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The Design and Validation Process of a Coaxial Swirl Injector Plate for Bipropellant Liquid Rocket

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This paper is a documentation of the research and development process of the coaxial swirl injector for Buckeye Space Launch Initiative (BSLI)'s first liquid rocket engine. Coaxial swirl injector is a high-performance design of a liquid rocket engine injector, optimal for limited chamber length and demanding mixing scenarios. This paper aims to provide entities with comparable size useful insights on how to develop a similar system and obtain higher performance.

I. Nomenclature

A	= Geometry characteristic constant
A_p	= feed port area, m^2
β	= Spray cone half angle, deg
C_d	= Discharge coefficient
D_c	= Exit diameter, m
D_s	= swirl chamber diameter, m
D_t	= tangential port diameter, m
D_0	= orifice diameter, m
h_e	= exit film thickness, m
$\dot{M}$	= mass flow rate, kg/s
$\dot{M}_0$	= oxidizer mass flow rate, kg/s
$\dot{M}_f$	= fuel mass flow rate, kg/s
$\dot{m}_l$	= liquid mass flow rate, kg/s
n	= tangential port number
σ	= surface tension coefficient
ΔP_l	= liquid pressure drop, pa
φ	= filling coefficient
ρ_g	= gas density, kg/m^3
ρ_l	= liquid density, kg/m^3
ρ	= density, kg/m^3
R_t	= tangential port inlet radius, m
SMD	= Sauter mean diameter, m
μ_l	= dynamic viscosity, Pa m
v	= flow velocity, m/s
V_0	= liquid film velocity, m/s

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II. Introduction

Injectors in a rocket engine feeds the combustion chamber with mixed, atomized fuel and oxidizer which ensure combustion efficiency in the chamber. A coaxial swirl injector is a high-performance rocket injector that provides excellent atomization and mixing. This paper documents both experimental and numerical design process of BSLI's coaxial swirl injector, and the reasonings behind design choices we made throughout the process.

III. Overview of Coaxial Swirl Injector

Coaxial swirl injector is a pressure atomizer designed to atomize the propellant as they flow into the combustion chamber so higher reaction surface area can occur and better combustion efficiency can be achieved. There are two designs for this type of injector: swirler channels and tangential port. Due to the simplicity of the latter design, it is chosen for our engine and is what this paper will be focusing on.

A tangential port type swirl injector contains the following features: tangential port, swirl chamber, orifice and can be further optimized with features like convergence section in the swirl chamber and pre-mixer. The basic system schematic is shown below (Fig. 1). As shown in the figure, the propellants are being fed in a tangential direction into the swirl chamber, where a large tangential velocity along the chamber wall is achieved, and the resultant centripetal acceleration forced the liquid to the swirl chamber wall to swirl down towards orifice. At a high enough operational pressure an air core is formed as shown in figure 1 and the flow can be treated as a liquid film. As the liquid film propagate down stream and leave the orifice, it forms a conical shape where, as the radius increases as the liquid propagate downwards the film thickness decreases. As the flow is turbulent, surface waves will start to form on the liquid film, where the energy in the waves overcome the surface tension of the film and rip it apart, achieving atomization. [1]

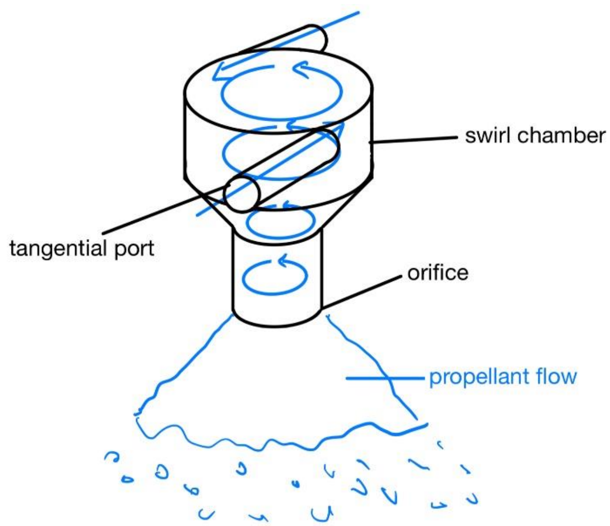

Fig. 1 Operation schematic of a swirl injector.

