ADDITIVE MANUFACTURING IN ROCKET COMPONENTS: ANALYSIS OF AN INJECTOR

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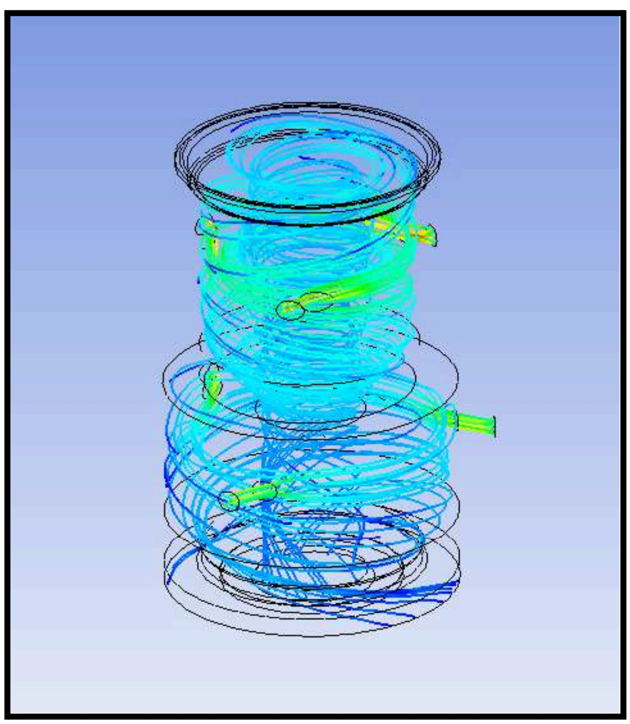
ABSTRACT

Additive Manufacturing (AM) is a fast approaching, relatively new solution to many complex engineering problems. It is seen as a potential enhancement to subtractive manufacturing such as machining, jetting and cutting. Like all other industries, the aerospace industry (with a specific target on the rocket manufacturing industry) has seen an advent of its use, evident by the 2012 experiments by NASA on injectors as one of the initial rocket components targeted for AM. The Selective Laser Melting (SLM) method of AM is seen to be the most popular for complex geometries among a variety of others. Rocket injectors are the most suitable rocket components to be manufactured through SLM as claimed throughout this paper. Lastly, water testing and CFD simulation data points are used to model a personally-designed coaxial swirl injector which will be 3D printed replicating AM at a basic level. Deviations in spray patterns were evident between the two models with a positive relation of the spray angle in response to pressure for both. However, the main difference lay in the mass flow rates with the paper inquiring the factors behind it.



INTRODUCTION

Additive Manufacturing (AM) – different from subtractive traditional manufacturing– is a method which fabricates three dimensional (3D) hardware geometries from layer by layer deposition of filament material through a heated printhead or LASER. The process involves using Computer-Aided-Design (CAD), with the help of a digital software further used by 3D printers to create exact hardware models. Machining on the other hand is subtractive in nature, meaning that larger metal blocks or bodies are machined to produce the desired geometry, leaving behind waste metal.

AM is not just a trend, however, with proven advantages beginning with significant waste reductions comparatively to traditional methods. The subtractively produced waste metals (swarfs) might be recycled by chipping and melting. However, in most cases, due to reasons pertaining to contamination by cutting fluid, irregular shapes after machining and the extra costs which go into recycling, they present significantly less value. AM produces significantly less waste with certain aerospace components reducing waste production by 90 percent. Let us take an example(Davis, 2021) in the Aerospace Community, NASA's Space Launching System (SLS), responsible for deep space exploration and the ARTEMIS mission, took about 11 years to produce its first mission (part of a series) mainly due to the need to manufacture the Vertical Assembly Center (VAC) a 170 foot tall tool to weld domes, rings and barrel sections of the rocket's fuel tanks. While this might be a requisite for deep space exploration missions with its emphasis on reliability, rigorous testing, with proven methods, Relativity Space has another way to look at their projects. Targeting the AM vision, they are testing to achieve faster, reusable aerospace production. After the initial one time set-up gestation period for the 3D printers and post-processing, they claim to produce low orbital rockets such as Terran 1 in a matter of months. The flexibility of the 3D printers in this scenario is a long term time-saver.

