Cold Flow Characterization of Triplet Injector Head Realized Through Additive Manufacturing

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Abstract

Additive manufacturing is an emerging field in the area of fabrication process and being employed for the realization of rocket engine systems and subsystems. This process is comparatively cheaper and requires less lead time compared to conventional machining process. PSLV, a workhorse launch vehicle of ISRO uses a pressure fed PS4 engine for its upper stage. This engine is realized through conventional machining routes and qualified for flight so far. An attempt has been made to realize the PS4 engine through additive manufacturing route at LPSC. Injector is the major part of the engine which controls the combustion process inside the combustion chamber of rocket engine. It is imperative to realize the injector head first through additive manufacturing and checked for its cold flow performance. The present work investigates the cold flow characteristics of PS4 triplet injector head realized through additive manufacturing. PS4 injector consists of 45 nos of triplet injector elements, injecting oxidizer through the two angular impinging orifices and fuel through the central orifice. There are also 36 nos of fuel film cooling elements placed at the periphery of the injector face angled at 45°. Cold flow characteristics were evaluated for both oxidizer and fuel flow paths at the rated flow rates. Experiments were also conducted at different pressure drops to evaluate the coefficient of discharge for both oxidizer and fuel orifices. Impinging patterns of the oxidizer flow path was also visualized through photographic method.

Keywords: *Triplet Injector head, Additive manufacturing, Coefficient of discharge*

1. Introduction

The combustion chamber is the most important part of any liquid rocket engine, gas turbine engine or automobile engine. In case of liquid rocket engine, propellants are injected in atomised form through injector inside the combustion chamber. The characteristics of the injector decides the efficacy of thrust chamber which in turn decides the performance of the liquid rocket engine. Injector should meter the correct proportions of the propellants, atomise it in the form of droplets and distribute these in correct proportions inside the combustion chamber in order to achieve stable combustion. Different types of injectors are used in liquid rocket engine such as impinging jet injectors, swirl coaxial injectors, shear coaxial injectors etc. Impinging type of injectors is commonly used with oxygen hydrocarbon and storable propellants. These injectors can be classified into doublet impinging and triplet impinging types [1]. PSLV, a workhorse launch vehicle of ISRO uses a pressure fed PS4 engine for its upper stage. This engine uses impinging type of injectors. PS4 injector head consists of 45 nos of triplet injector elements, injecting oxidizer through the two angular impinging orifices and fuel through the central orifice. There are also 36 nos of fuel film cooling elements placed at the periphery of the injector face angled at 45°. This engine is realized through conventional machining routes and qualified for flight test so far. An attempt has been made to realize the PS4 engine through additive manufacturing route at LPSC.

Additive manufacturing is an emerging field in the area of fabrication process and being employed for the realization of rocket engine systems and subsystems. This process is comparatively cheaper and requires less lead time compared to conventional machining

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process. It is imperative to realize the injector head first through additive manufacturing and checked for its cold flow performance. The present work investigates the cold flow characteristics of PS4 triplet injector head realized through additive manufacturing. Cold flow characteristics were evaluated for both oxidizer and fuel flow paths at the rated flow level. Experiments were also conducted at different pressure drops to evaluate the coefficient of discharge for both oxidizer and fuel orifices. Impinging patterns of the oxidizer flow path was also visualized through photography method.

2. LITERATURE REVIEW

Additive manufacturing is a non-conventional manufacturing process which has progressed over the last decade. Due to its inherent advantages above the conventional process, this technology is being employed for the realization of various systems or sub systems of liquid rocket engine throughout the world.

