USE OF ADDITIVE MANUFACTURING TO MODEL AND DEVELOP ADVANCED LIQUID PROPULSION DESIGNS

Distro-A: Approved for Public Release

MIDN 1/C James Catina, USN and Maj. Kristen Castonguay, USAF
United States Naval Academy Rocket Propulsion Program
Annapolis, MD 21402

ABSTRACT

Additive manufacturing has become an increasingly more affordable and capable engineering tool over the last decade. Its role in the engineering industry is becoming ever more important as the technology improves in accuracy, speed, efficiency, and affordability. Additive manufacturing gives researchers the opportunity to develop and manufacture new designs that would have been impossible to produce with traditional, subtractive means. The ability of this technology to produce parts with many alloys allows for engineers to develop new innovations that can be used in real-world practice. This is particularly advantageous in the high-pressure and temperature environments in which rocket motors and engines perform. Along with its well-documented benefits in cost- and time-savings, additive manufacturing represents a more technically-effective solution to the manufacturing of aerospace propulsion systems. Recently, researchers at the United States Naval Academy have worked to acquire, develop, and collaborate with others within the engineering field that can perform additive manufacturing of parts. Through this research, additive manufacturing will be used to design, manufacture, test and confirm the ability of additive manufactured designs to reduce the weight of liquid propulsion systems, while still maintaining functionality and structural reliability.

Computational modeling through SolidWorks will be used to design the injector as well as complete stress analysis of the structure. Computational fluid dynamics (CFD) will be completed using standard engineering CFD software. Injectors will be manufactured using fused deposition modeling (FDM) to test the feasibility of acceptable flow with additive manufacturing. This paper will cover the mission objectives, planning, design, and testing of additive manufacturing for injector applications.

INTRODUCTION

Additive manufacturing is a method of developing parts or assemblies by laying down successive, micron-thick layers of material under the control of a computer. The process is referred to as additive because machines add layers on to each other to create the part[1]. The layers are melted or sintered together, depending on the process, in order to effectively hold the material together. This is different from subtractive machining because subtractive machining requires removing pieces of stock to create the part, resulting in wasted material, unlike additive manufacturing. Since its inception in the 1980s, additive manufacturing has become significantly cheaper and much more accurate[1]. The printer resolution, or the ability for the layers of material to blend together, has also improved dramatically. In today's industry, additive manufacturing has found its way into many different applications, allowing major advances in the ways of aerospace and military applications.

In today's world of aerospace research, a profession driven by low costs and fast manufacturing time, additive manufacturing's role is dramatically increasing because of its benefits in this realm. Additive manufacturing allows researchers to develop tangible designs and examine them in more accurate, real-world tests rather than only theoretical analysis. Additive manufacturing greatly reduces the outlay costs of testing these parts in addition to greatly reduced weight when compared to subtractive manufacturing methods due to the utilization of techniques and designs that can only be implemented with additive manufacturing. Today's engineering techniques involve the use of theoretical modeling software such as SolidWorks in order to create designs of an assembly or system. The assembly or system is then analyzed through various simulations and analysis before finalizing a specific design. This process can often take months or even years.

Even with all of these inherent benefits, additive manufacturing is still a relatively new entity. There are many emerging concerns with additive manufacturing including part resolution, which can lead to turbulence in fluid flow, accuracy in design replication, and assembly size limitations[2]. Because of this, additive manufacturing is not widely accepted or used in engineering practice because of researcher uncertainty in its reliability and helpfulness in meeting mission objectives. Additive manufacturing products are still a relatively new concept to the field of aerospace engineering. There has been little to no flight history for the hardware. Thus, engineers are still uneasy using these concepts. Universities offer a great opportunity in testing new designs or developing existing hardware for industrial purposes through increasing its reliability. Researchers will perform Computational Fluid Dynamics (CFD) and experimental analysis on the additive manufactured injector designs and evaluate additive manufacturing's effectiveness by comparing the theoretical and physical models.

DESIGN APPROACH AND THEORETICAL ANALYSIS

The mission of this research was to design and analyze additive manufacturing when integrated into liquid propulsion systems. To accomplish this mission, engineers must assess if additive manufacturing would be a safe means under the extreme conditions. To answer this question, flow and destructive testing were conducted to show that the injectors are acceptable and safe by comparing the flow and strength data to theoretical calculations. Flow and stress analyses were performed in computer models. These injectors were designed to determine additive manufacturing's effectiveness in matching theoretical and physical test results.

Three injectors were tested for their effectiveness during cold flow testing: the showerhead, self-impinging, and triple impinging injectors. A honey-comb interior design was used to manufacture a second iteration of the showerhead injector to demonstrate the additional benefits of weight-savings while aiming to achieve both similar structural and flow properties. The cold flow testing was completed using shop water, rather than a fuel and oxidizer configuration, to simplify the system design. The injectors were manufactured using Fused Deposition Modeling (FDM) and the material chosen for the injectors was Acrylonitrile Butadiene Styrene (ABS), a standard thermoplastic. One of the inherent issues of additive manufacturing that gives engineers a cause for concern is high porosity parts manufactured by the machine that can lead to decreased tensile strength. This can lead to premature failure from predicted measurements. This must also be analyzed to ensure the safety of the injectors and their ability to function properly. Although these injectors cannot be subjected to the same pressure and temperatures seen in real-world applications, this test represents a means of determining the anticipated performance of additive manufacturing in this application.