Some other benefits of AM include eliminating the requirement of extra assembly processes due to technical limitations, making the entire manufacturing process less labor intensive and more automated. AM allows for a single manufacturing process to produce the design instead of assembling 100s of different machined parts together as seen in the production of cooling channels, ducts (specially around the nozzle) and injectors. The time saved thus makes it possible for continuous prototyping and various hardware iterations which become extremely beneficial for engineers to experiment and customize a complex design. (Video: How Additive Manufacturing Is Advancing the Space Industry | Additive Manufacturing, 2019)

Laser Powder Bed Fusion

Laser Powder Bed Fusion, also known as Selective Laser Melting (SLM), is the most common process used in aerospace components. The process begins with the 3D CAD being sliced into thin, almost two-dimensional layers that dictate the operation of the laser beams, directed by motor controlled mirrors (scanning system). (Preparation of Papers for AIAA Technical Conferences, 2018) A layer of powder is flattened on a build platform. Precise laser positionings, sinters (heats but not melts) the powder to produce layer-by-layer geometries according to the 2D slices.

After the geometry is formed, the fabrication pistons descend, moving the platforms, allowing the lasers to work on top of the previous layer. (Preparation of Papers for AIAA Technical Conferences, 2018) Post-building, the product is to be kept inside the printer for a further duration to cool it down and avoid warping. The reason behind its wide-scale application edging over other processes is because of its high tolerance to complex geometries producing finer detailing. However, like all manufacturing techniques, it comes in a mixed bag. For instance, the rough, grainy finish on the body surface may demand post processing to an extent. Also, it might not be applicable for extremely large components like body tubes or even nozzles due to build plate limitations with present technology being of dimensions up to 850x850x1,000 mm^3.

Direct Energy Deposition (DED)

DED was introduced before SLM. It involves a slightly different process including a 4 or 5 axis arm with a nozzle fixed to it. The nozzle deposits the melted material onto a surface which then solidifies to fuse with the preceding layers. The material, a wire, or powder is either melted by a laser or an electron beam (Directed Energy Deposition | Additive Manufacturing Research Group, n.d.). The most common type of DED, which is the Laser Wire Deposition technique, provides the lowest heat flux and uses thin wire diameters. Either the arm moves in multi-axial directions or, in rare cases, the surface itself. A purging gas, an inert gas such as argon, is used with the nozzle operation to prevent oxidation at high temperature in the case of highly reactive metals like titanium, or aluminum, while also preventing contamination improving overall deposition quality. Taking the example of Relativity again, they use wire based DED to manufacture major rocket parts like the fuel tank and nozzle of their rocket Terran 1. They use this process over SLM due to the main advantage of dimensional flexibility in the build area, opening the doors to print bulkier components. Since there is absence of an airtight build container, the included sizes push beyond the limit for sub 1 m3 constraints by its counterpart: SLM. However, the resulting products are prone to a rougher surface finish comparatively to SLM and a major problem regarding the absence of adequate support. SLM uses a powder bed for support. Conversely, DED lacks any legitimate support structure, unless manufactured separately, with only the previous layers acting as it. This limitation can make it challenging to produce complex geometries. In fact, until recently, it was mostly used for repairs instead of actual manufacturing for this reason.


Figure # 1.1
DED(left) - wire based vs. SLM(right).
(Preparation of Papers for AIAA Technical Conferences, 2018)

INJECTORS

Injectors of liquid or gaseous propellants, placed in the engine at the start of the combustion chamber really do have a simple purpose: mixing. They need to ensure appropriate atomization, a mixture of the fuel and oxidizer molecules (in cases of bipropellant, fuel and oxidizer stored in separate tanks), to produce efficient and reliable combustion providing the enormous thrust amplified further through the nozzle. A poor injector design often results in the expulsion of unburned propellants decreasing combustion efficiency. The speed of the fluid flow is related to the pressure drop across the high and low pressure sides of the injector by Bernoulli's principle which states within a streamline fluid flow, higher fluid flow regions have lower pressure and vice versa.

$P + \frac{1}{2}\rho v^2 + \rho g h = constant$ Or simply, $v = \frac{\sqrt{2\Delta P}}{\rho}$

Assuming incompressible, steady, laminar flow with an inviscid fluid stream.
(Bernoulli's Principle & Bernoulli Equation - Definition, Derivation, Principle of Continuity, Applications, Examples and FAQs, n.d.)

Where,
P = *Pressure of the fluid at a point*
ΔP = *Pressure Drop*
ρ= *Density of the fluid*
v= *Velocity of the fluid at a point (m/s)*
g = *Gravitational acceleration*
h = *Height of the fluid*

$\frac{1}{2}\rho v^2$ = *Dynamic pressure*
$\rho g h$ = *Hydrostatic pressure*

In most cases, rocket injectors are considered to be one of the most complex and important parts in a rocket. The following are a few types of the injectors: shower heads, impinging(doublets or triplets), swirls, pintle.

