Triplet Arrangement for Gas-on-Liquid Impinging Injectors

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Literature on gas-on-liquid impinging doublet injectors have shown that it is difficult to get desired spray mass distribution for the required liquid to gas mass ratio. Gas penetration and spray deflection were often found to be problems even at desired mass ratio which an be avoided by by reconfiguring the orifices. In the present study an attempt is made towards understanding the effect of reconfiguring the orifices. Reconfig- uring the orifices involves using multiple gas orifices for a given liquid orifice. The possible arrangements could be a triplet, quadlet or a pentad configuration. In the present study, triplet configuration comprising of two equally inclined gas orifices impinging on central liquid jet is used with water and air as simulants in place of actual fuel and oxidizer. As in the case of doublet arrangement normal gas momentum to liquid mass (NMGL) was found suitable to express the spray characteristics. The study delineates the operational range of gas pressures before bifurcation is encountered. The Sauter Mean Diameter (SMD) of triplet spray was found to be comparable to doublet spray at high mass ratios, though at low mass ratios SMD is small which may due to gas penetration problem.

I. Introduction

Impinging jet Configuration is an oft preferred injector geometry for rocket engines that use storable liquid bipropellants. Considering the relative advantages in terms of simplicity in design, quality control and low fabrication cost, these injectors an also substitute coaxial injectors which are the mainstay for the current gas and liquid propellant ombinations as mentioned by [1]. But the present design principles and performance characteristics of unlike impinging injectors have not been as well enunciated as for coaxial injectors. Compared to shear coaxial atomizer impinging jet injectors are easy to manifold and simple to design. In addition they an provide reasonably good mixing. However, the performance features and operational limitations have to be based on detailed studies, the literature on which is rather scanty. It is also important that the basic mechanistic features of sprays from such injectors are understood before one looks into their performance as engine components. The present experimental work aims to resolve some of these issues.

The basic geometric and operational parameters of impinging injectors are the diameter, length and in- lination of the orifices, inter-orifice distance which along with the inclination decides the pre-impingement development

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of the jets, the pressure drop across the orifices and the operating pressure and temperature conditions. While like-impinging configuration with identical conditions on the two jets provides symmet- ric impinging and the eventual spray characteristics, the unlike impinging is a little more complex even for liquid-on-liquid jets. One can expect the gas-on-liquid impinging to be still more complex because of large density differences and expansion of jets downstream of the orifice.

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Most of the published work on impinging injectors deal with liquid-on-liquid type of atomizers, al- though a few among them deal with unlike liquid media. Parametric studies on such atomizers as men- tioned by [2] have given insight on the extent of influence that different variables exert with respect to final spray features.The orifice diameter determines the jet diameter and the mass flow rate of the liquid for a given pressure drop. The influence of orifice on drop size is described in [3], smaller the jet diameter, smaller the mean drop size. The orifice length to diameter ratio and the surface finish of the orifice have a role on the jet development. A progressive increase in the L/D tends to increase the losses by friction and hence to reduce the jet velocity, which in turn will have an effect of increasing drop size.It was found that (as mentioned in [4] greater the impingement angle, greater the amount of propellant backflow. In fact propellant backflow is proportional to the cosine of the impinge- ment angle. The angular distribution and mixing uniformity also depend on the impingement angle as mentioned by [5].The normal component of momentum of liquid jet increases with an increase in impingement angle, which is expected to increase the quality of atomization. As mentioned earlier, the inter-orifice distance and the impingement angle will together decide the preimpingement length which when increased progressively is likely to introduce disturbance in the velocity profile of the liquid jet with free boundary, due to interaction with the surrounding gaseous medium. Further, it has been also found that mis-impingement of jets cause rotation of jets and affect mixing uniformity and drop size as cited in [3].