Soller et. al. [2] discussed regarding the injector development logic followed for the injectors realized through additive manufacturing. They discussed about the material characterization, single element characterization, sub scale testing and then full scale demonstrator. They used Vulcain 2 gas generator injector for the introduction of additive manufacturing on a full scale engine. They also investigated the thrust chamber injector of Vinci engine was with respect to the possibilities to apply additive manufacturing on a larger injector in addition to the Vulcain gas generator. Paul et. al. [3] provided the details of various internal programs at the NASA MSFC using additive manufacturing to develop combustion devices hardware. They informed that combustion devices component hardware ranging in size from 100 lbf to 35,000 lbf have been designed and manufactured using SLM and deposition-based additive manufacturing processes, and many of these pieces have been hot-fire tested at the NASA MSFC. The different combustion devices component hardware like thrust chamber injectors, injector components such as faceplates, regeneratively-cooled combustion chambers, regeneratively-cooled nozzles, gas generator and preburner hardware, and augmented spark igniters are fabricated using additive manufacturing method. They explained the results on the hot fire tests conducted on these subscale and large scale components. David et. al. [4] investigated the design modifications using CFD and experimentally tested a single-element liquid oxygen/kerosene swirl coaxial injector fabricated using additive manufacturing method. Reddy et. al. [5] compared the spray and liquid sheet characteristics of single element injector with different orifice shapes fabricated using additive manufacturing method. Ahn et. al. [6] investigated the cold flow characteristics of five different types of coaxial injector fabricated using additive manufacturing. They analyzed the injection pressure drop, discharge coefficient, spray pattern, breakup length, and spray angle for each injector and concluded that the shape of the oxidizer post had a significant influence on the performance of the injector. Jedesky et al. [7] investigated the effect of fabrication method and surface roughness on spray characteristics for pressure swirl atomizers. They evaluated the spray characteristics of these injectors using PDA and mechanical patternator.

Though a number of studies have been conducted for cold flow characterization of swirl injectors fabricated using additive manufacturing, there is not enough information available for impinging type of injectors. The present paper details about the cold flow characterization carried out on triplet impinging injector head manufactured using additive manufacturing.

3. Experimental hardware and objectives

A triplet injector head with film cooling orifices is realized through additive manufacturing process. The test article consists of 45 nos of triplet injector elements, injecting oxidiser through the two angular impinging orifices and fuel through the central orifice. There are also 36 nos of fuel film-cooling elements placed at the periphery of the injector face angled at 45°. The objective is to study the performance of injector manufactured through additive process. Cold flow evaluation consists of pressure drop estimation of oxidiser and fuel orifices for nominal and off-nominal flow rate, impingement pattern of doublet (oxidiser) and spray pattern of fuel orifices and measure the percentage of fuel available for film cooling of the chamber wall.

4. Description of experimental setup

The experimental setup consists of a VFD controlled multistage centrifugal pump to generate required injection pressure for the test medium stored in a run tank. Each feedline consists of perforated filter elements to limit particle size above 50microns entering test article. The mass flow rate through each flow path is independently measured using Micromotion make Coriolis mass flow meters. The injection pressure of the test medium is tapped close to inlet manifold to eliminate pressure drop in feedline and is measured using Rosemount make pressure transmitters. DM water is used as simulant fluid for characterizing the injector. Ambient pressure is assumed as 1 bar. The schematic of the setup is shown in Figure 1.