CASE STUDY - ROCKETDYNE F1 ENGINE

NASA's Saturn V rocket with its first mission over 50 years ago, Apollo 4 essentially led the foundations for modern rocketry and space habitations. It is most famously known for the Apollo 11 mission credited for the first manned moon landing. Utilizing five F-1 rocket engines, the Saturn V rocket's first stage generated 7.5 million pounds (3.4 million kg) of thrust during its two-minute launch. It consumed 40,000 pounds, or 20 tons, of fuel every second. (F-1 Engine Injector, n.d.)

A LOX dome serves as a connector for Liquid Oxygen (LOX), channeling the oxidizer from storage tanks to the combustion assembly through its two inlets. Similarly, the fuel inlet manifold performs the same function for RP-1, a type of kerosene used as fuel. These components feed into an impinging injector, designed to atomize the propellants by colliding the oxidizer and fuel streams at precise angles. The resulting fine spray enters the thrust chamber, where it is ignited to produce the thrust necessary for propulsion.

From the mission requirements of the first stage of Saturn V we know that the necessary delta V (an indicator of combustion efficiency needed for the 67 Km journey of the stage) is 2400 m/s. Using the Tsiolkovsky rocket equation we can find the mass flow rate to be achieved by the injector:

$$dv = v_e . ln\frac{m_0}{m_f} = ISP. g. ln\frac{m_0}{m_f}$$

and to find mass flow rate:

$$\mu = \frac{dm}{dt} = \frac{m_f - m_0}{dt} ,$$

where

dv = *the change in velocity of the rocket (m/s)*
v_e = *the effective exhaust velocity of the propellant (m/s)*
m_0 = *the initial mass of the rocket (kg)*
m_f = *the final mass of the rocket after propellant burn (kg)*

μ = *mass flow rate (kg/s)*
dm = *change in mass of the rocket (kg)*
ISP = *Specific impulse (s)*
g = *acceleration due to gravity at sea level (m/s^2)*
dt = *change in time*

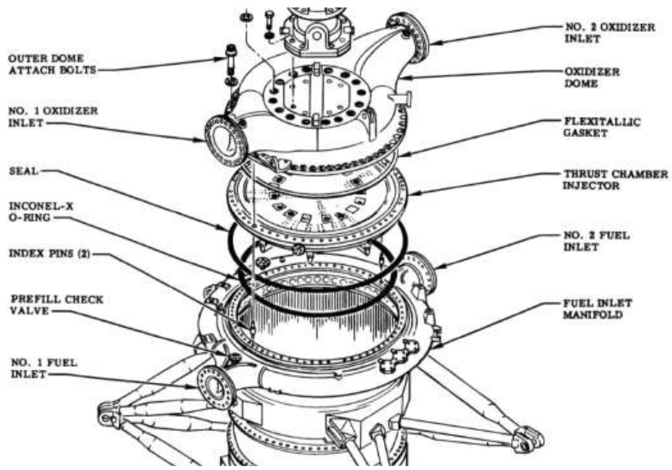


Figure # 1.2 (F-1 Engine Injector, n.d.)

Project First, the F-1 combustion stability program, conducted 2000 out of the 3200 full-scale tests. The engine uses an impinging style of injector which are basically angled orifices, or holes, which strike fast flowing fluid on each other to atomize. This can be further classified to like-like, unlike-like in terms of fuel-oxidizer, fuel-fuel or oxidizer oxidizer components, or doublets and triplets (F-1 Engine Injector, n.d.)

The injector featured 15 rings of oxidizer orifices and 14 rings of fuel orifices, totaling 2,832 orifices on the injector face. It received propellants through 31 ring grooves – 16 for fuel and 15 for oxidizer – with the fuel and oxidizer rings brazed to copper rings holding the orifices. The fuel grooves were fed by 32 radial passages from the fuel inlet manifold, while the oxidizer grooves were supplied axially by LOX domes. Machining these intricate, angled orifices and grooves was difficult and time-consuming, with any error potentially causing combustion instabilities from poor mixing, leading to hot spots and pressure oscillations.

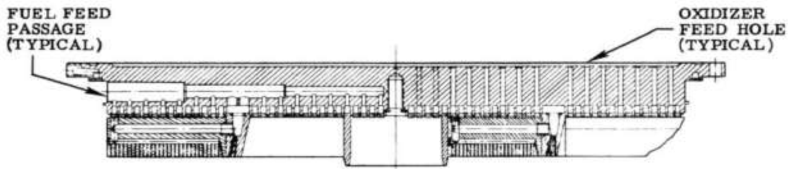


Figure # 1.3 (F-1 Engine Injector, n.d.)