The reports available on gas-on-liquid configuration are scanty. One such study by [6] has shown that the dominant factors for gas-liquid impingement which influence drop size are the in- jected momentum ratio of jets, the dynamic pressure of injected gas and orifice diameter ratio. This configuration does not seem to have attracted much interest later although it appears to have cer- tain application potential and also involves very interesting physics.The study of gas-on-liquid doublet configuration has revealed that normal gas momentum to liquid mass as an apt parameter as cited in [7] describing the spray condition. However gas-on-liquid impinging doublet failed to the give the desired mass distribution for the mass ratios required for certain appli- ations as mentioned in [Rakesh and Raghunandan, 2013a. Moreover the skewness of the spray to- ward the combustion chamber walls may cause hotspots damaging the combustion chamber as cited in [8]. The present study therefore re-examines this configuration by split- ting the total gas mass flow rate into two equal parts impinging on the central liquid mass. The gas used is air and the liquid is water in proportions which simulate the fuel and oxidizer components of the propellants in rockets. A limitation, however is that the typical Reynolds number and Weber number of jets encountered in actual rocket engines are higher than the ones configured in the laboratory conditions.

II. Experimental Setup

Figure 1 shows the experimental setup used for studying the Characteristics of gas-on-liquid impinging injectors. It consists of a two stage reciprocating compressor with an intercooler and an automatic shut off facility and is driven by a three phase 10 hp motor. The air from the compressor is stored in an air storage tank which is designed for air pressure up to about 15 atm. From the air storage tank two air lines are taken, one of which is connected to a water storage tank of about 40 l capacity and the other end to the control board for the impinging injectors. The air line is then connected to the air injectors on the left side and right side of the injector plate through a valve and a pressure gauge. A water tapping is taken from the bottom of the water storage and is conne ted to a filter on the control board. The line from the water filter is then led to the central injector through a control valve and a pressure gauge.

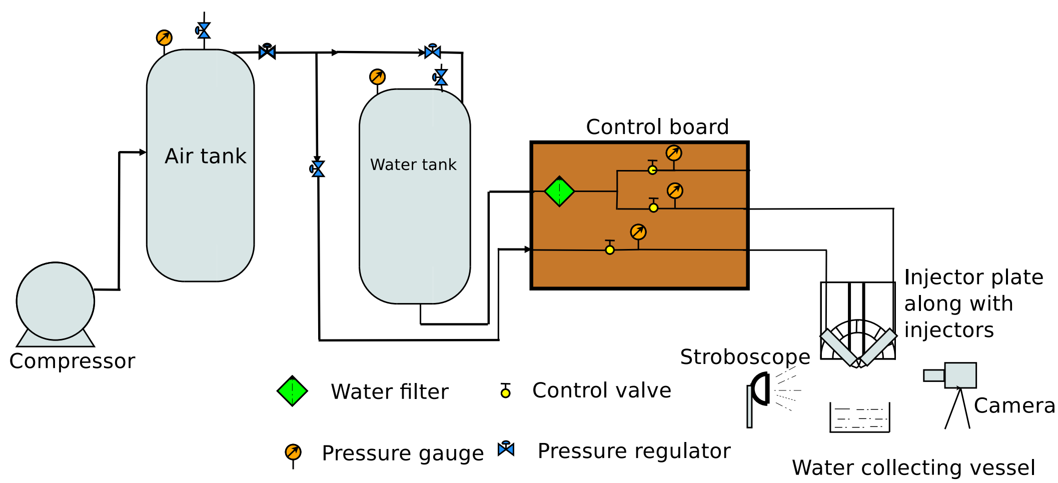


Fig. 1 Schematic of Experimental Setup

Figure 2 shows the details of the injector used for the study. It consists of an injector body which is modular in design so that injectors of different diameters an be inserted with relative ease. The inlet of the injector element is smoothly converged so as to minimize pressure loss. The arrangement permits variations in orifice sizes, inter-orifice distance and the inclination of the jets. The orifice size used in the present work is 1 mm for all injectors and the pressure drop up to 7 atm. Calibration runs have shown that typical orifice discharge coefficent was above the sharp edge value of

0.61 but rarely above 0.9 . Under the operating onditions the liquid side Reynolds number works out to be around 30 000 and the Weber number about 10 000 . These are lower than those encountered in rocket motors largely because of the flow rate vis-a-vis orifice size limitations in the laboratory.