Design features can be added to enhance the performance of this injector better, the two we choose to investigate into are a converging portion of the swirl chamber and a pre-mixer. In the swirl chamber, when flow is chocked downstream, with the principle of conservation of angular momentum, a higher tangential velocity can be achieved, which can lower the film thickness at the orifice, decreasing the length needed in combustion for sufficient atomization. Since our injector design is coaxial for the two propellants, a pre-mixer can be implemented where the inner injector unit's orifice is a certain distance short from the injector face, and the spray cone is sprayed onto the swirl chamber of the outer unit where the two propellants mix before being injected into the combustion chamber. This design enhances the mixing of propellants and brings a more efficient combustion process.

When implemented onto a rocket engine, multiple injector units described above are usually implemented into the injector plate where feed chambers will feed the propellants into the units to undergo atomization. Main considerations of the design of this are: the pressure drop across the feed chamber, method of manufacturing and integration to the engine and rest of the rocket/support equipment.

IV. Design Process of injector elements

As our research into this type of injector and our main reference paper have directly implied, the atomization process of the injector was not researched to the fullest and many design methods and formulations are based on experimental data [1]. As we use these numerical methods, great difficulties occurred as many of the experimental equations only work with a certain range of Reynolds number where our design does not fall in the range of. Hence an experiment heavy method is implemented, as the design process can be different depending on the design itself and how specific team demand their injector to achieve, I will discuss the thought process of designing, the development methods and then our approach to the design of this injector.

To design the injector, we define the following demands for the injector: first, supplying the combustion chamber with the correct mass flow of propellants; second, ensuring the correct mass flow rate between the fuel and oxidizer; third, ensuring a good atomization and finally Providing a good mixing between fuel and oxidizer. These demands can be changed depending on the engine design and the need of the team, an example being if coaxial design is not optimal for the manufacturing methods, the ensuring good mixing task can be assigned to chamber design like implementing a longer combustion chamber. After defining these tasks to be fulfilled, each should be assessed to see if an experimental or numerical method should be used for optimization, where the design can then be validated and optimized.

For our design, we approached all the problems except for the mixture ratio control with a mostly experimental method with minor numerical validations. This is mainly due to the turbulent nature of the operation mechanics of this type of atomizers, as many equations for numerical characterization are deduced with experimental data, which, a lot of them does not fit our design conditions and give orders of magnitudes off results. Hence, we chose to not rely on those but our observations. The mass flow on the other hand is calculated by assuming the feed flow velocity of fuel and oxidizer are the same and solving for feed port area ratio with mass flow equation. The results are near correct and are corrected using experimental data obtained by using FDM printed units at a lower but still operational pressure.

For all others, we used the design's geometry to run equations and roughly see weather the order of magnitude is correct, where an injector unit test article will then be printed with FDM printing and tested with a simple test stand, if the observation shows desirable results, the design will be chosen. Usually, multiple designs will be printed and tested at the same time, so that different geometries can be tested next to each other where we compare their performance, and fast and effective design iteration can be achieved

V. Experimental setups

The development process of our injector is very experiment intense, hence in this section we will be discussing the experimental methods we used for fast iteration and design validation.

Our experimental setting for atomization is a garden hose with a supply pressure of around 50 psi, the significantly low pressure is due to two reasons: the lack of structural strength of FDM printed test articles and the difficulties of operating high pressure test stand. However, according to previous study [2], after the full development of the spray cone, the increase of back pressure decreases the Sauter main diameter, which means better atomization. Hence for atomization, testing with a lower pressure than operational is acceptable since the performance is known to increase as pressure rise.

Fig. 2 Experimental setup for atomization.

To take measurements under the limited budget and time, we used a simple setup consisting of a LED lamp to measure the droplet size to an order of magnitude accuracy to compare and validate designs. We make these measurements by taking measurement from the photos and using the length ratio between droplets and the orifice which have a known radius. The final measurements obtained for droplet size lay in the order of magnitude of 100 μm which is typical [1]. Hence, we settled on the geometry and started implementing other features, as features got smooth out this test was also done repeatedly to verify added features does not lower atomization performance significantly.