Combustion instabilities, caused by uneven fuel-oxidizer mixtures, led to test failures, including engine explosions and violent vibrations. This was addressed by adding 12 baffle-inspired pods, based on the V2 injector design which divided the injector into 13 compartments. These reduced acoustic resonance and instability shock waves. Coaxial swirl injectors, which provide stable combustion, were also used.

Additionally, orifices for the fuels and oxidizers underwent design changes. The uniform orifices would counter-intuitively produce uneven spray distributions and localized hot spots to form. Therefore, the injectors went through design changes in angling the orifices and sizes were made uneven, focusing on optimizations by mainly filling in excess spaces requiring several iterations which would have been easier to go about today with Additive processes or Computational Fluid Dynamics (Thiel, n.d.).

SWIRL INJECTORS

Swirlers are a particular type of injectors which work on the principle of centripetal force. Let us take an example of a rotating wine bottle facing downwards as illustrated by Markus Grigo. The liquid inside starts to spin around the bottle's axis as it descends producing a swirling effect. The spinning of the liquid is a result of the centripetal force acting on the fluid elements which is directed towards the center (Pedersen, 2019). However, each fluid element has inertia, which resists the inward pull, causing the liquid to push outward against the walls. This outward movement forms a low-pressure vortex core in the center, allowing air to flow in through the cavity. The simultaneous inflow of air and outflow of liquid enhances mixing and increases the overall flow rate. A similar process occurs in a rocket injector but not by actually rotating the body. Instead, we apply a tangential velocity to the fluid flow providing a natural swirl discussed later.

Figure # 1.4 (Volumetric Flow Rate: Equation & Units, n.d.)

The following CAD example, in Figure 1.5, is of a coaxial swirl injector design developed by Copenhagen Suborbitals for their modified BM P5 engine. In this model, we can see the injector being divided into two major spaces: Outer channel (lower) and inner channel. Both the channels have three tangential inlets with the fuel transacting through the lower inlets and the oxidizer (Liquid) through the inlets attached to the core or inner channel. The fluid streams make their way down by swirling around the injector walls in thin films to finally exit as cones. With the right geometry, the two cones (fuel and oxidizer) exit homogeneously breaking up into tiny atoms (Pedersen, 2019).

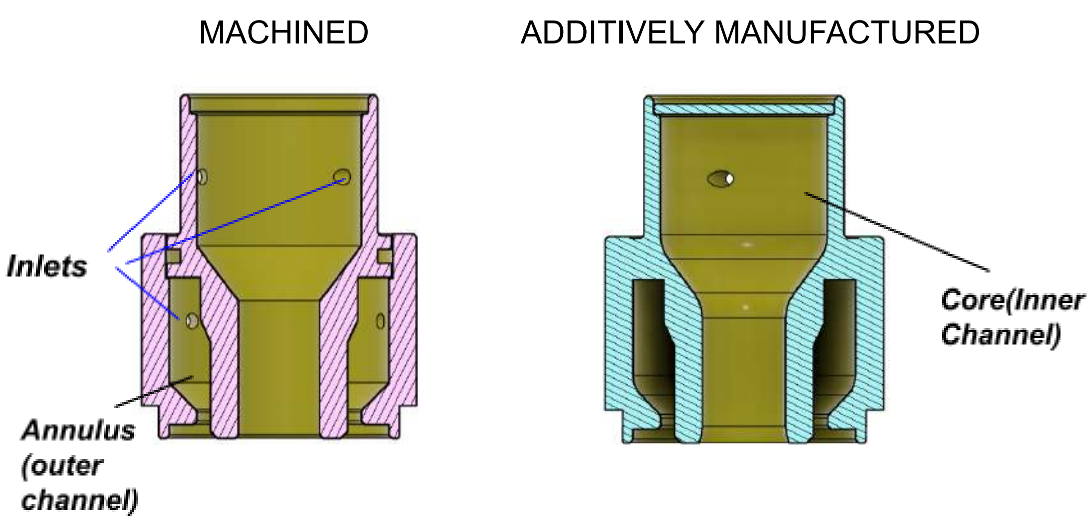


Figure # 1.5

There is speculation as to whether additive manufacturing could live up to the traditional standards of the injectors in terms of the flow rate. However, contrary to this notion, programs by NASA MSFC testing LOX/H2 coaxial swirls (Preparation of Papers for AIAA Technical