The design for the injector test stand was broken into two parts: the injector and the fluid containment assembly. The fluid containment assembly was designed out of 6061 aluminum because of its high yield strength, low cost, and lack of surface imperfections that could potentially cause turbulent flow within the assembly. The fluid containment assembly was manufactured and shown in Figure 1.

Figure 1. Fluid Containment Assembly

The design is a basic, conical-shaped diverging containment area within the aluminum to decrease the flow velocity of the fluid, shop water. At the top of the cone is a 1 in. National Pipe Thread (NPT) in order to connect the assembly to a flow meter, and ultimately to the shop water hose to measure inlet conditions. The working fluid then moves through the containment area to a six-inch diameter cross-section outlet which exposes the flow to the injector. The different injector designs are inserted for testing at the bottom of the assembly. The test stand included, from inlet to outlet of flow, the containment system, the injector and a custom-made injector adapter. Figure 2 displays the SolidWorks test assembly with the showerhead injector.

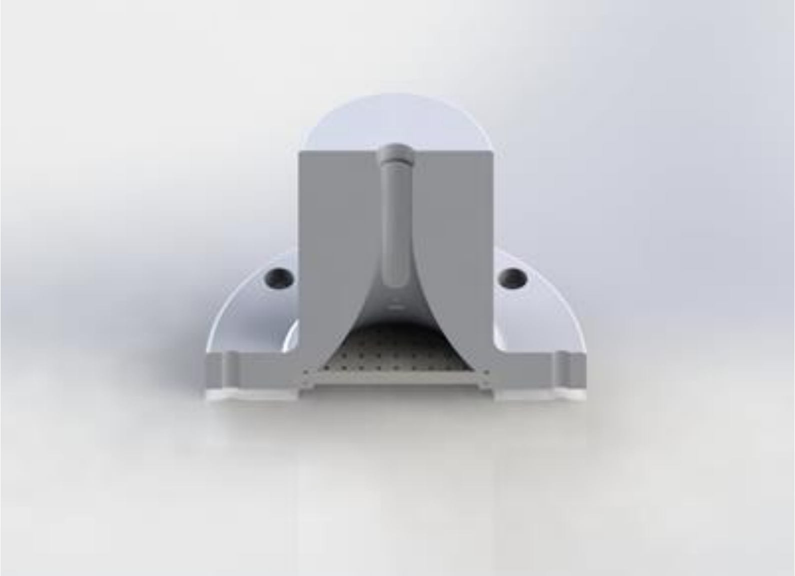


Figure 2. Solid Works Rendered Image of Fluid Containment Assembly

Each injector plate measures six inches in diameter is a half an inch in thickness, and each element on the injector face is 1/8 of an inch in diameter, with an L/D ratio of 4. ABS was selected for this manufacturing application because of its strength, low cost and ability to print with very high resolution, resulting in less turbulence. ABS is also the most common material used in FDM manufacturing processes. Each of the injectors completed post-processing in which the injectors were washed in a high-frequency bath to remove excess material on the faces and within the injector elements to reduce possible boundary layer thickness. There are fifteen outlet elements on each injector plate, allowing for more accurate comparisons between injectors designs when completing flow analysis. Each element is separated from each other element by a half an inch in both the x- and y-directions on the injector face. Images of the three injectors are shown in Figures 3-5.

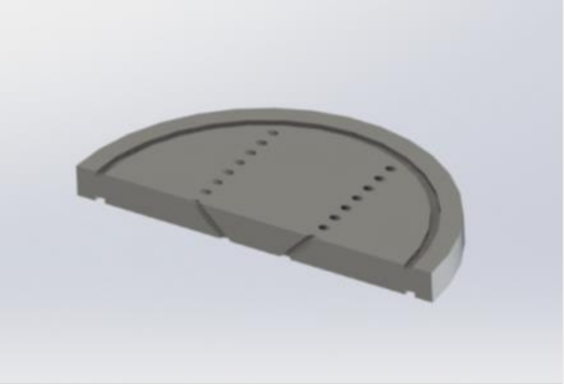


Figure 3. Self-Impinging Injector

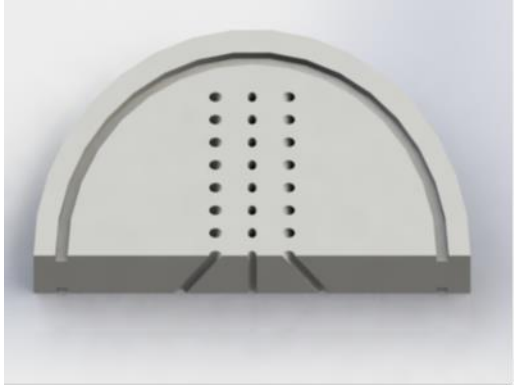


Figure 4. Triple-Impinging Injector

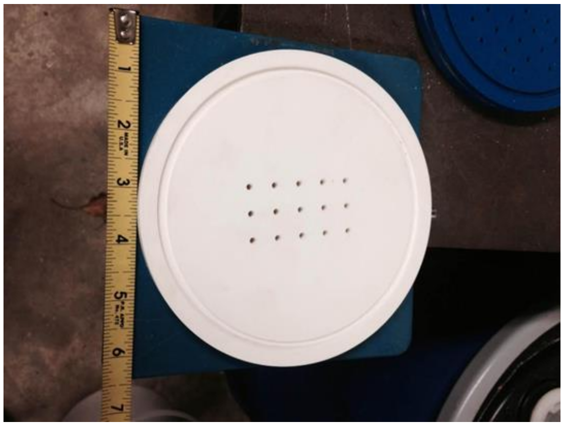


Figure 5. Showerhead Injector Design Post-Processing

In the self-impinging injector, the fluid impinges one-half of an inch below the injector face, with each fluid entering at a forty-five degree angle. For the triple impinging injector, the same forty-five degree angle elements are used, along with an element normal to the injector face, again impinging one-half of an inch below the injector face. The showerhead injector utilizes only a vertical element in the injector face.