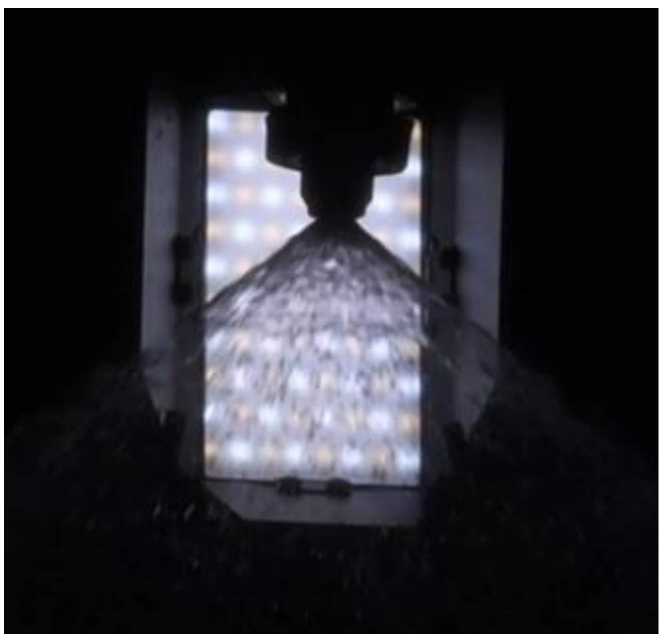

Fig. 3 Backlit photos for droplet size measurements.

The mass flow rate is measured using the same method, but the test article is the entire injector plate with multiple injector units rather than a singular injector unit. Since the discharge coefficient increase with back pressure but at a small amount (raised from 0.38 to 0.395 as back pressure raised from 0 Mpa to 5 Mpa) in previous studies [3] , the error caused by the lower than operational pressure is acceptable considering the amount of extra time and budget required to run full pressure. Due to the limitations of metal 3D printing we currently use to manufacture our engine; the feed chamber was designed with supports for the injector units and the injection face and are not removable as the opening for propellant feed is too small for tools to access. The geometry was also too complicated to simulate with the amount of calculating power we have on student license, so real-life testing is performed to measure the discharge coefficient correctly which corrections can then be made on the venturi tube feeding the engine to achieve desired mass flow rate.

The mixture ratio test is slightly more complicated than the previous two as the two flows must be measured separately to determine the ratios of mass flow rates. To achieve this, our team built a small test stand shown in figure 4 capable of supplying a back pressure of 110 psi with capability of supplying two lines separately with different substances. To separately measure the fuel and oxidizer while running the test with the pre-mixer feature, we used the property of oil and water don't mix so that after letting the mixed liquid sit for some time they separate, and we will be able to measure the mixture ratio if we keep the run time of the two lines identical. In the experiment we ran using water and canola oil, where we obtained a slightly higher mixture ratio of 2.55 than designed mixture ratio of 2.36, we suspect this is partially due to the significantly higher viscosity of canola oil compared to kerosene we use as propellant and are planning to run additional experiments with kerosene.

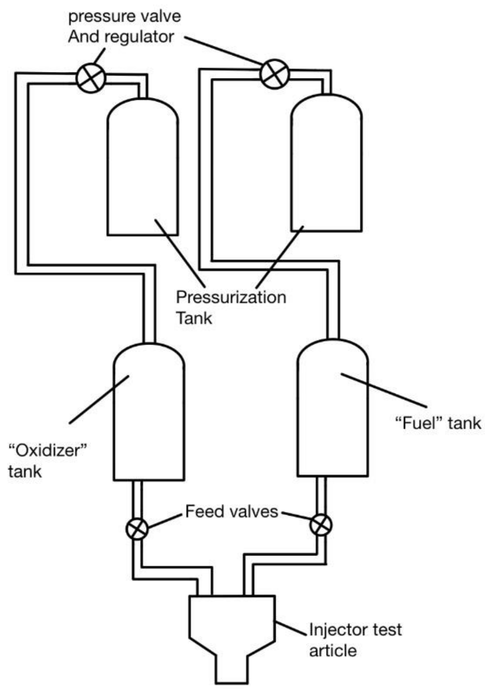

Fig. 4 Mixture ratio test setup.

Our team are currently working on using a mini test stand capable of running at operational pressure and metal printed injector unit test pieces to further verify our design and obtain further data to help our understanding of this type of injector. We will also be implementing laser for flow imaging for more accurate data collection and are aspiring to deduce a system of equations that characterize designs at our scale better.

VI. Numerical verification

During the design process, our group used equations from previous studies [1] to predict the performance of the injector design before printing and testing to save time and resources.