Conferences, 2018) compared to machine counterparts, subscale hot fire tests by Airbus Safran Launcher Stepwise dealing with small orifice geometries (Soller, n.d.), indicate otherwise. In fact, Copenhagen Suborbitals have indicated better flow characteristics with their own AM versus. traditional tests thanks to a unique feature which is not so much possible in traditional small scale productions: fileting. Rounding of steep edges within the flow route of the swirl core and the annulus reduces internal turbulence caused by flow separation from the injector walls. Involving edge filets ensures a more laminar flow and an even mixing around the orifices. There is the added benefit of reduced thermal stress concentrations arising due to sharp edges. Another benefit is that the latter does not require o-ring cavities, therefore reducing assembly costs and times by building the two main parts together. Additive manufacturing might pose the added benefits of not having to individually assemble inter-propellant plates. Instead, the entire build process will have it routed together minimizing assembly weight.

WATER TEST

For the water test of the two injector models - one with steeper edges as commonly produced through CNC and lathing injectors vs. one with filet edges with 3D printing techniques. The following is the experimental design mechanism:

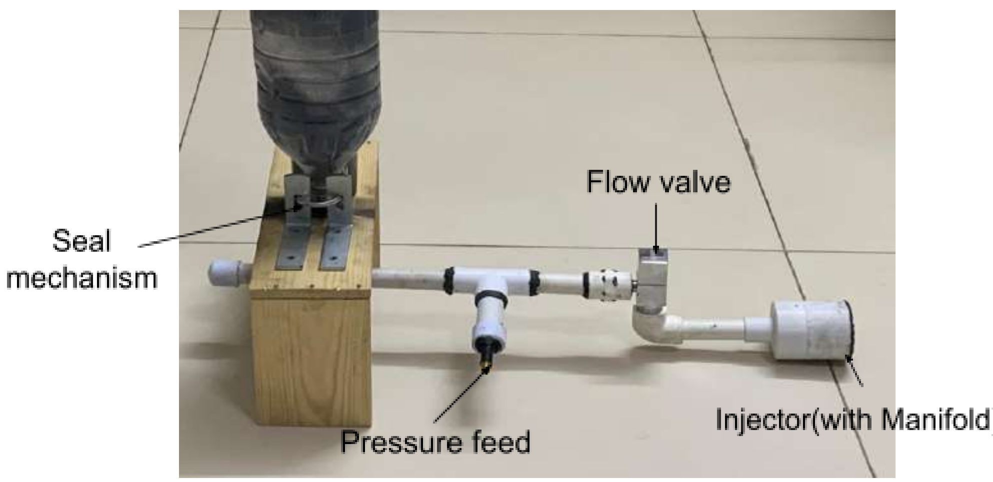


Figure # 1.6

The above pipe mechanism is made with PVC. The water for the experiment is stored in a pressurized reservoir. The pressure changes are measured through the pressure feed system connected to a hand pump with a pressure(in bar) gauge. This allows flexibility in the conserved internal pressure. The flow valve is responsible for stream transit to the manifolds(larger containers for the injector inlets), further detailed below:

Figure # 1.7

Injector type 1 represents the injector suited for machining and injector type 2 is the one suited for additive manufacturing. The system includes a manifold which equally transmits the high pressure water to the 3 center and 3 annulus holes.

Spray angle: The general trend concerning this parameter is that a wider angle means better atomization, providing better breakup of the liquid fuel into fine droplets, and promoting better mixing ratio across a larger volume of the combustion chamber (Experimental and Theoretical Study on Spray Angles, n.d.). A narrower angle, meanwhile, could mean localized concentration of the ejection leading to uneven spray distributions leading to vortex creations and instabilities. In fact, coaxial swirls are famous for their wide spray angle and hence, stability providing qualities.

Droplet size: In this experiment, in addition to the spray pattern record, a transparent surface is kept below the active injector to record the droplet size and their variations with gauge pressures across the spray length. Smaller droplet sizes increase the surface area-to-volume ratio of the liquid propellant and thus, also the combustion stability (Combustion of Liquid Fuels, n.d.).

