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# **EFFECT OF VARIABLE GAS ORIFICE GEOMETRY ON GAS-ON-LIQUID IMPINGING INJECTORS**

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## **ABSTRACT**

Impinging jet injectors has often been a preferred con-figuration in liquid propellant rockets, the most common form of which is the Liquid-on-Liquid doublet. This config-uration provides numerous advantages that it can be pro-posed as an alternative to coaxial injectors for engines em-ploying gas-liquid propellants. Efforts to achieve this re-sults in Gas-on-Liquid impinging injectors employing iden-tical orifices. Nevertheless a problem identified with it tha t it could not give desired mass distribution for a given mass ratio (MR). This problem could be corrected by using vari-able gas orifices. In the present work the effect of employ-ing variable gas orifices is investigated. It has been found that at low MR the SMD (Sauter mean diameter) obtained by using variable gas orifices are comparable and at high MR the small orifice yields low SMD. For the MR used for cryogenic application the large orifice require only low pressure budget rendering it a suitable choice.

## **NOMENCLATURE**

MSR Mass ratio (liquid to gas)

SMD Sauter mean diameter

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## **1.INTRODUCTION**

Impinging jet configuration is an oft preferred injector geometry for rocket engines that use storable liquid bipro-pellants. Considering the relative advantages in terms of simplicity in design, quality control and low fabrication cost, these injectors can also substitute coaxial injectors which are the mainstay for the current gas and liquid pro-pellant combinations [1]. But the present design principles and performance characteristics of unlike impinging injec-tors have not been as well enunciated as for coaxial injec-tors. Compared to shear coaxial atomizer impinging jet in-jectors are easy to manifold and simple to design. In ad-dition they can 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 to be 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 [2] are the diameter, length and inclination of the orifices, inter-orifice distance which along with the inclination decides the pre-impingement development 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 symmetric 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.

Most of the published work on impinging injectors deal with liquid-on-liquid type of atomizers, although only a few among them deal with unlike media. Parametric studies on such atomizers [3] 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 Douglass et al. [4] 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 [4] greater the impingement angle, greater the amount of propellant back-flow. In fact propellant back-flow is proportional to the cosine of the impingement angle. The angular distribution and mixing uniformity also depends on the impingement angle [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 [6].

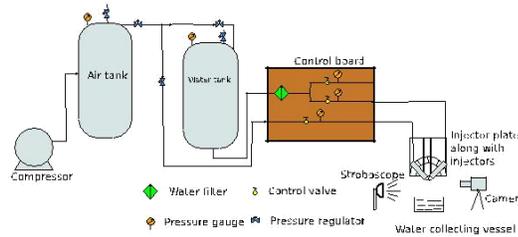
The reports available on gas-on-liquid configuration are scanty. One such study [3] has shown that the dominant factors for gas-liquid impingement which influence drop size are the injected momentum ratio of jets, the dynamic pressure of injected gas and orifice diameter ratio. For constant orifice diameter ratio increase in dynamic pressure decreases the spray diameter [3]. The effect of the ratio of liquid orifice to gas orifice as studied by Mehegan reveals that for constant dynamic pressure it increases the spray drop size. The spray shaping effect of the variable gas orifice configuration has been shown to some extent by Douglass [4]. This configuration does not seem to have attracted much interest later although it appears to have certain application potential as well as possess very interesting physics. The study by Rakesh et al. [7] revealed that normal gas momentum to liquid mass ratio as an important parameter in describing the spray at various operating conditions. However the study with equal sized injectors found spray deviation towards the wall at desired mass ratio to be a major problem. The present study therefore re-examines this by employing variable gas orifice size for a fixed liquid orifice which may solve the problem. The gas and liquid used in present study are air and 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 experienced in the laboratory conditions.

## 2. EXPERIMENTAL DETAILS

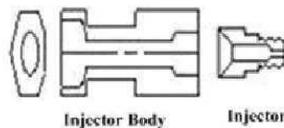
In the present study the gas used is air and the liquid used is water which simulate at appropriate mixture ratios the propellants such as gaseous hydrogen and liquid oxygen which is used in shear coaxial atomizers. Figure 1 shows the experimental setup used for studying the characteristics of gas-on-liquid

impinging injectors. It consists of a two stage reciprocating compressor with an intercooler 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 at 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 injector on the left side of the injector plate through a valve and a pressure gauge. A water tapping is taken from the bottom of the water storage tank and is connected to a filter on the control board. The line from the water filter is then led to one of the injectors through a control valve and a pressure gauge.