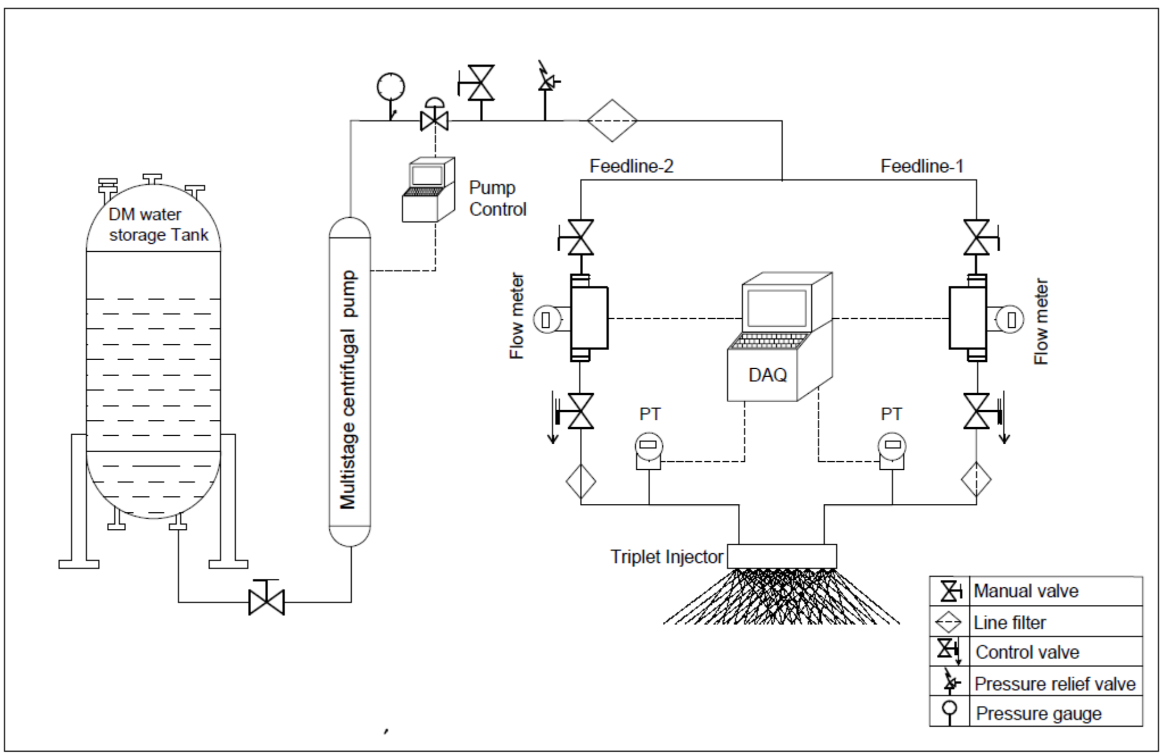

Figure 1: Schemtic of Experimental Set up

5. MEASUREMENT METHODOLOGY

Three different fixture configurations were used to carry out the measurements depending on the parameter being investigated. Figure 2 shows the different types of fixtures used during the experiment. Fixture-1 was configured to measure pressure drop through the fuel flow path of the injector head with minimum pressure drop in fixture. This fixture configuration had shorter tube length to minimise pressure drop in line and had a projection from injector face due to which visualisation is inaccessible. Fixture-2 was used for proper visualization of spray impingement pattern. This fixture was configured to enhance visualisation by directly connecting feedlines into fuel flow manifold. Fixture-3 was used to independently measure flow available for film cooling. Oxidizer flow was not routed through fixture part as it can be directly connected to facility flange.

Fixture-1 Fixture-2 Fixture-3

Figure 2: Fixture configurations used during experiments

The combination of experiments conducted using different fixtures are shown in Table 1:

Table 1: Test details with fixture configuration

Sl.No.	Test details	Flow path	Fixture	Flow condition	Flow rate (g/s)
1	Flow visualisation and impingement pattern	Oxidizer	Directly mounted to facility interface	100%	1194
				50%	597
				15%	180
2		Fuel	Fixture-2	100%	1093
4	Pressure drop estimation	Oxidizer	Directly mounted to facility interface	100%	1093
				50%	597
5		Fuel	Fixture-1	100%	1093
				50%	547
6	Film cooling percentage	Fuel	Fixture-3	100%	1093
7				50%	547

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6. Results and discussion

6.1. *Flow through oxidiser orifices*

Hardware was subjected to cold flow evaluation of injection through the oxidiser flow paths alone. Experiments were conducted at various pressure drops ranging from 1 bar to 6 bar and oxidiser flow rates were measured. During the experiments, the flow rate was varied in such a way that it covers the flow range from 55 % to 128 % of nominal value. The pressure drop value was also observed to be normal.

Figures 3 and 4 respectively show the variation of oxidiser mass flow rate and CdA with respect to pressure drop. It is seen from the data that the CdA decreases with increase in pressure drop. This is expected due to the contraction coefficient for orifices at higher velocities.