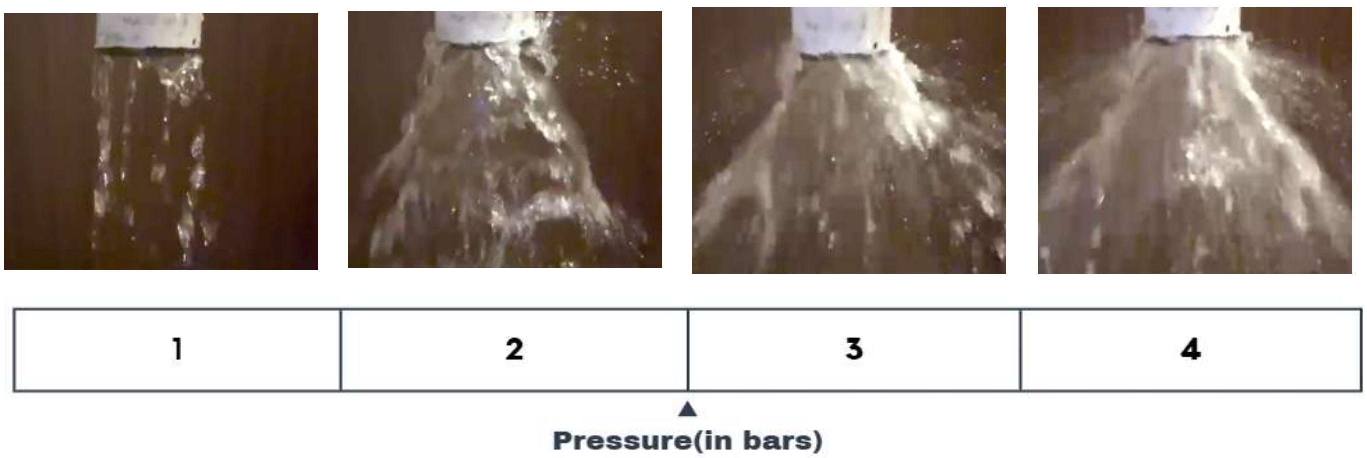


Figure # 1.8

The above injector, Figure # 1.8, is the traditional prototype. It shows a general increasing trend in the spray angle with the pressure (bars) and a rough conical shape. The spray angle shift is quite drastic in the lower regions, eventually stabilizing. However, atomization is not efficiently achieved at the tested pressure levels leading to undesirable patterns with high mean droplet sizes (taken 0.5 meters away from the laterally placed models) averaging at 3 mm radius. The maximum achieved spray distance is 0.75 meters.

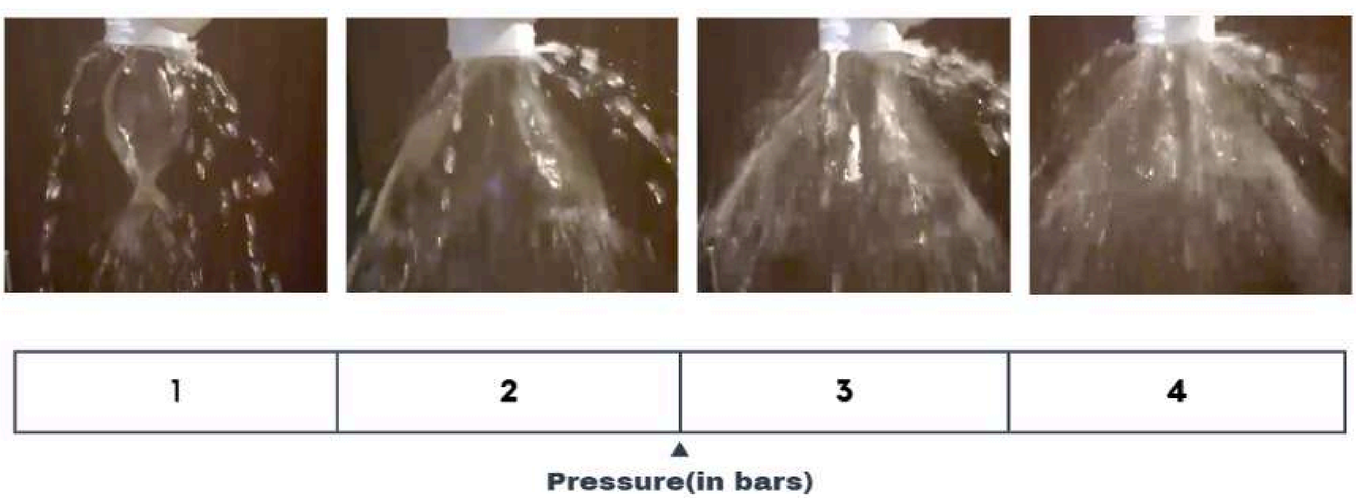


Figure # 1.9

The above injector presents the additively manufactured model. Again there is a positive correlation with the pressure and spray angle, forming a clearer, conical shape with an increase in pressure and a maximum spray distance of 0.7 meters. The angular difference is relatively even compared to the previous type showing a stabler shift. Atomization is better here. However, the presence of water residue diverging from the main pattern persists. Droplet sizes (taken 0.5 meters away from the laterally placed models) average at a 2 mm radius.