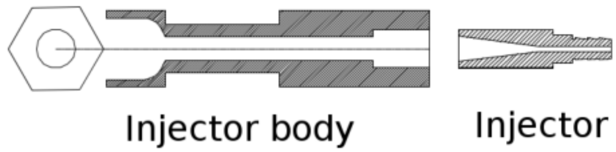


Fig. 2 Schematic of Injector Assembly

A mechanical patternator has been extensively used in the present experiments for finding the spray mass distribution. The main aspect considered in the design of this patternator was to allow maximum area for sample collection with minimum blockage. The patternator was designed with 144 metallic tubes lumped together in a 12×12 array. This provides a square of 144 mm side as the sample collection area. Each metal tube is fitted at the bottom with a wooden plug through which a plastic tube is inserted in the metallic tube. The other end of the plastic tube goes to the test tube where sample is collected for measurement. The test tubes are also arranged in a 12 × 12 matrix in a specially designed tray. The test tubes used for sample collection are of 100 ml capacity that allows to keep collection time of around 15 to 20 s. The schematic of the patternator is shown in Figure 3. Typical spray collection efficency for the mentioned patternator is around 80%.

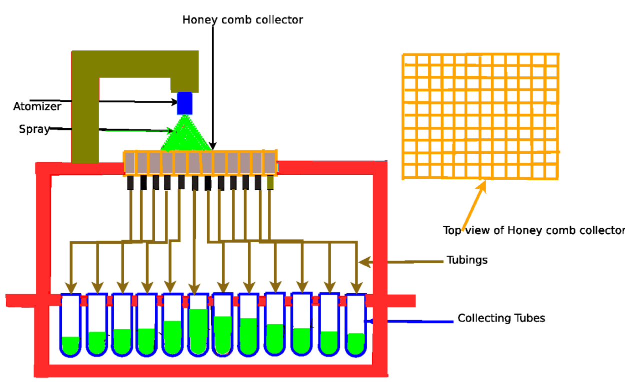


Fig. 3 Schematic of Patternator used in the study

In addition to some of the direct measurements, photography has been extensively used in the diagnosis of spray features.A Nikon D-300 SLR camera with strobe light is used to capture the images of the spray at different conditions. The strobe light used is Strobodriver MSP-120 which is capable of providing pulsed light upto 30,000rpm. The droplet diameter and size distribution are measured using Malvern Mastersizer X particle analyzer which works on the principle of diffraction of a laser beam in the presence of droplets in a spray. The instrument provides the line of sight averaged diffraction data. A large number of experiments are conducted to find out the governing parameters that dictates the characteristics of the gas-on-liquid triplet spray.

III. Reults and Discussion

Experments have been done with triplet with liquid injection through the central injector and gas injection through the side orifices to verify its suitability as a substitute for gas-on-liquid impinging doublets.Experments have been done with triplet with liquid injection through the central injector and gas injection through the side orifices to verify its suitability as a substitute for gas-on-liquid impinging doublets.

