Experimental study of effects of type of injectors on the performance of gas generator of liquid rocket engine

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Abstract. The role of the injector is atomization and mixing. It dictates the size and geometry of the combustion chamber and gas generator. Experiments are conducted with water-cooled adjustable length gas generator for a liquid rocket engine with two types of injectors at a lower mixing ratio. Tests are conducted at characteristic length of 1.75 and 4.27 m. Liquid oxygen and kerosene are used as propellants. Single pressure swirl coaxial injector and three like doublet impinging injectors are used. Combustion performance is studied and compared on the base of characteristic velocity. Characteristic velocity is found high at short length but is found low at larger length for pressure swirl injector as compare to impinging injectors.

1. Introduction
Atomization and mixing are two main parameters based on which type of injectors are selected and distributions of injectors are made in a liquid rocket engine. Various types of injectors and patterns have been used in past in different engines [1–3]. Popular injectors used in rocket engines are impinging injectors, pressure swirl injectors, and pintle injectors. Pressure swirl injectors are more widely used due to its performance over large range flow rates [4, 5]. Impinging injectors are simple in construction and can be used for higher oxidizer to fuel mixing ratio effectively [6]. Poor atomization with bigger droplet size requires more time in the chamber for complete evaporation and burning. The exit of unburned fuel droplet decreases the efficiency of combustion. The more characteristic length of the chamber is required for bigger droplets as compared to the smaller droplet.

In the gas generator cycle liquid rocket engine, the gas generator is used to produce gas to drive the turbine, which produces the power to run fuel and oxidizer pumps. The power of the turbine is dependent on the energy available in the gas and mass of the gas. The energy of the gas is a function of temperature and pressure of gas generator. More gas is required if the pressure and temperature of the gas are low. The temperature of the gas is limited by the material of the turbine [7]. If the performance of the gas generator is low then it uses more propellant to produce required pressure at the desired temperature. The use of extra propellant will decrease the overall specific impulse of the system, resulting in extra weight and volume. An increase in the weight is afforded at the cost of the payload of the vehicle. An increase of one kg of weight of system causes a reduction of one kg of payload if the system is the last stage of the vehicle. A comparative study is always required to select a proper type of injector and configuration for the desired project.

2. Experimental setup
The experimental setup used in the present experiments consists of portable test stand, high-pressure nitrogen bottles, manifold, pressure regulators, pressure sensors, k type thermocouple, PT100 thermocouple, adjustable length gas generator with replaceable head, two heads and data acquisition system.

Figure 1 shows the test stand which was used in these experiments for testing. The design of the test stand was such that it could test a small gas generator in horizontal position. The test stand had two tanks one for liquid oxygen and another for kerosene. Tank for liquid oxygen was a double wall with vacuum insulation. There were five switching valves, three for the on-off purpose of liquid oxygen, kerosene, purging supply to the gas generator and two for the liquid oxygen tank and kerosene tank for emergency evacuation. Two ball valves were used for the fuel tank, one at the filling point and the other in the supply line. One ball valve was used at the liquid oxygen filling point. Pressure sensors were used to measure pressure at injection and in the chamber.

Three high-pressure nitrogen bottles were used to pressurize the fuel tank. The flow rate of oxidizer was less in this case so the oxidizer tank was pressurized with one high-pressure bottle.

![Figure 1. Test stand.](image1)

Figure 2 shows the bank of high-pressure bottles. The outlet of all three bottles combines in a manifold and a single outlet pipe from manifold passes through pressure regulator into the fuel tank. Figure 3 shows a single injector gas generator. This gas generator was water cool and the characteristic length was adjustable. Characteristic length was adjusted as 1.75 m and 4.27 m for different tests. Figure 3 shows, pressure ports, spark plug, K type thermocouple connection and water flow in and out connections. Every two parts of the gas generator were bolted together with the help of M10 bolts. Two heads were used in these tests one with pressure swirl injector and other with like doublet impinging injector. Spark plug was used for ignition in the gas generator.

![Figure 2. High pressure bottles bank.](image2)  
![Figure 3. Adjustable length gas generator fitted for testing.](image3)

Figure 4 shows a pressure swirl injector fitted in replaceable head and detail of pressure swirl injector used in this gas generator respectively. Details of the impinging injector used in one head are
shown in figure 5. Three doublet injectors one for oxidizer in middle and two for fuels at ends are prepared in a single piece which is fitted in place of pressure swirl injector.

Figure 4. Replaceable injection head with pressure swirl injector.

Figure 5. Detail of impinging injectors in a single piece.

3. Experimental procedures
The flow rates of the injectors were measured experimentally at the pressure of 6, 7 and 8 bar for both types of injectors and both paths with water. A plot shown in figure 6 and 7 is produced based on Eq.-1 to simulate flow rate of oxidizer and fuel at different pressures for pressure swirl and impinging injector respectively. Experimentally measured flow rates of water were used as a base to calculate the flow rate of kerosene and liquid oxygen. The discharge coefficient of pressure swirl atomizer has no or very less dependency on pressure drop and viscosity [8]. The discharge coefficient is independent of Reynolds number for Reynolds number of more than 4000, which was more in this case [9]. Pressure swirl injector used for fluid having low viscosity has a constant discharge coefficient [2]. Therefore results of Eq-1 were reliable where the discharge coefficient had been taken constant and the effect of
viscosity on flow rate had been neglected. The outer passage was used for fuel and inner passage for oxidizer in the pressure swirl injector.

\[ m = \text{water flow rate} \times \sqrt{\frac{\text{fuel or LOX density}}{\text{density of water}}} \times \sqrt{\frac{\text{new pressure}}{\text{pressure of water test}}} \]  

(1)

where \( m \) is mass flow rate in Eq-1.