CFD

ANSYS 2024 R2 Student Version was used to model laminar flow in a simplified coaxial injector geometry. Focused on incompressible fluid flow, the continuity and Navier-Stokes equations were solved on a finite mesh using a second-order numerical solution. Boundary conditions included a set intake velocity and zero static pressure at the output to replicate water streamline flow.

Using the theoretical formula from Bernoulli's equation for a simple flow rate equation, we can hypothesize the CFD findings:

$$Q_t = A\frac{\sqrt{2(P_1 - P_2)}}{\rho^{1/2}}$$ (Volumetric Flow Rate: Equation & Units, n.d.)

where,

$Q_t = Theoretical\ flow\ rate$

$A = Outlet\ area = 2.4 * 10^{-3} m^3$

$P_1 - P_2 = Pressure\ difference\ between\ the\ inlet\ and\ outlet\ orifice = 1,990,000\ Pa$

$\rho = density\ of\ fluid(here:\ water) = 997\ kg/m^3$

Substituting, we get:

$Q_t = 164.6\ g/s$

The assumptions of this equation include incompressible, inviscid and steady-state flow. The above calculations are an example of the 3D printed injector at maximum provided gauge pressure.

Comparing this theoretical value with the experimental value (with the experimental flow rate measured by a weighing scale), we get the Coefficient of Discharge using the following formula:

$$C_d = \frac{Q_e}{Q_t},$$

where:

$Q_t = Theoretical\ flow\ rate$

$Q_e = Experimental\ flow\ rate$

$C_d = Coefficient\ of\ Discharge$

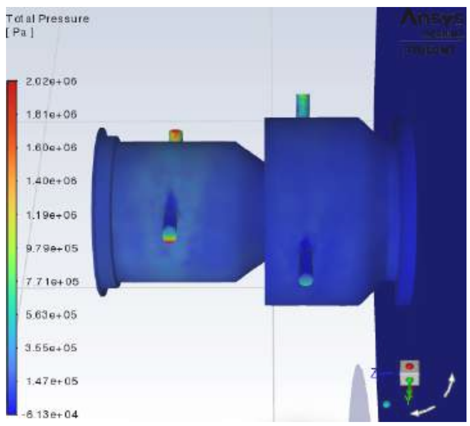


Figure # 2.0

Figure 2.0, shows pressure contours (in Pascals) of the given colour scale and ranges across the injector sections.