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 can be inserted with relative ease. The injector is smoothly con-verged so as to minimize pressure loss. The arrangement permits variations in orifice sizes, inter-orifice distance and the inclination of the jets. The orifice sizes in the present work range between 0.5 and 1.5 mm and the pressure drop up to 7 atm. Calibration runs have shown that typical orifice discharge coefficient was above the sharp edge value of 0.61 but rarely above 0.9. Under the operating conditions 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 orifice size limitations in the laboratory.

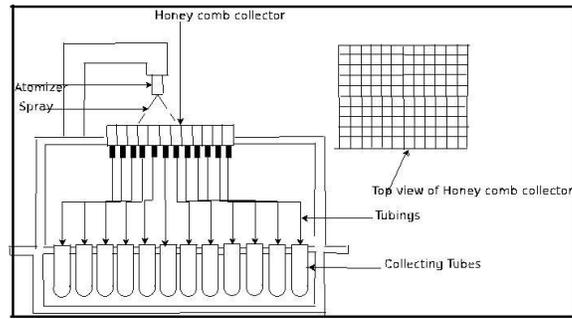


**FIGURE 1. SCHEMATIC OF EXPERIMENTAL SETUP.**



**FIGURE 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 clamped 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 the sample is collected for measurement. The test tubes are also arranged in a 12 × 12 fashion in a specially designed tray. The test tubes used for sample collection are 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 efficiency for the mentioned patternator ranges from 65 to 80 % .



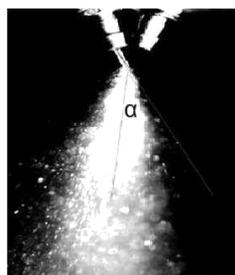
**FIGURE 3. SCHEMATIC OF THE PATTERNATOR USED IN THE STUDY**

The droplet size distribution was measured using Malvern Mastersizer X particle analyzer which works on the principle of diffraction of a laser beam in the presence of droplets in the spray. The instrument provides the line of sight averaged diffraction data. A large number of experiments are conducted to bring out the effect of variable gas orifice area on the Gas-on-Liquid impingement process. This includes oversizing and undersizing the gas orifice in relation to the liquid orifice.

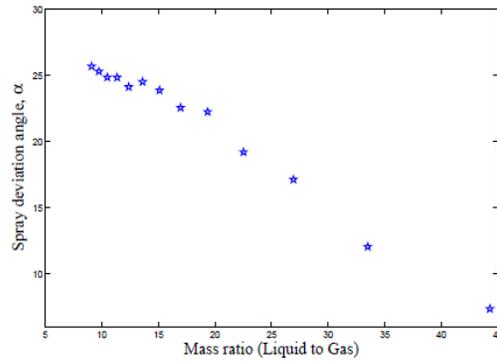
### 3. RESULTS

Experiments with equal orifice Gas-on-Liquid impinging injectors have revealed that for a required mass flow ratio it is difficult to obtain a desired mass distribution. Moreover as the gas pressure drop increases for a fixed liquid pressure drop the resulting spray mass gets skewed to one side of the combustion chamber resulting in hotspots on the walls, thus resulting in combustion chamber damage. The study of the spray deviation angle reveals that it is very much depending on the momentum ratio (MR) of the jets. Since the density of gas is less than that of liquid, a very high pressure drop is required for the gas jet to achieve the same mass flow rate of liquid. Thus for the required mass ratios in some applications the equal orificed impingement may give skewed spray distribution

A mass distribution study has been conducted for finding the spray mass concentration at different mass ratios. The mechanical patternator mentioned earlier has been used for the purpose. Figure 5 shows the mass distribution for various gas and liquid pressure drops. In order to study the effect of momentum ratio on the mass distribution



(a) Spray deviation angle (view in the plain of orifices)