The assembly uses an O-ring fitting on the injector plate itself, sealed on both the top and bottom faces of the injector, to connect the injector to the fluid containment assembly. The O-Ring is engaged on the inlet face by the assembly, while on the outlet face, a ½ inch thick piece of 6061 aluminum was cut to engage the O-Ring. Figure 6 shows the showerhead injector with the O-ring fitting inserted into the face.

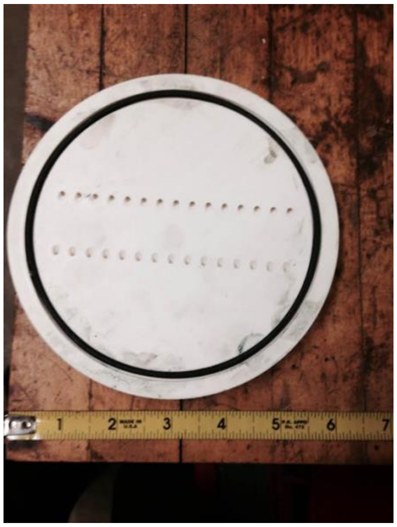


Figure 6. Self-Impinging Injector with O-ring Inserted

Note that the face of the injector looks as if it is dirtier than in Figure 5. The dirtier appearance in Figure 6 is due to greasing the O-Ring prior to insertion on the injector in order to allow for easier integration of the O-ring onto the injector face. The grease is of negligible thickness on the injector face and is able to be neglected for flow calculations.

STRESS ANALYSIS

After completing the assembly design, calculations were performed in order to predict the maximum stress the injector face is subjected to in operation. Failure analysis could then be simulated depending on the location and magnitude of the applied loads. It was determined that due to the direction of the flow of water, more stress would be applied at the center of the injector plate rather than on the sides. Stress analysis was completed using SolidWorks Simulation Xpress to ensure that the loads placed on both the fluid containment assembly and the injector itself would not damage the parts. After completing analysis assuming loads of 75 psi, both the injector and the fluid containment assembly experienced loads that were well below their max tensile strength. The end result for the SolidWorks fluid analysis is shown in Figure 7.

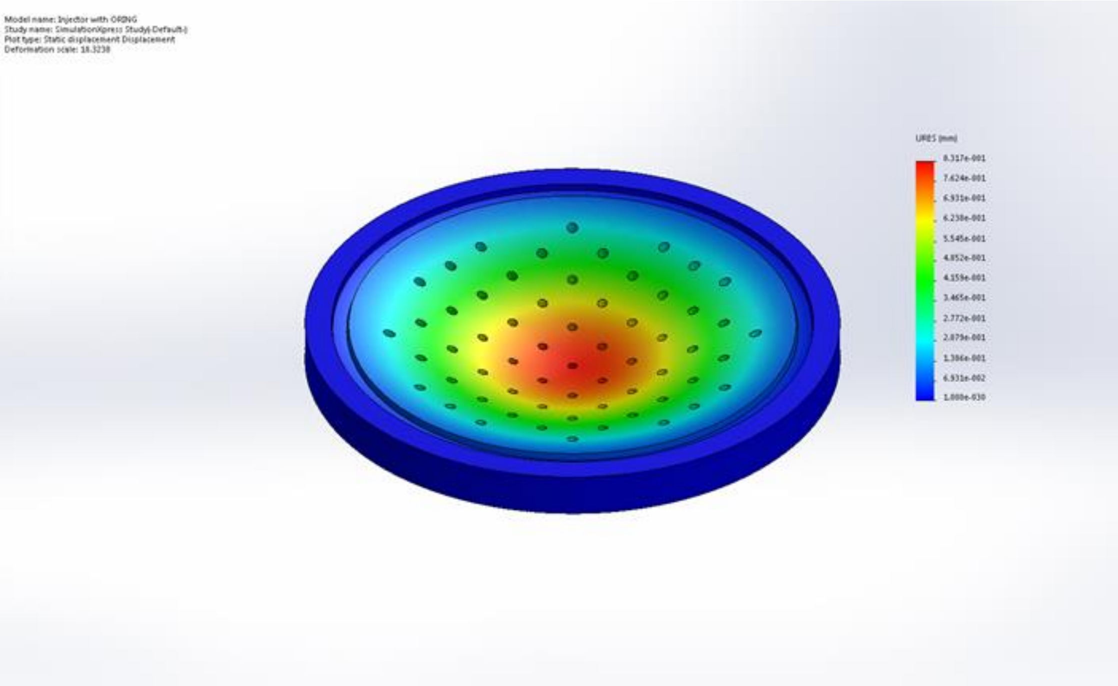


Figure 7. SolidWorks Stress Analysis Performed on the Injector.

As shown in Figure 7, the placement of the load was in the center of the injector face. Moreover, time progression showed eventual wearing and failures at the center of the injector. The applied pressure for both the hand calculations and the SolidWorks model were within one psi, which shows the expected results when testing the additive manufactured models. This gives the researchers a baseline of what to expect when testing their new design models.