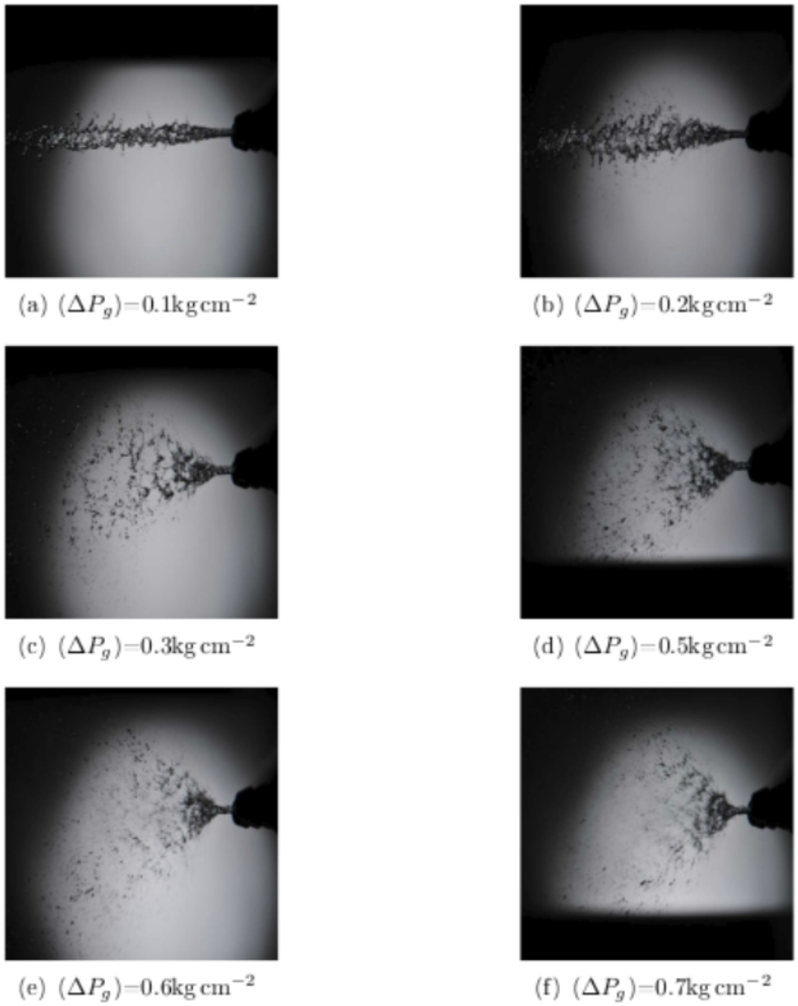
A. Visualization of Triplet spray

It has been found that the liquid jet gets flattened as the gas pressure drop ΔP_g is increased and after a particular pressure drop (for a constant liquid pressure drop ΔP_l), the liquid jet bifurcates into two. The divergence and bifurcation of the triplet spray with increasing gas pressure drop is clearly evident from the photographs shown below in Figure 4. If the gas pressure drop is increased after the the liquid jet bifurcation, the gas jets meeting at the axis of the original liquid jet expands more causing the bifurcated liquid jets to expand further.

The divergence of the triplet spray is expected to depend on the gas momentum, impingement angle and the central liquid mass flow rate. The dependance of the triplet spray on these fa ctors are studied independently as shown in Figure 7. It may be inferred from the Figure 5b) that as the half impingement angle is increased the spray divergence angle increases for fixed gas and liquid pressure drop in the spray triplet. It may also be observed in Figure 8b that for a half impingement angle the initial increase of spray divergence angle is more with normal gas momentum and then it asymptotically approaches a constant value. The dependence of spray divergence angle on central liquid mass flow rate was studied by keeping the normal gas momentum constant and varying the liquid pressure. It is seen from Figure 5c as the liquid

pressure drop increases the spray divergence angle decreases, though at high liquid pressures the variation is small. Since the spray divergence angle is dependent on the momentum, impingement angle and liquid pressure, efforts were made to combine all these into a single parameter.

Going by the trends seen in Figure 6 and the information on doublet spray chara cteristics, the ratio of normal gas momentum to liquid mass flow (NMGL) appears to be the logical unifying parameter. Although this parameter was used for drop size only in the case of doublets, it is invoked for spray divergence angle here. Figure 6 conclusively demonstrates this indeed work as a single control parameter dictating divergence angle of triplets



(a) (ΔP_g)=0.1kg cm^{-2} (b) (ΔP_g)=0.2kg cm^{-2}

(c) (ΔP_g)=0.3kg cm^{-2} (d) (ΔP_g)=0.5kg cm^{-2}

(e) (ΔP_g)=0.6kg cm^{-2} (f) (ΔP_g)=0.7kg cm^{-2}

Fig. 4 Evolution of Gas Centered Triplet spray with constant ΔP_l and increasing ΔP_g

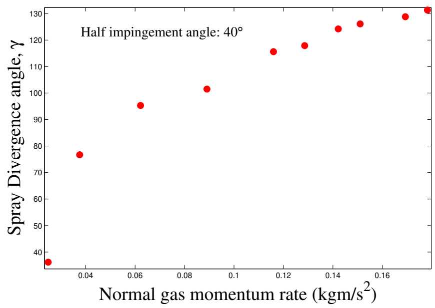
B. Liquid Mass Distribution

The bifurcation of the triplet spray at high gas pressure drop compared to liquid pressure drop was reconfirmed from the mass distribution study conducted using a mechanical patternator.