Figure 6. Flow rate variation with pressure drop for pressure swirl injector.

Figure 7. Flow rate variation with pressure drop for doublet impinging injectors.

The schematic diagram of the procedure is shown in figure 8. To save time liquid oxygen tank was time optimized chilled with opened vent and filled with liquid oxygen from the bottom side [10,11]. The vent was closed and the supply tank was disconnected. Liquid oxygen was passed from the oxygen tank through the injector into the chamber. The temperature of the liquid oxygen in the dome was noted and was kept under observation. The thermocouple used for this purpose was Pt100. The chilling process was continued till the temperature of the liquid oxygen reached -155 °C. Oxygen is in the liquid phase at -140 °C and 14 bar pressure [12]. Both liquid oxygen and kerosene valves were opened simultaneously. The spark plug was triggered to start ignition. At shutoff, both propellant valves were closed, the spark was off and the purging valve was open to make a smooth end.

Figure 8. Flow chart of the experimental setup: (1)high pressure bottle (2)Ball valve (3)Manifold (4)Pressure regulator (5)Oxidizer line (6)Double wall oxidizer tank (7)Fuel tank (8)Solenoid valve (9)Purging line (10)Fuel line (11)Gas generator.
4. Results and discussion

Initial three important pressures are plotted in figure 9. Pressure drop for an initial fraction of second is low at the start of the test. As tanks pressures were regulated at a required pressure so pressure drops for both injectors were high due to low chamber pressure at the start. There was an increase in the mixing ratio from 0.31 to 0.37 as shown in figure 10. Drop in the mass flow rate was compensated by an increase in the mixing ratio to maintain a steady chamber pressure of 6.3 bars. There was drop in mass flow rate from 0.093 to 0.087 Kg/sec in the steady period of the test. Figure 9 and 10 are showing results of the test at a characteristic length of 1.75 m.

Figure 9. Chamber pressures with pressure swirl injector at characteristic length of 1.75 m.

Figure 10. Mass flow rate and mixing ratio with pressure swirl injector at characteristic length of 1.75 m.

Figure 11 and 12 show results of the gas generator at the characteristic length of 4.27 m. Even at a lower mixing ratio as compared to the previous test with a characteristic length of 1.75 m, there was an increase in chamber pressure with an increase in the characteristic length of the chamber.

Figure 11. Chamber pressures with pressure swirl injector at characteristic length of 4.27 m.

Figure 12. Mass flow rate and mixing ratio with pressure swirl injector at characteristic length of 4.27 m.

Combustion chamber pressure shown in figure 13 for the gas generator with the same characteristic length as shown in figure 9 is less. The mixing ratio as shown in figure 14 is less as compared to the gas generator with pressure swirl injector and same characteristic length.

Figure 13. Chamber pressure with impinging injector at characteristic length of 1.75 m.

Figure 14. Mass flow rate and mixing ratio with impinging injector at characteristic length of 1.75 m.

Figure 15 and 16 show the results of the gas generator with impinging injectors and a characteristic length of 4.27 m. Due to the pressure drop in the fuel tank, there was a decrease in fuel flow rate but an increase in the mixing ratio. Chamber pressure was stable between 7.4-7.2 bars.
Figure 15. Chamber pressures with impinging injector at characteristic length of 4.27 m.

Figure 16. Mass flow rate and mixing ratio with impinging injectors at characteristic length of 4.27 m.

Figure 17 and 18 shows a comparison of characteristic velocity at characteristic lengths of 1.75 and 4.7 m respectively. Characteristic velocity is a measure of the performance of the gas generator and is given by the following equation as [3].

\[ C^* = \frac{P_c A_T}{m} \]  

(2)

It is clear from these two figures that the performance of the gas generator with a pressure swirl injector was good at low characteristic length but was low in performance with a higher characteristic length of 4.7 m even mixing ratio was high as compared. The reason for the low performance of the impinging injector at lower characteristic length is the low mixing ratio. At low mixing ratio, the temperature of the chamber is low and fuel droplets require more time in the combustion chamber for complete burning. Moreover, droplet size may be more in the case of the impinging injector.

Figure 17. Characteristic velocity of gas generator with characteristic length of 1.75 m.

Figure 18. Characteristic velocity of gas generator with characteristic length of 4.27 m.

5. Conclusion
Tests were conducted to test the performance of the gas generator at two characteristic lengths of 1.74 and 4.27 m with two different injection head. Water cool gas generator with liquid oxygen and kerosene as fuel were used as propellants. Pressure swirl coaxial injector and impinging injectors were used. The performance of the pressure swirl injector at lower length was found better but the performance of the impinging injector was better with larger characteristic length.

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