For mixture ratio, the design process is more numerically intense than other features where the feature is optimized using equations and the experimentation only assists with eliminating uncontrolled errors like the turbulence in the swirl chamber. The equations used are simple:

$$o/f = \frac{\dot{M}_o}{\dot{M}_f} \tag{1}$$

$$\dot{M} = \rho v A_p \tag{2}$$

For atomization and mixing, the team used equations [1] to determine the order of magnitude is correct. This numerical check is not used for more certain validation mainly because most of the equations developed for this type of injector is based on experimental data where different data and experiments yielded different equations. Thus, completely relying on these equations is not a reliable choice. Calculations on atomization meanly focused on extracting Sauter mean diameter with current geometry. The following equations are used:

$$SMD = 1.88\sqrt{\frac{4h_e}{\frac{\rho_g V_0^2}{2\sigma}}}\left(1 + 3\frac{\mu_l}{\sqrt{\rho_l \sigma \sqrt{\frac{4h_e}{\frac{\rho_g V_0^2}{2\sigma}}}}}\right)^{\frac{1}{6}} \tag{3}$$

$$h_e = 3.66\left(\frac{D_c \dot{m}_l \mu_l}{\rho_l \Delta P_l}\right)^{0.25} \tag{4}$$

By combining these and using data from simulations the Sauter mean diameter can then be calculated.

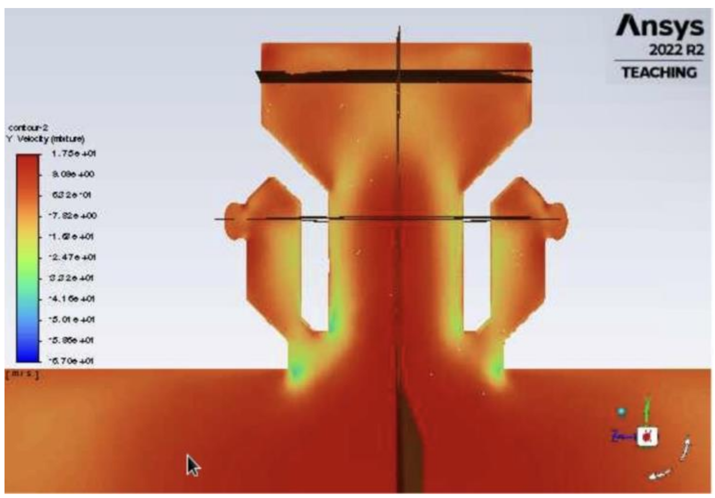

Fig. 5 Ansys fluent result for y velocity.

The pre-mixer calculations focused on spray cone half angle to ensure the inner spray cone collide with the wall of swirl chamber of the outer unit. The equations used are as follows:

$$\tan\beta = \frac{2\sqrt{2}(1-\varphi)}{\sqrt{\varphi}(1+\sqrt{1-\varphi})} \tag{5}$$

$$A = \frac{(1-\varphi)\sqrt{2}}{\varphi\sqrt{\varphi}} \tag{6}$$

$$A = \frac{(D_s - D_t)D_0}{4nR_t^2} \tag{7}$$

For discharge coefficient, we calculated and got data according to the following equation combined with equations (6) and (7) from above:

$$C_d = \sqrt{\frac{\varphi^3}{2-\varphi}} \tag{8}$$

However, they are quite off from what we've seen in real life testing and are not representative enough for our purposes, the feed chamber due to its geometric complexity is also very hard to calculate using hand calculation and with the limit on calculation power for ANSYS due to the lack of a powerful license, and little useful data yields. Hence, we used solely the experimental data to obtain the discharge coefficient to adjust the feed system to obtain desirable mass flow rate.

VII. Injector plate design and design strategies for additive manufacturing

The injector plate is a structure that connects the injector to the rest of the chamber assembly, provide feeding flow to the injector units and often integrates multiple injector units into the injector plate. The mean complexities with designing this part are: first, ensuring the manufacturability of the structure and second, ensuring a low enough pressure drop across the injector face. For our design we utilized metal 3D printing which eliminates many of the problems associated with manufacturability, however additive manufacturing also brings its own challenges which we will discuss in detail in this section.

An injector plate usually contains several injector units evenly distributed throughout the injector face which provides a more even flow across the chamber in turn a more even combustion temperature. To integrate these units, conventionally engineers will machine the individual injectors and use techniques such as welding to join the units and seal off gaps in the feed chamber. While this method brings a better surface smoothness which provides better discharge coefficient, our team do not have any welder capable of performing such delicate welding task and since the regeneratively cooled chamber and nozzle also requires additive manufacturing considering the team's machining capabilities, the injector plate is designed to be manufactured additively.