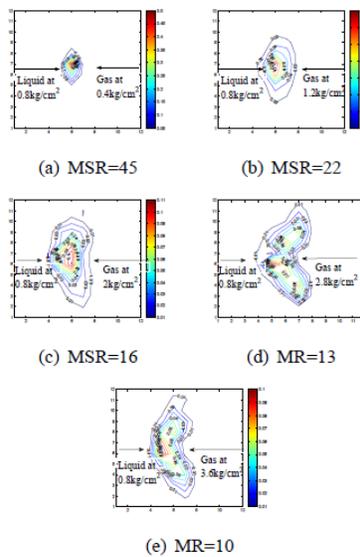
(b) Spray deviation angle variation with MSR

**FIGURE 4. SPRAY DEVIATION ANGLE VARIATION WITH MSR**

of Gas-on-Liquid impinging jets, test were carried out by keeping the pressure drop of water at  $0.8 \text{ kg cm}^{-2}$  and the air pressure drop varying from  $0.4 \text{ kg cm}^{-2}$  to  $3.6 \text{ kg cm}^{-2}$  thus changing MR from above unity to below unity. The re-sult of the mass distribution study is shown using contour plots which is suitable for any injector.

It was observed that initially the mass distribution is el-iptical and when the gas pressure drop is increased a dent is formed on the elliptical surface. This dent increases with MSR and after some MSR the dent size doesn't vary much. We can see from the above contour plots that the location of maximum mass region represented by the red region in the contour plot shifts with gas pressure drop and after a particular MSR it's position is mainly stagnant. It was ob-served that that as the MSR increases the spray major axis width increases.

Thus we have seen from the above plots that for re-quired mass ratio's of about 10, the spray mass distribution may not be a desired one.



**FIGURE 5. EFFECT OF MASS RATIO ON THE MASS DISTRIBUTION OF GAS-ON-LIQUID IMPINGING JETS (a) MSR=45, (b)MSR=22, (c)MSR=16 (d)MSR=13,(e)MSR=10**

Thus in order to obtain the desired mass distribution experiments are done with variable gas orifices. The size of the gas orifice is varied from 0.5 to 1.5 mm. The pressure drop for gas nozzle was varied from 0.4 kg cm<sup>-2</sup> to 4.8 kg cm<sup>-2</sup> and that of liquid nozzle kept constant at 1.2 kg cm<sup>-2</sup>. Figure show the plot showing the effect of orifice diameter on SMD at various mass ratio's. The plot revealed that that SMD obtained with various gas orifices depends upon the MSR. As MSR increases the SMD in the case of large orifices increase rapidly because most of the mass goes out without impinging the liquid jets. The gas jet issuing out of the orifice diverges rapidly (divergence phenomenon varies depending upon the gas jet is subsonic or under expanded sonic). This divergence along with the large width cause most of the gas jet to pass without impinging the liquid jet. The large gas jet may also reduce the divergence of the spray. For a given MSR the small orifice gives a small SMD. This is because for a small orifice, to keep the same mass flow rate as that of large orifice, large dynamic pressure should be high. This dependence of the dynamic pressure on drop size has been verified by Mehegan.

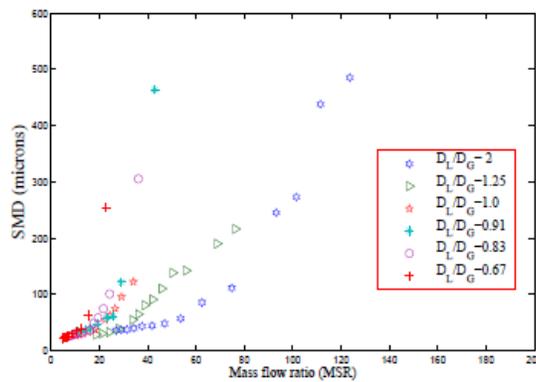


FIGURE 6. EFFECT OF VARIABLE GAS ORIFICE ON SPRAY SMD

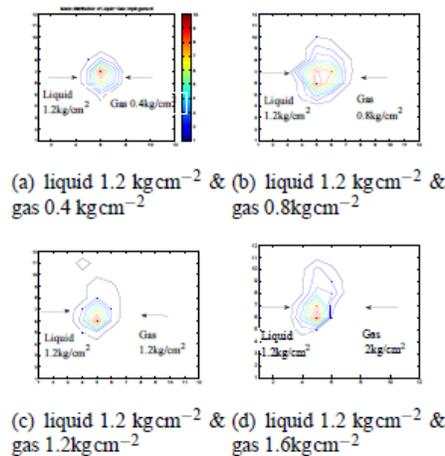
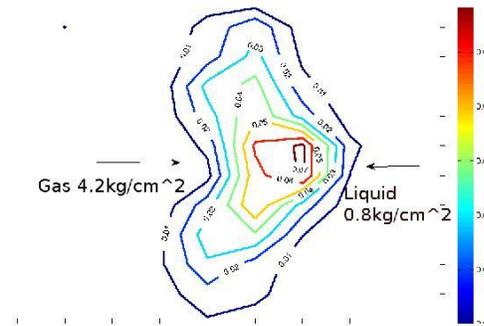