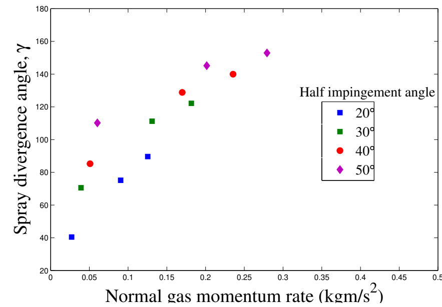
The penetration of the triplet spray is defined as the state when the gas jets breaks the liquid jet into two halves and expand like a gaseous fan. The penetrated gas jets come to a stagnation region increasing the total pressure. This high pressure gas jet then expands against the low pressure surroundings, bifurcating the liquid spray. The images in Figure 8 show the bifurcated water jet.

C. Drop Size Measurements

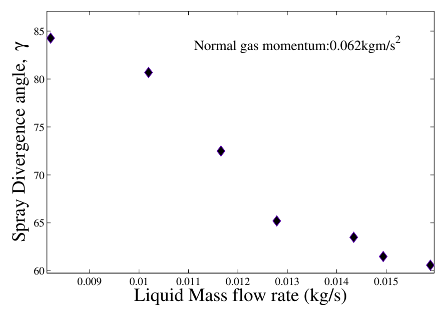
The SMD of a triplet spray depends on many factors like gas pressure drop, liquid mass flow rate, impingement angle etc. Efforts have also been made to describe the SMD of the spray in terms of a single parameter as earlier. The global SMD at an axial station of 6 cm from the injec tor tip at various impingement conditions like impingement



(a) Variation of Spray divergence angle with Normal gas momentum



(b) Variation of Spray divergence angle with Half Impingement angle



(c) Effect of central liquid mass flow rate on Spray divergence angle

Fig. 5 Variation of Spray divergence angle with different parameters

pressures and angles are plotted against the ratio of normal gas momentum to liquid mass flow rate. The plot shows a very high value of correlation coeffcient indicating once again that it is the appropriate parameter to describe the spray.

The effect of gas pressure on SMD at any particular radial location is shown in the Figure 10. This set of measurements are made at a further downstream location where the laser beam can provide resolution of radial distance . It can be seen that the spray SMD increases when measured along the width due to the thinning of the inner region. Moreover it may be observed from the above figure that as the NMGL increases, the SMD at any lateral position decreases.

A comparative study of gas-on-liquid impinging injector for triplet and doublet configuration as cited in [[9]] has been performed to understand the effect of configuring the orifices on spray SMD. It has been observed that at high mass ratios's the SMD are nearly comparable. At low mass ratios the SMD of triplet configuration drops down to very low value. This may be due to the gas jet penetrating and bifurcating the liquid spray whereas there is no such penetration through the doublet spray. The plot as shown in Figure 11 is in terms of mass ratio as the triplet configuration was introduced to reduce spray asymmetry for a given mass ratio.