The honey-comb structure is extremely difficult to model in SolidWorks, making stress analysis nearly impossible by simulation without buying new CFD software which was outside this project's budget. Thus, to determine the structural properties of the honey-comb showerhead design versus the standard showerhead design, destructive testing was utilized. The test completed was to determine the yield stress on the injector face when a load normal to the face was applied. In order to achieve this, a mechanism was created using a small steel plate and an equally-sized piece of rubber. As shown in Figure 8.

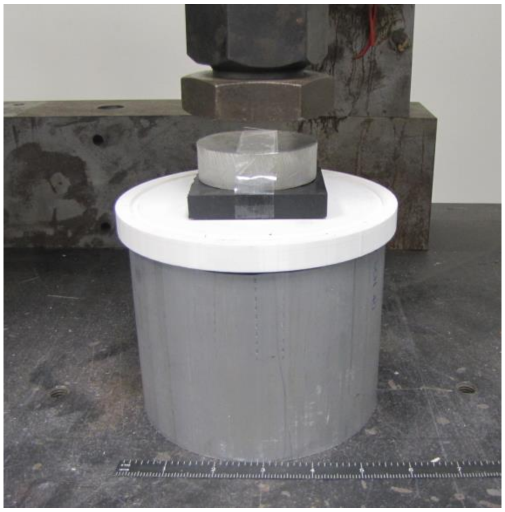


Figure 8: Yield Stress Determination Test Set-Up

The area of the steel plate covers each of the elements on the face, thus applying force across the injector face in the same manner at the beginning of the test, prior to deformation. As the face begins to deform, the rubber piece attached to the steel plate deforms at a similar rate. Thus, the force applied to the face continues to act normal to the injector, resulting in the most accurate representation of the operating stresses. The load was applied to the area surrounding the elements because all stress simulations indicated that the most likely failure mode would occur at the center of the injector face. Figure 9 and 10 below show the resulting failure modes from the testing in both the honey-comb and standard cases.

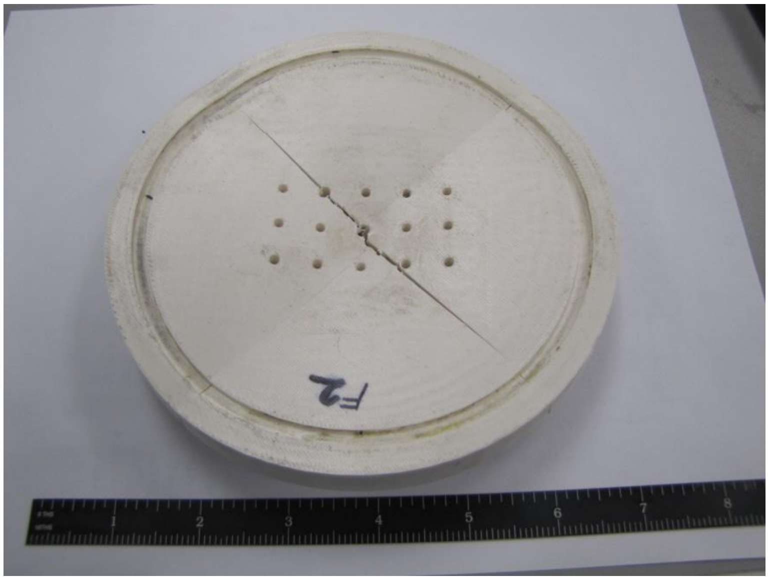


Figure 9: Failure Mode of the Standard Showerhead Injector

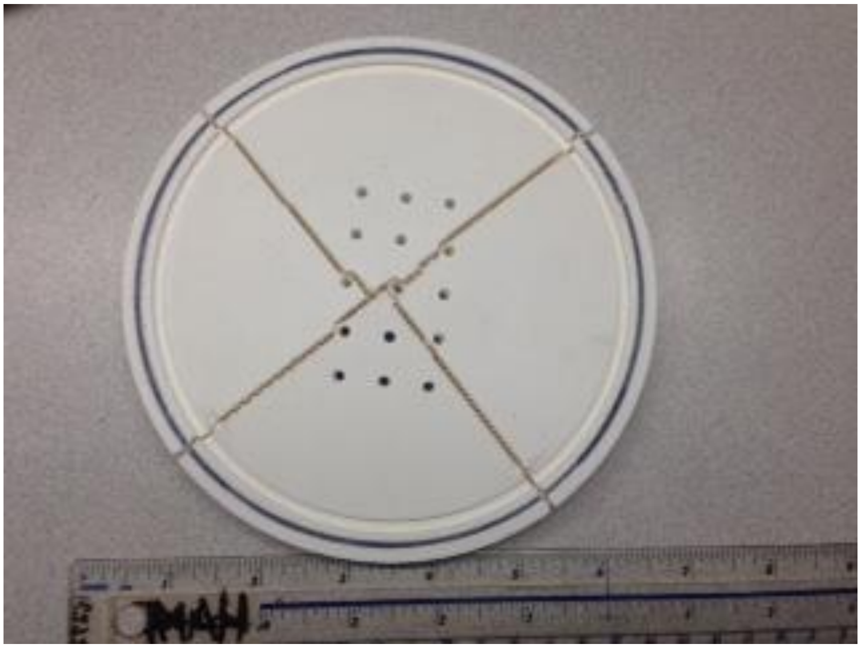


Figure 10: Failure Mode of the Honey-Comb Showerhead Injector

Both failure modes resulting from destructive testing show that the simulation predictions were correct. The injector failed at the center of the injector face around the middle-most element, an area of stress concentration, and emanated outward in opposite directions. From this testing, the yield stress and strength-to-weight ratios were calculated. Table 1 shows the results from this testing:

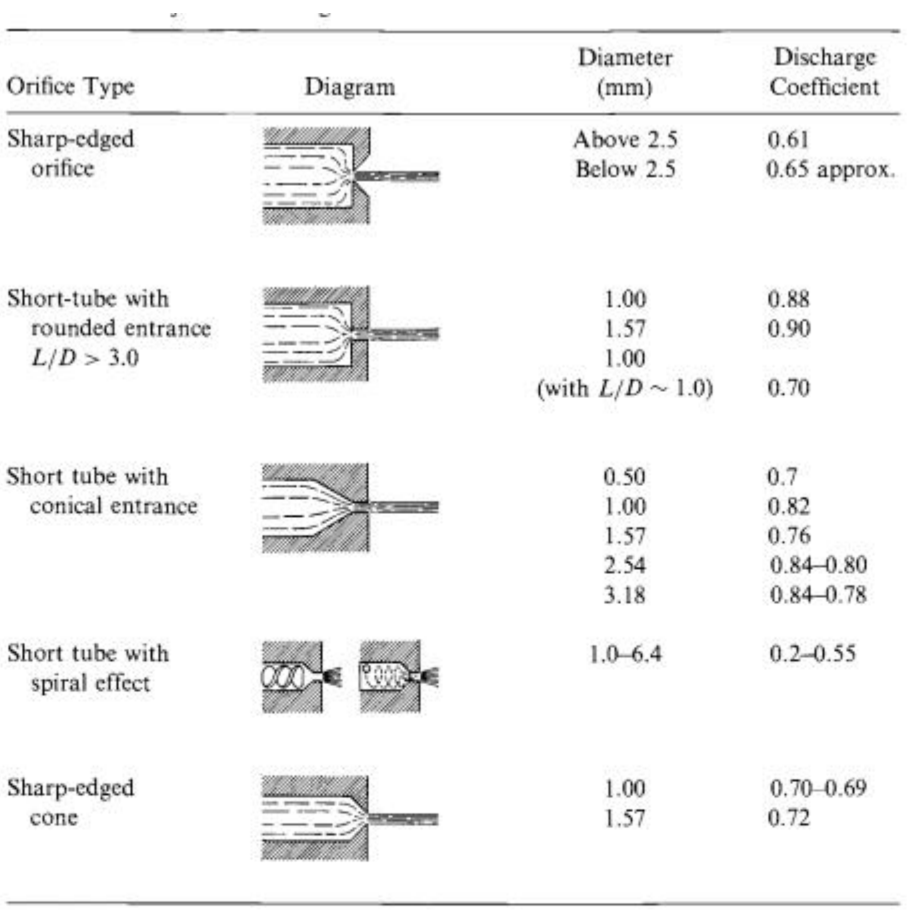
Table 1: Destructive Testing Results for Showerhead Injectors

Injector Type	Yield Stress (PSI)	Strength-to-Weight Ratio
Standard Showerhead	621.02	3838.96
Honey-Comb Showerhead	302.55	3026.44

The standard showerhead injector yielded at a much higher pressure than did the honey-comb injector. This is due to the greater amount of material in the injector that allows the stress to be more evenly distributed compared to the honey-comb injector. Because of the vast difference in yield strengths, even with the honey-comb injector weighing significantly less, the strength-to-weight ratio was larger for the standard showerhead by 26.83%. Further investigation of this phenomena is required to better understand if there are certain interior patterns which may more accurately mimic strength-to-weight ratio of the solid injector.

FLUID ANALYSIS

A CFD analysis was also performed in the same manner as the stress analysis. Using the calculated L/D of 4, the coefficient of diffusivity was determined using the chart in Sutton's text[3] shown in Figure 11.



Orifice Type	Diagram	Diameter (mm)	Discharge Coefficient
Sharp-edged orifice		Above 2.5	0.61
		Below 2.5	0.65 approx.
Short-tube with rounded entrance $L/D > 3.0$		1.00	0.88
		1.57	0.90
		1.00 (with $L/D \sim 1.0$)	0.70
Short tube with conical entrance		0.50	0.7
		1.00	0.82
		1.57	0.76
		2.54	0.84–0.80
		3.18	0.84–0.78
Short tube with spiral effect		1.0–6.4	0.2–0.55
Sharp-edged cone		1.00	0.70–0.69
		1.57	0.72

Figure 11. Table used to Determine the Injector Discharge Coefficients[3].

The coefficient of diffusivity was 0.9, since the test stand resembled a short tube with a rounded entrance. Using the injector flow equations, the volumetric flow rates, flow velocities, and change in pressures for each injector faces were calculated. They are shown in Table 2. The mixture ratio was a value of one, since water was used in the experiment as both the fuel and oxidizer in this analysis. In a more complex analysis, different fuels and oxidizers could be combined and analyzed to provide a more thorough testing of the injector faces. But for this basic experiment, general flow and stress analyses would suffice. Because only water was used, the angle of impingement has negligible effect on the flow properties. Atmospheric temperatures and pressures for Annapolis, MD were used. From past experiments, the shop water flow in the lab was measured at 50°F with an initial mass flow rate of 1.53 lb/sec that was measured using a flow meter.

Table 2. Calculated characteristics for each injector design.