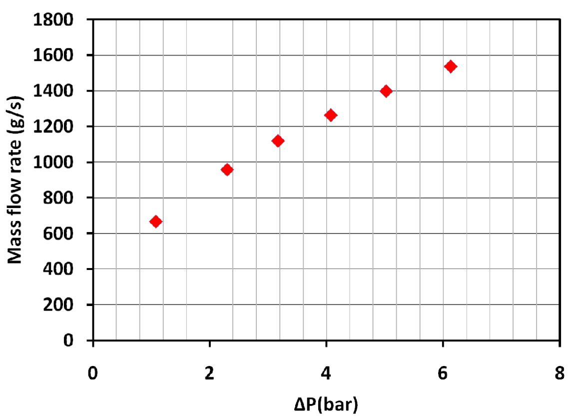

Figure 3 Mass flow rate vs. ΔP (Oxidiser orifices)

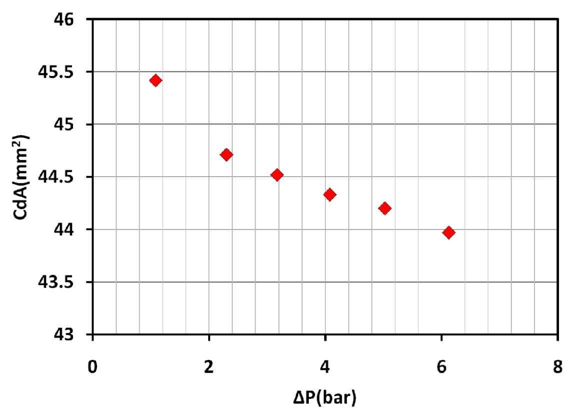

Figure 4 CdA vs. ΔP (Oxidiser orifices)

Further visualisation tests were also conducted simulating the nominal mass flow rate and off-nominal flow rate at 50% and 15 %. All orifices were visually verified for impingement pattern. These doublets were impinging at uniform distance and fan formation was also in the perpendicular direction as shown in Figure 5.

Figure 5: Impingement and fan formation of doublet oxidiser jets at 15% flow rate

Figures 6 and 7 show the impingement pattern for 100% of flow rate and 50% of flow rate through oxidiser path respectively. Overall the cold flow performance of oxidiser flow paths realised through additive manufacturing is in line with that of conventional manufacturing.

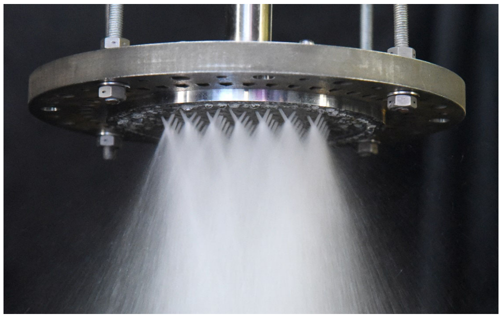

Figure 6: Impingement at 100% flow rate

Figure 7: Impingement at 50% flow rate

6.2. FLOW THROUGH FUEL ORIFICES

Experiments were also carried out for fuel flow path (combined flow of core and film cooling) at various pressure drops ranging from 1 bar to 6 bar. During the experiments, the flow rate was varied in such a way that it covers the flow range from 57 % to 131 % of nominal value. Figures 8 and 9 show the variation of fuel mass flow rate and CdA with respect to pressure drop respectively. It is seen from the data that the CdA decreases with increase in pressure drop like oxidiser path. The reduction in CdA value is comparatively less compared to oxidiser path. This can be attributed to the difference in entry configuration of the orifices. The fuel orifices of core flow are open to a common manifold where the oxidiser doublet configuration has a U shaped cavity into which the orifices are connected with an inclination to create doublet exit jet configuration.

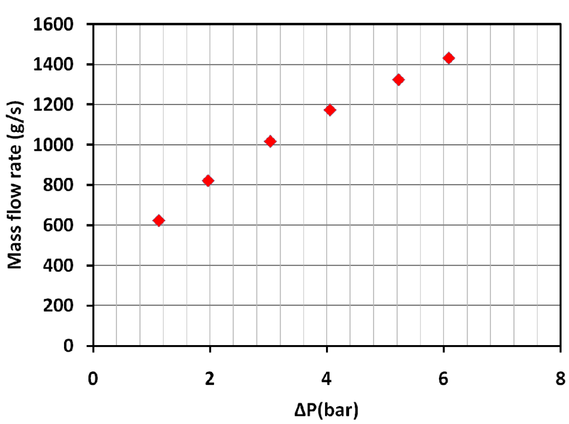

Figure 8 Mass flow rate vs. ΔP (Fuel orifices)

