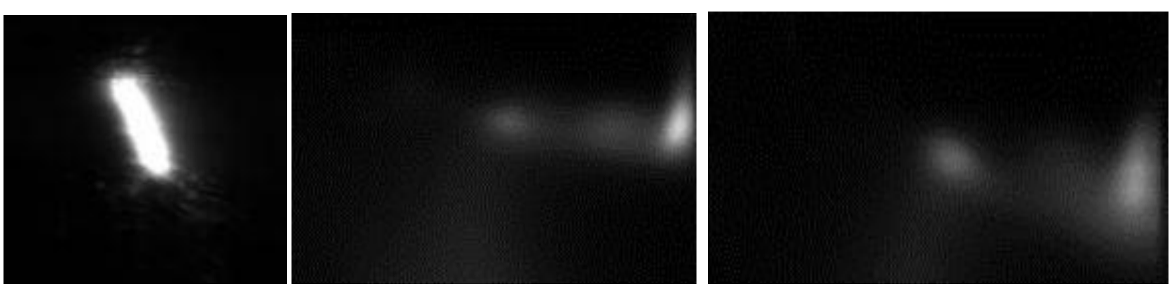

Figure 7 Mie scattered image at location 13mm from injection point. a) q=0 b)q=35 c) q=45

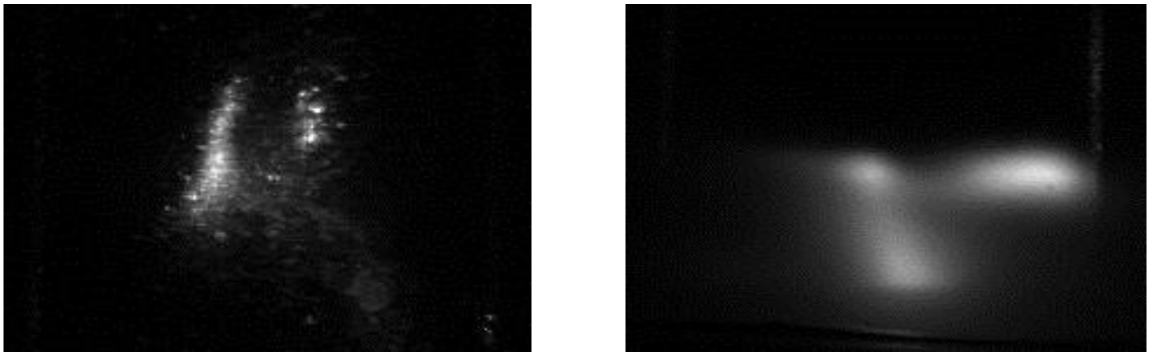

Figure 8 Mie scattered imageof non-impinging injection at location 13mm from injection point. a) q=0 b) q=45

V. CONCLUSION

Laser shadowgraphy, Particle master shadowgraphy and Mie scattering visualization experiments was carried out on liquid like doublet jet injection in supersonic flow. The results from the experiments clearly show the formation of very fine droplets at higher jet momentum ratio or at supersonic flow. This is highly favorable condition for supersonic combustion. The achievement of fine sized droplets within a short distance for parallel injection through doublet injection is highly appreciable because parallel injection reduces the drag and avoids the formation of strong shock losses in the mainstream. The penetration of drops/mist at the far end is high due to the interaction with shear layer. The impact of aerodynamic forces due to relative velocities of air and jet dominates all other forces. Further experiments are to be carried out to study the effect of impinging angle on supersonic mixing.

References

[1] Liyin Wu, Zhen-guo Wang, Qinglian Li, and Jiaqi Zhang"Investigations on the droplet distributions in the atomization of kerosene jets in supersonic crossflows," APPLIED PHYSICS LETTERS 107, 104103 (2015)

[2] S. S. Lee1, W. H. Kim and W. S. Yoon, " Spray formation by like-doublet impinging jets in low speed cross-flows " Journal of Mechanical Science and Technology 23 (2009) 1680~1692.

[3] R. P. Fuller, P. K. Wu, K. A. Kirkendall and A. S.Nejad, Effects of injection angle on atomization of liquid jets in transverse airflow, AIAA Journal,38(1) (2000) 64-72.

[4] A. Paull and R. J. Stalker, "Scramjet Testing in the T3 and T4 Hypersonic Impulse Facilities," *Progress in Astronautics and Aeronautics,* pp. 1-46.

[5] K. Ramamurthi, K. Nandakumar and P. K. Patnaik,Characteristics of spray formed by impingement of a pair of liquid jets, J. Propul. Power, 20(1) (2004)76-82.

[6] K. A. Sallam, H. M. Metwally and C. L. Aalburg,Deformation and surface waves properties of round non-turbulent liquid jets in gaseous crossflow,ASME Fluid Engineering Summer Conference,ASME Paper No. FEDSM2005-77469, Huston, TX,America, (2005) 19-23.

[7] S. L. N. Desikan and J. Kurian, "Experimental investigation of the role of struts in high speed mixing," *The Aeronautical Journal,* vol. 117, pp. 193-211, 2013.

[8] X. Zhang and J. A. Edwards, "An Investigation of Supersonic Oscillatory Cavity Driven by Thick Shear

Layers," *The Aeronautical Journal,* vol. 94, pp. 453-477, 1990.

[9] M. C. Mohammad Ali and J. Kurian, "Cavity–Based Injections into Supersonic Flow," *Journal of Propulsion and Power,* vol. 21, pp. 1130-1132, 2005.

[10] C. D. Bolszo, V. G. McDonell, G. A. Gomez, and G. S. Samuelsen,Atomization Sprays 24, 303–348 (2014).

[11] A. S. Yang, W. H. Hsieh and K. K. K., "Theoretical Study of Supersonic Flow Separation over a Rearward-Facing Step," *Journal of Propulsion and Power,* vol. 13, pp. 324-326, 1997.