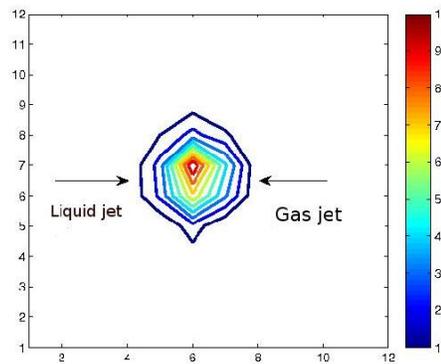
FIGURE 7. MASS DISTRIBUTION PLOTS FOR LIQUID DIAMETER 0.5mm & GAS ORIFICE DIAMETER 1.2mm (a) LIQUID 1.2 kg cm<sup>-2</sup> & GAS 0.4 kg cm<sup>-2</sup>, (b) LIQUID 1.2 kg cm<sup>-2</sup> & GAS 0.8 kg cm<sup>-2</sup>, (c) LIQUID 1.2 kg cm<sup>-2</sup> & GAS 1.2 kg cm<sup>-2</sup>, (d) LIQUID 1.2 kg cm<sup>-2</sup> & GAS 1.6 kg cm<sup>-2</sup>

Due to this higher mass flow rate is required for large orifice for getting the same SMD as of smaller orifice. As seen from the figure the slope of each set of data points changes after reaching a particular mass ratio, which is higher in the case of small orifice. The following figure 7 shows that mass distribution plot for variable gas and liquid orifice diameters. The gas orifice diameter being 1.2 mm and

liquid orifice diameter being 0.5 mm.



(a) mass ratio:8 &  $D_1/D_g$ : 1



(b) mass ratio:8 &  $D_1/D_g$ : 0.4166

**FIGURE 8.** MASS DISTRIBUTION AT VARIOUS  $D_1/D_g$  (a)MSR:8 &  $D_1/D_g$ : 1, (b) MSR:8 &  $D_1/D_g$ :0.4166

Thus for the process of getting uniform distribution gas orifice diameters were changed for a constant liquid orifice diameter. It was found that as the gas injector diameter increases in relation to the liquid diameter more uniform distribution is obtained. As the gas diameter increases in relation to the liquid diameter, more gas mass flow rate is obtained at a less pressure drop. Thus more or less a elliptical mass distribution can be obtained at desired gas mass flow rate. Moreover for a particular liquid to gas orifice diameter as the gas pressure increases in relation to the liquid diameter the distribution becomes more non-uniform as confirmed from the mass distribution studies. The following plot shows a comparison of the mass distribution obtained for equal orifice gas and variable gas orifice nozzle for a mass ratio of 8. Thus Fig. 8 and Fig. 6 confirm that using variable gas orifice geometry helps to achieve the desired spray characteristics.

#### 4. CONCLUSION

The effect of variable orifice geometry on Gas-on-Liquid impingement has been studied. The motivation for the work came from the disadvantages occurred with equal orifice Gas-on-Liquid injectors. For equal orifice injectors sometimes the desired mass ratio cause skewness of the resulting spray which cause it to impinge the combustion chamber walls thereby damaging it. Moreover with equal orifice

injectors it is difficult to obtain desired mass distribution for a given mass ratio as the gas jet needs more pressure drop for a given mass flow rate. The study with variable gas orifice injectors reveals that in the range of mass flow ratio's used with cryogenic applications the dependence of SMD on gas orifice size is negligible. At high mass ratio's the small orifice gives better atomization which may be due to its high dynamic pressure at same mass flow rate. The mass distribution plots with variable gas orifice injectors confirm that desired mass distribution can be obtained which makes it superior to the equal orifice configuration.

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