Volumetric Flow Rate (ft^3/sec)	0.0245
Pressure Change (psi)	17.31
Outlet Flow Velocity (in/sec)	1.50
Mass Flow Rate (lb/sec)	1.53

After completing the design in Solid Works, fluid analysis was completed using SolidWorks' Fluid Xpress simulation to study the fluid dynamics of the assembly. In order to complete the analysis, both the inlet and outlet were sealed using two caps in the model. This can tend to skew analytical results, but only slightly. After running the simulation using inlet conditions for standard tap water (inlet flow of 11 gallons/minute, external pressure of 1 atmosphere, a temperature of 50 degrees Fahrenheit and an inlet pressure of 14 psi), the results showed that the max velocity of the fluid would occur near the inlet at about 42 inches per second (in/sec). At the injector face, the fluid velocity is predicted to flow about 12 in/sec. Once the flow has exited, the flow rate is about 3.41 in/sec. The flow analysis in the SolidWorks is shown in Figure 12 and 13.

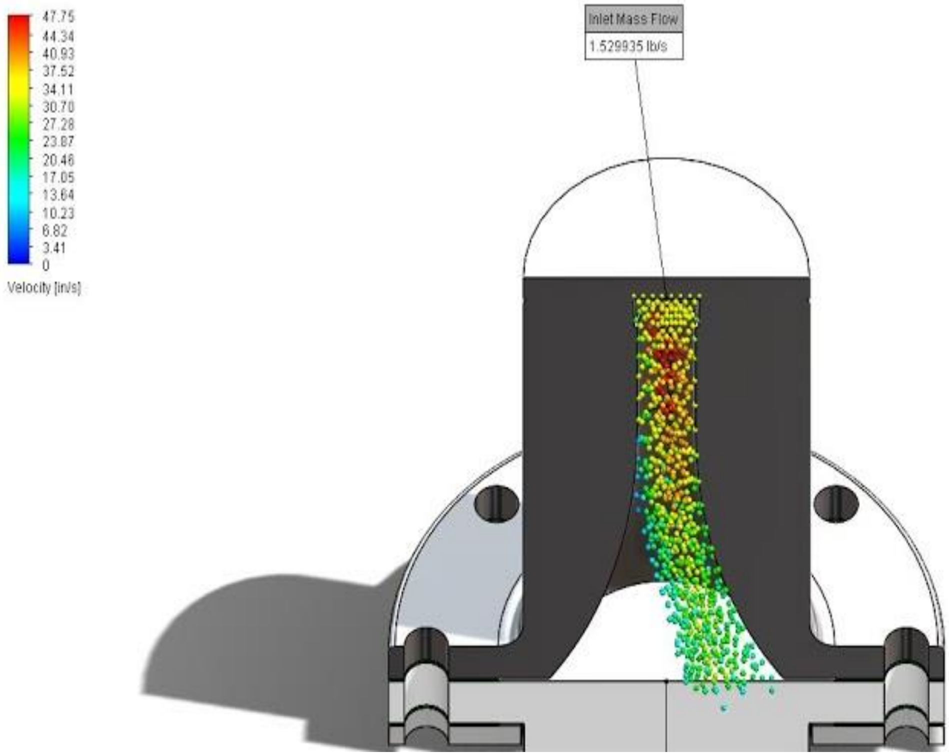


Figure 12. SolidWorks Flow Analysis Performed for Inlet Conditions.