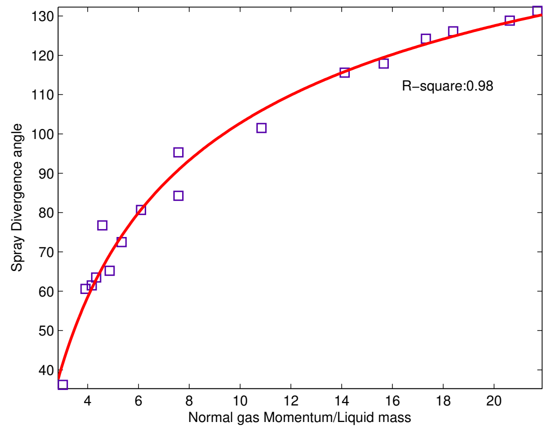


Fig. 6 Spray divergence angle with respect to nramal gas momentum to liquid mass

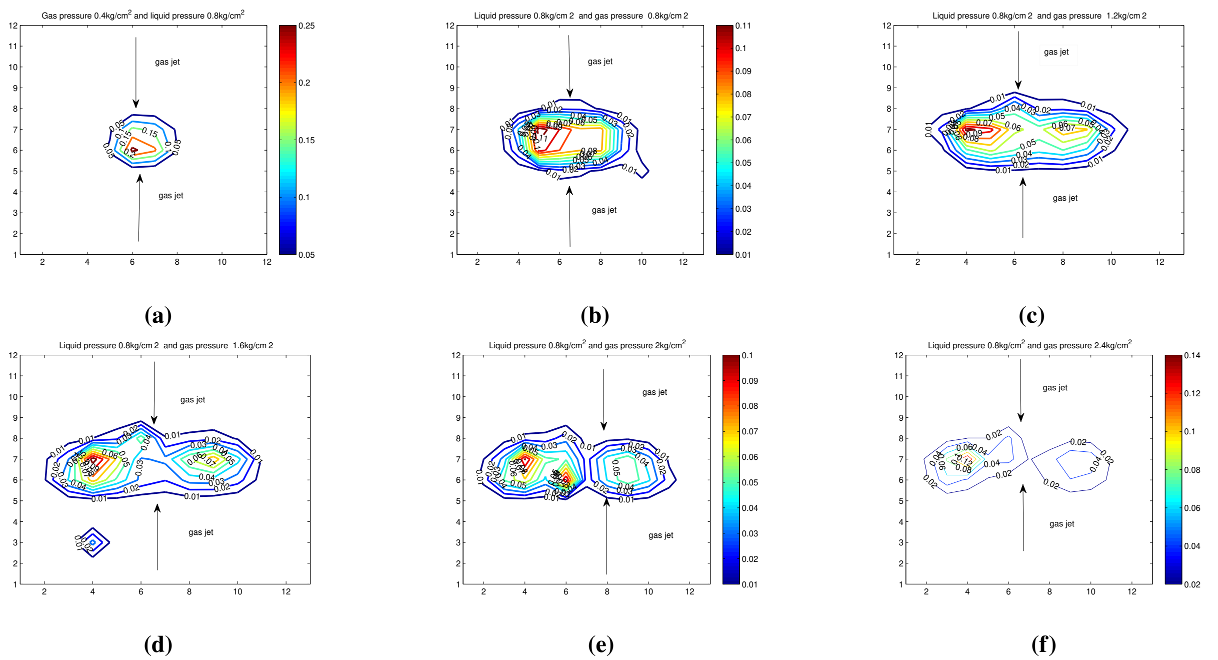
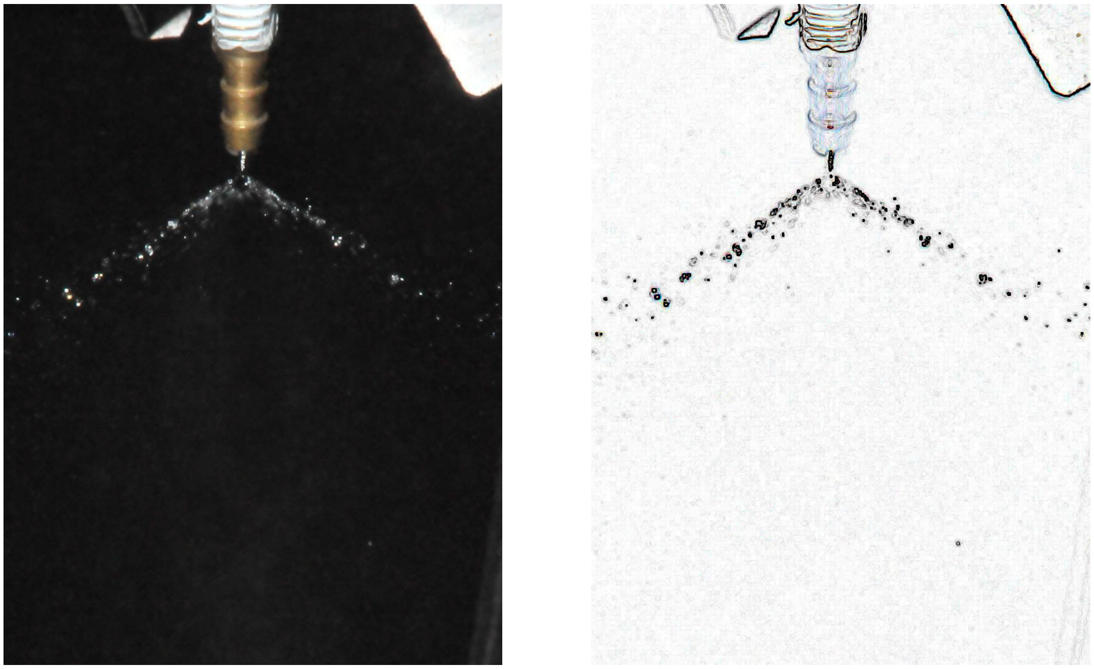