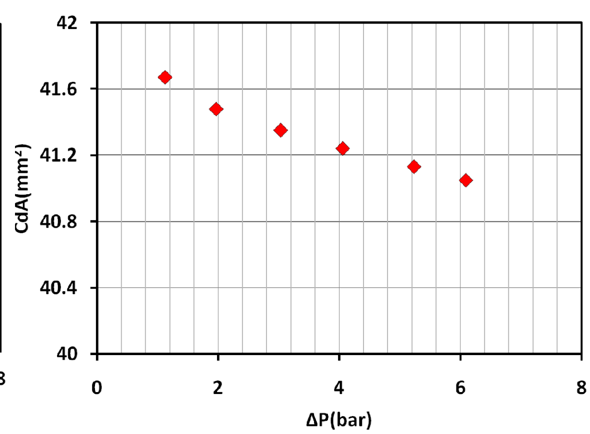

Figure 9 CdA vs. ΔP (Fuel orifices)

Further, visualisation experiments were also conducted for fuel orifices at nominal mass flow rate and at 50% of nominal value. Each fuel orifices were visually verified for individual core fuel flow jets and film cooling jets. All the orifices were having normal flow pattern and film cooling jet through radial passages were exiting. Figures 10 and 11 show the jet pattern for fuel orifices at100% of flow rate and 50% of flow rate respectively.

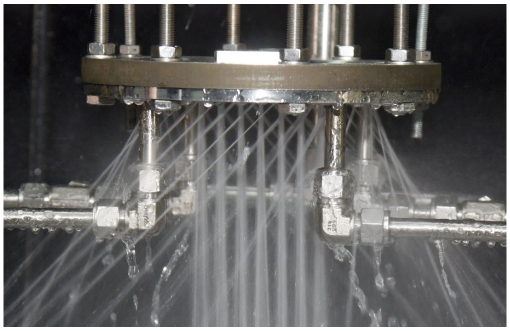

Figure 10: Fuel jet pattern at 100% flow rate

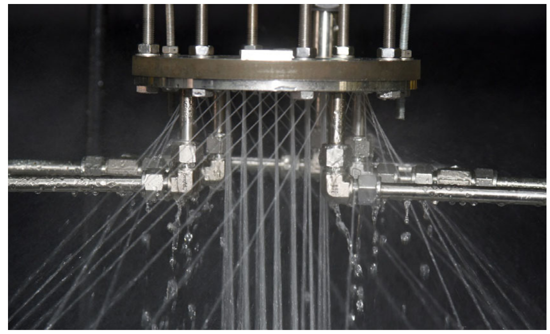

Figure 11: Fuel jet pattern at 50% flow rate

6.3. Evaluation of film cooling percentage

To measure the percentage of flow through film cooling orifice, flow through central orifices were isolated using Fixture-3. Flow through the core fuel orifices was collected for a specific duration and flow through the film cooling orifices were computed from the total flow rate. Film cooling percentage was measured for both nominal flow and 50 % nominal flow. Results shows reduced flow (~26-27%) through film cooling passage against the design value(~30%) at 50% flow rate and in case of nominal flow rate, reduction in percentage of film cooling by about 1% was observed compared to 50% flow rate .

7. Conclusions

Experiments were conducted for a triplet injector head manufactured through additive manufacturing for its cold flow characterization. Flow behavior of both oxidizer and fuel orifices were measured. Results indicate that pressure drops observed for both oxidizer and fuel paths are within the design specifications. Visualization experiments show that impinging pattern of oxidizer orifices and jet pattern of fuel orifices are normal. The percentage of fuel available for film cooling is marginally lower than the design specifications.

8. Future work

Experiments are planned to evaluate the effect of surface finish and geometrical tolerances of injection orifices using triplet injector head. Experiments are also intended to evaluate its spray characteristics using high speed imaging and drop size and its distribution using Malvern Particle Sizer. Further comparative spray characterization studies of this injector is also planned with respect to triplet injector head through conventional machining process.

Acknowledgements

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