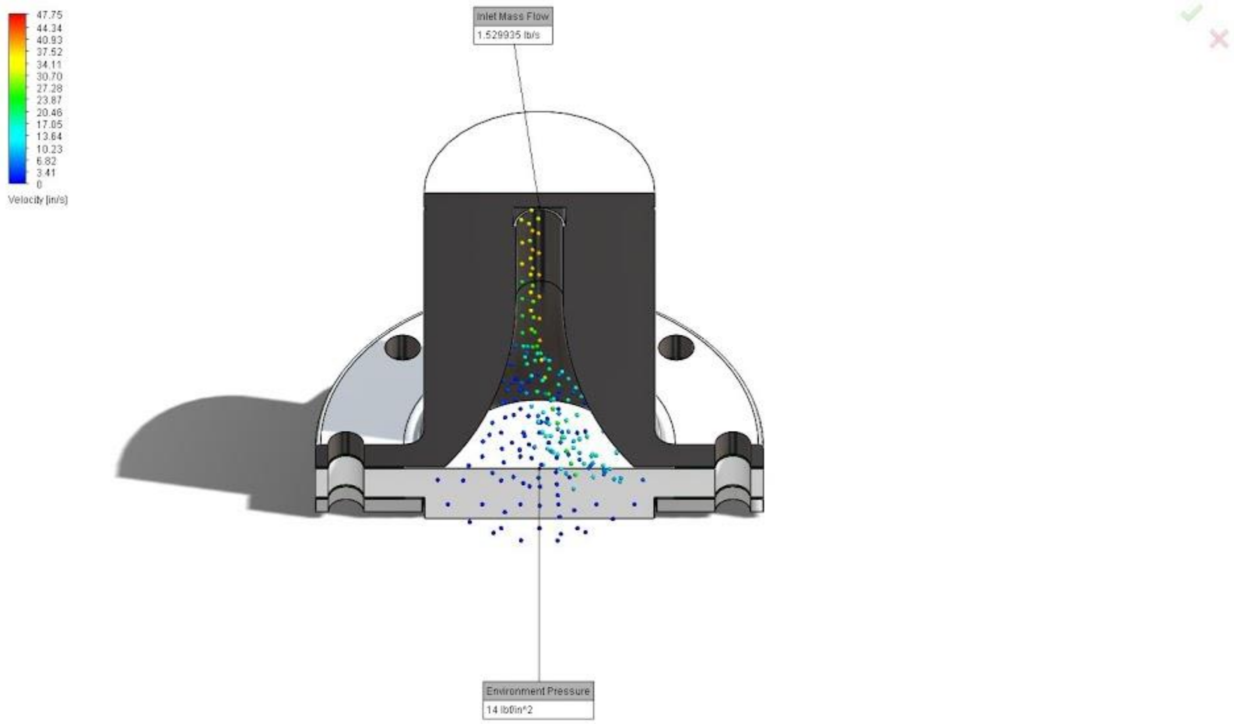


Figure 13. SolidWorks Flow Analysis Performed for Outlet Conditions

As shown in Figure 12 and 13, there is little risk of back pressure buildup occurring within the assembly. There is also no expectation for turbulent flow within the assembly to develop, barring that the containment assembly interior remains smooth. Any type of turbulence within the fluid could cause the results to become problematic. The lack of the possibility of increasing back pressure means that there is little to no risk that the injector face could break or be blown out of the assembly during a test. The results produced in Table 2 were within 1 in/sec compared to the numbers that were being calculated in the SolidWorks flow analysis. This further supports the fact that the simulation is accurate and reliable. It gives a reasonable base of expectations as the additive printing design models are tested. After the models were designed and simulated, the injectors were drafted and sent for printing. The printed models will now undergo immediate testing rather than repetitive theoretical analysis.

SYSTEM DESCRIPTION AND EXPERIMENTAL ANALYSIS

When testing the injector assembly, the containment assembly was attached to a shop water hose. No added air pressure was applied. A flow meter was calibrated and attached in order to analyze the flow velocity of the water. A non-external pressurized vessel can be used to accomplish this task. The expectations of the injector prior to the experiment were to see a flow rate of about 14 gallon per minute and to be able to see cohesive flow leaving the injector face. This idea was derived from the flow models that were simulated in the SolidWorks analysis.

The testing was conducted on each injector in order to determine if additive manufacturing would meet theoretical expectations. The procedure involved placing a bucket underneath the injector face in order to contain the fluid running through the injector face. Once the water reached a pre-determined height, the time it took to reach the height was measured and the amount of water in the bucket was recorded. The total amount of water that was held to the predetermined line was about 30.5 pounds of water. This allowed for the flow rate of the water to be determined. If the flow rates matched, then the additive manufacturing, indeed, models the theoretical solution. If the flow rate is below that of the model, then turbulence is developing within the path of the flow and could indicated faulty aspects of the additive manufactured injectors. Each of the flow tests were performed twice. The data was recorded, and the flow rates were calculated for each injector face. Figures 14 and 15 show the setup and flow of water as the experiment was conducted.

Figure 14. Full Experimental Setup.

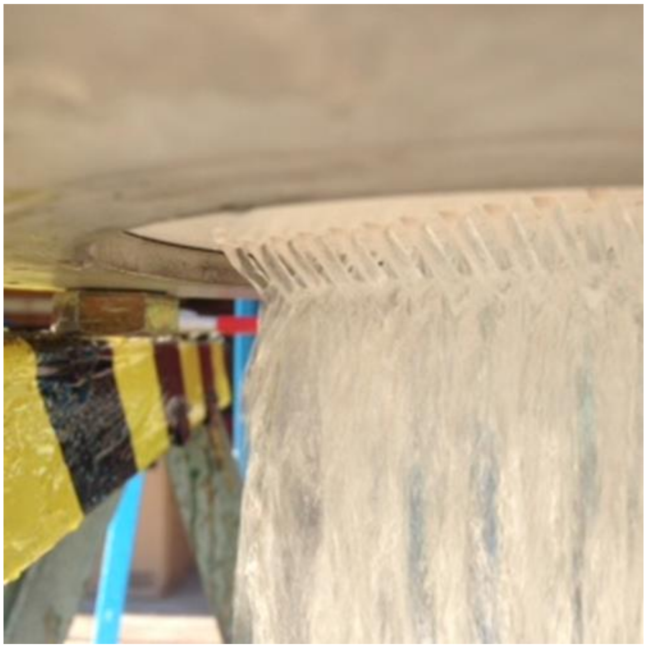


Figure 15. Flow of Water through the Self-Impinging Injector as the Test was Conducted

RESULTS AND DISCUSSION

The porosity of each injector was calculated using a simple fluid displacement test. Porosity testing allows for an accurate and reliable method of characterizing the additive manufactured parts. Porosity indicates the accuracy to which the FDM machine is capable of producing parts and can influence the structural properties of the injector plates.

Table 3. Porosity Testing Results of Injectors

Injector Design	Weight (lb)	% Porosity
Standard Showerhead	0.509	13.24
Honey-Comb Showerhead	0.314	31.10
Self-Impinging	0.498	19.45
Triple-Impinging	0.496	19.81

As shown in Table 3, the standard showerhead was the heaviest and least porous of the injectors. This can largely be attributed to the fact that the showerhead requires the least amount of inlet elements per outlet element. By using the honey-comb design, the weight savings over the standard showerhead were about 40%. Not only does this correlate to lower weight, but also lower cost and manufacturing time. The porosities for each injector were determined to be well within the allowable porosity of 30%, meaning there is no concern of decreased resistance to compressive loads. The experimental results for flow measurements and calculations are shown in Table 3. The flows were done with full release of the water (90^o), which corresponded to 1.53 lb/sec of flow rate, and half release of the water (45^o), which corresponded to 0.77 lb/sec of flow rate, as calibrated from the hose.