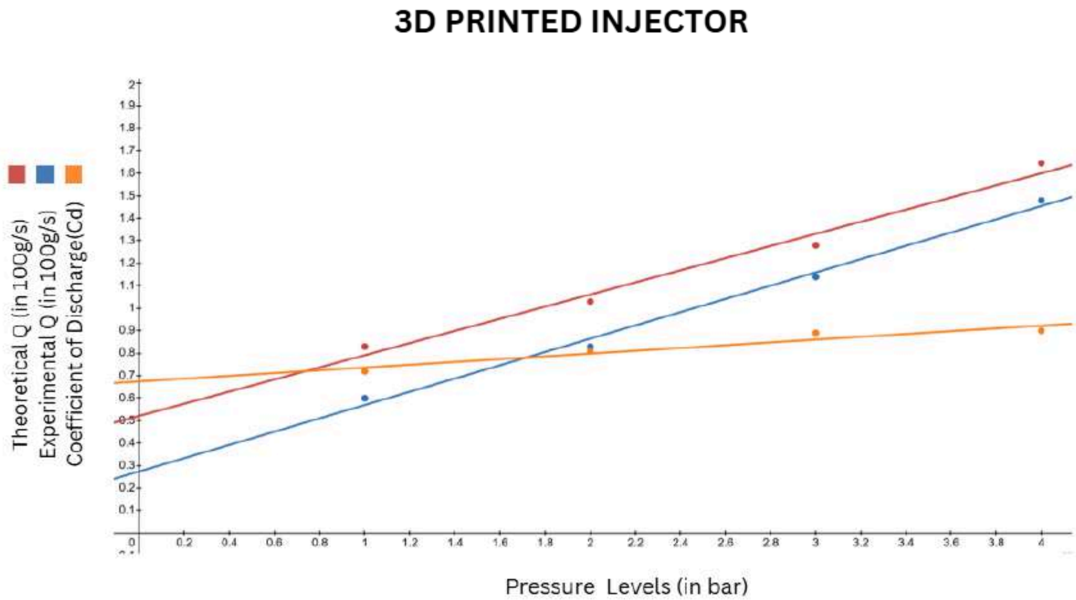


Figure # 2.1

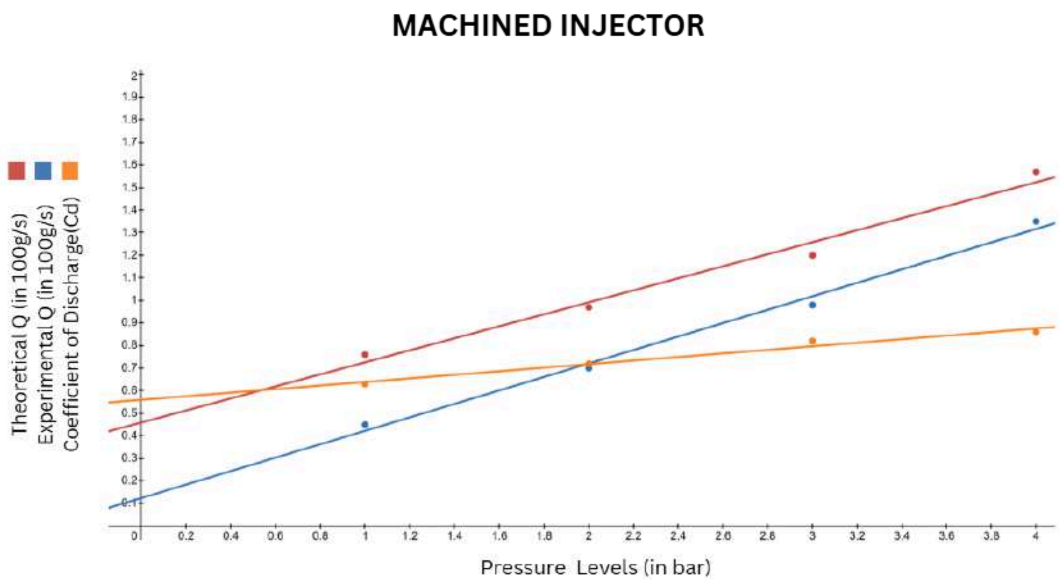


Figure # 2.2

DISCUSSION

From Figures 2.1 and 2.2, it is evident that the experimental and theoretical mass flow rates for the machined injectors are consistently slightly lower than those of their counterparts across all pressure levels. As previously discussed, this discrepancy may be attributed to surface friction, particularly at steep edges along the stream path, assuming ideal manufacturing precision and

stable experimental conditions for both types. This highlights the potential influence of surface texture and flow path geometry on the overall performance.
Moreover, it is essential to acknowledge minor inaccuracies, such as the device's least count of ±0.1 bars, which could have impacted the mass flow rate plots. These small deviations, while seemingly negligible, can have an effect on the observed data.

Also interestingly, the “machined” injector designs suitable for machine manufacturing are actually 3D printed due to lack of appropriate tools. However, consideration is given to differentiate the designs based on respective manufacturing method suitability. The discharge coefficient for both designs shows a clear trend of increasing with pressure, gradually converging toward unity. On average, the coefficient was around 0.7, maintaining reasonable alignment with theoretical predictions. A higher discharge coefficient is generally indicative of reduced turbulence and improved theoretical accuracy, which are desirable outcomes in such experiments. In the end, even though the spray pattern was uneven, with pulsation over time, the high discharge coefficient and favorable flow rates suggest that the experiment achieved its objectives.

CONCLUSION

Additive Manufacturing (AM) is a promising field for the future of engineering with empirical evidence of applicability through prevalent laser melting and direct deposition methods. In aerospace, injectors are arguably the best suited for 3D printing, especially the coaxial swirl based types which ensure a vortexual spray pattern with low combustion instabilities. The successful fluid simulation and water testing of a coaxial swirl injector prototype, in comparison to a “traditionally” manufactured design, along with a high discharge coefficient further validate AM’s role in advancing injector designs. As AM technologies continue to evolve, their application in rocket injector manufacturing will undoubtedly pave the path for more efficient, cost-effective, and innovative space exploration solutions.

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