Pressure drops across the plate is an important issue to consider about as it changes mixture ratio between the injector units and can cause parts of the engine burning excessively oxygen rich which can create hot spots in the chamber and eventually lead to engine failure. This problem is most problematic when mixture ratio closer to the wall is too high which can raise the thermal flux at the wall beyond what wall cooling is designed for and cause melting of the inner chamber wall. To avoid this issue, we designed the engine to feed the fuel from the edge of the plate into the fuel feed chamber via regenerative cooling channels and oxidizer from the center so that the pressure drop only cause the mixture ratio on the edge to lower rather than rise, which lowers the combustion temperature near wall by burning fuel rich. There are room for improvement for this chamber design as the team choose to utilize additive manufacturing, optimizing the feed chamber geometries can potentially eliminate the pressure drop and bring the mixture ratio to the desired level for every individual injector unit. Despite the complexity of this part's geometry, with recent developments regarding generative design and AI assisted design, this level of optimization can be done, however with the limited amount of design time, we decided to not implement this for the current design and implement this in a future design.

Designing for additive manufacturing brings its own advantages and challenges. The advantages being the ease of implementing complicated geometries and internal geometries that conventional machining methods will not be able to reach. The challenges encountered in our case being supporting the overhang materials if auto-generated supports work poorly for the application, designing for powder removal for any SLM printed parts and ensuring rigidity of features so the risks of features being knocked broken by print recoder is eliminated. For the supporting issue, auto-generated supports do not provide us with enough control over the geometry within flow region which can cause excessive pressure drop issues addressed in the previous paragraph, we opted for manually design a supported structure. Shown in Fig.6 the injector units are "grown" out from pillars connected to the top bulkhead, the overhanging angles except for small ones on the wall between fuel and oxidizer feed chamber and the ones on the injection face are all lower than 45 degrees to ensure print quality. Tangential ports are designed to a shape of oval and feed port for oxidizer the size of a droplet to minimize arcing distance. The powder removal is solved by ensuring a good enough clearance within the chamber which is also the design strategy used for solving the pressure drop issue. Thus, with the design unchanged powder can be removed quite easily by blowing compressed gas or liquid through the feed ports and out of the injector orifice. Finally, all the long supporting pillars are reinforced with structural fins to increase rigidity and ensuring a reliable print, this feature is also shown in Fig.6.

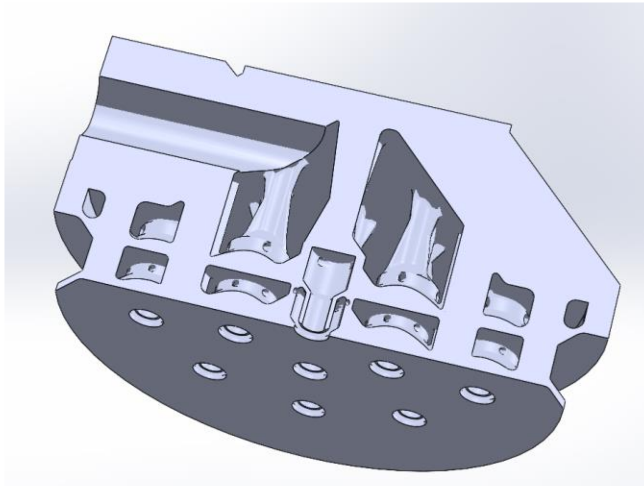

Fig. 6 Additive friendly injector plate design.

VIII. Conclusion

Despite we are yet to print and test the engine as of the time of the finishing of this paper, cold flow tests on injector units already shown promising performances that are exceeding what's typically seen in impingement injectors commonly used among student teams. However, as discussed in the previous sections, there are still rooms for further research and development, namely enhancing experimental processes and data collection, investigating further into how numerical methods like computational fluid dynamics (CFD) can be utilized, gaining access to more calculating power and implementation of generative design to further optimize the system so the performance can be further improved.

The team is already working on making a mini stand capable of fitting into a laser imaging facility which will provide us with much more accurate data that resembles operating conditions better. To date the team already received metal printed test articles from ursa major and are well on track to testing the injectors next semester. The final goal of these experiments is to provide experimentally deduced equations that fits better specifically for smaller engine designs and gain understanding on the mechanics of atomization for this type of injector.

Throughout the process of injector development numerous CFD attempts are performed, however due to the complexity of geometry combined with multiphase flow and phase interactions the problem toughness is very high and the timestep sizes are forced to a very low 10^{-7} seconds per timestep. Simulations takes days to weeks to complete due to that reason and are still prone to float point exception, even with some simulations progressing smoothly for days and occasionally even weeks, the data gained was still quite limited. Thus, the team decided to turn to an experiment intense methodology for this design. However, the team have been talking with ANSYS and Converge CFD to find support and positive progresses are made, so more numerical development methods can be expected in the future.

Finally, we are currently looking into learning generative design tools like CREO and CATIA, we expect to start producing algorithm designed injectors in the years to come.

Acknowledgement

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