Fig. 7 Mass distribution at dierent normal gas momentum to liquid mass ratio, (a) NMGL:2.4, (b)NMGL:5.6, ( )NMGL:8.09, (d)NMGL:9.42, (e)NMGL:11.12, (f)NMGL:12.67

IV. Conclusion

The suitability of central liquid triplet configuration for the gas-on-liquid impingement atomization has been studied. The motivation for the study was the fact that the triplet configuration was able to give more uniform distribution compared to doublet configuration for certain mass ratios. The bifurcation and separation of the jets dictate the limit for such configuration. Like the doublet gas-on-liquid impinging doublet jets, the normal gas momentum to liquid mass was found to be a suitable parameter in describing the triplet spray parameters covering the divergence angle, mass distribution as well as spray drop size. The nature of penetration of gas jet in the present case of triplet is very distinct



(a) bifur ation of water jet **(b) image processed for greater clarity**

Fig. 8 Bifurcated water jet

from the doublet case as described in [10].The SMD of the triplet spray is comaparable to doublet arrangement at high mass ratios, however finer atomization is observed at low mass ratios.

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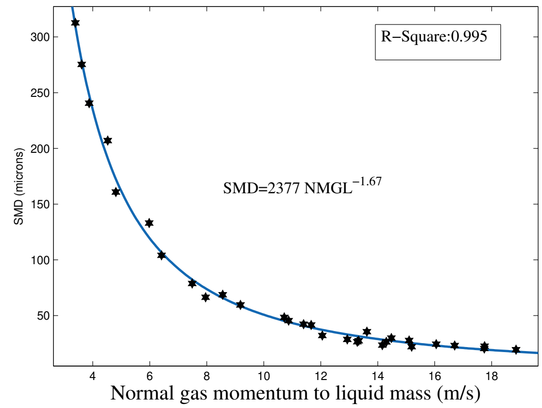

Fig. 9 Significance of total normalgas momentum to liquid ratio

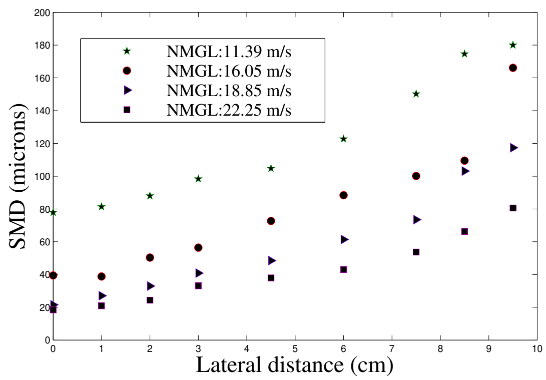

Fig. 10 Significance of total normalgas momentum to liquid ratio

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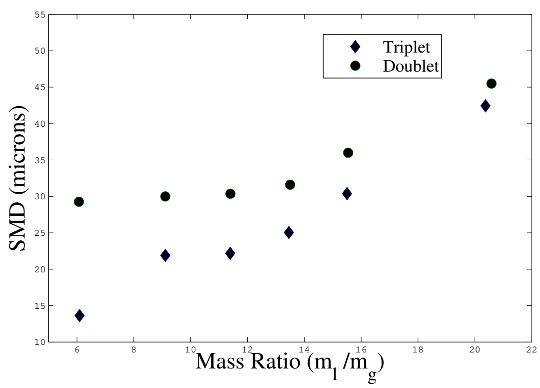

Fig. 11 Comparison of doublet & triplet configuration for gas-on-liquid impingement