Table 4. Experimental Flow Results

Injector Type	Time (sec)	Mass Flow Rate (lb/sec)	Flow Velocity (in/sec)
Standard Showerhead (90^o)	22.02	1.81	0.66
Standard Showerhead (45^o)	32.17	1.24	0.32
Honey-Comb Showerhead ($45^˚$)	31.24	1.28	0.33
Self-Impinging (45^o)	30.97	1.29	0.53
Triple-Impinging (45^o)	33.19	1.20	0.49

The experimental results shown in Table 4 were 2 in/sec lower than the flow rates and velocities that were calculated and analyzed in Table 2 using theoretical equations and simulations. The flow rate was also about 0.23 lb/sec slower than the predicted flow rates in the theoretical models. This shows that the experimental results are more accurate, since they account for friction and other forces that the theoretical models are not well adept to predicting. Also, the result of the honey-comb injector is extremely close to the result of the standard showerhead, within 3%. These results indicate that the additive manufactured designs are able to produce real world performance expectations that the pure theoretical methods may not be capable of perfectly modeling. It allows for the engineer to truly see what their designs are capable of producing when taken into effects such as friction and air resistance, as well as be able to perform with reduced weight.

As expected, flow rates varied depending on the type of injector face used. At 45^o open flow, the mass flow rate was of the self-impinging injector was about 0.05 lb/sec faster compared to the showerhead injector. The flow velocity was also a 0.21 in/sec faster. This shows that the impinging of the water accounted for more fluid flowing through the outlet elements, resulting in higher mass and flow velocities. It also decreased the amount of water that was being passed through the injector every second. However, this pattern is not continued when applied to the triple-impinging. The most probable reason that this discrepancy in the data occurred is due to a lower flow pressure being applied to the injector because of lack of pressure in the shop water hose. The triple impinging injector was the last hose to be run, and over time, the shop water hose has shown a tendency to decrease in flow pressure as the flow is run of a period of time. In the future, the injectors will be run in different orders in order to produce more accurate flow measurements, removing the uncertainty of the shop water hose.

The flow was only able to be calculated in the full 90˚ open position for the showerhead injector due to an increased error when running the test at higher pressures in the self- and triple-impinging injectors. This error occurred because the shop water underwent a smaller version of atomization when at the higher pressure, in which the two flows converged on each other at a half inch below the injector face, causing some of the flow to scatter and not be collected by the bucket. The high percentage of flow undergoing this process would have resulted in a very high degree of error in the flow measurements, and thus the test was not completed.

The weight savings of the injector prove that additive manufacturing can significantly reduce launch and manufacturing costs for liquid propulsion systems. Assuming a standard-sized 200 pound injector, a weight savings of 40% can save up to $1 million dollars per launch. But, the data is based off of this FDM approximation, so a full-scale test will be required to determine if the weight savings will continue to show similar performance.

A total of two days was spent manufacturing and testing the injectors, while the theoretical analysis took almost a week long. Much less time was also spent on manufacturing and testing the equipment. This method of additive manufacturing design testing is much less tedious than inputting the many conditions in Solid Works and later troubleshooting it. One could further expand this to perform iterative additive printing experimental analysis. Thus, it is shown that additive printing is very accurate and reliable form of engineering design.

Conclusions

The use of additive printing allows for flexibility within the design process, lower costs for manufacturing, and faster and more accurate testing. The test results were acquired at the same rate by using a preliminary design and additive manufacturing compared to performing theoretical calculations and simulations. The main advantage as shown in this research is that additive printing allows for a much more of a real world analysis of the engineer’s design rather than heavily relying on simulations. It is no doubt that the theoretical calculations are accurate and essential to the engineer’s design work and analysis to set a baseline for performance expectations. However, additive printing brings a whole new dynamic in that it allows for further validation of the designed product through real-world testing. It allows engineers to freely develop and test designs and get results rather than just iterating purely in theoretical simulations. At the same time, additive manufacturing allows for significant weight savings in design for similar performance, if the engineering can sacrifice some strength properties in turn. Additive printing further enhances the student engineer’s learning experience and his rate at learning and developing his engineering skillset. Through this research, we have determined that additive printing is a reliable engineering tool and will enhance future engineering endeavors.

FUTURE WORK

Currently, research is being done to further characterize the effects that additive manufacturing has on boundary layer conditions of the injector due to the increased surface roughness, paying particular attention to how best to minimize this characteristic. USNA is also looking to develop its own coaxial injector to complete full cold flow and hot fire testing, to further determine areas of improvement for additive methods in aerospace applications.

ACKNOWLEDGEMENTS

A special thanks to Dr. Angela Moran for knowledge and expertise on material characterization. Thank ENS Kenji Dinelli, USN, Daniel Rodgerson, Brandon Stanley, Louise Becnel and Fritz Woolford of the USNA Aerospace Department Labs and Machine Shop for all of their support in the design, manufacturing, and tests presented in this paper.

REFERENCES

1. Gibson, Ian., ***Additive Manufacturing Technologies*****.** New York, NY: Springer, 2010

2. Chua, Chee K., and Kah F. Leong. ***3D printing and additive manufacturing: principles and applications*****.** Hackensack? New Jersey: World Scientific, 2014.

3. Sutton, George P., and Oscar Biblarz. ***Rocket Propulsion Elements.*** Hoboken, N.J: Wiley, 2010