Development of a Student-Built LOX/Jet-A Coaxial Swirl Injector

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The Yellow Jacket Space Program (YJSP), the liquid rocketry student organization at Georgia Tech, has a goal of launching a vehicle to the edge of space. The injector is one of the most important components on a liquid rocket engine, directly affecting the performance and efficiency of an engine. YJSP started developing a coaxial swirl injector in January 2023 starting with single element tests followed by subscale demonstrators. Using the data learned in these tests, a 2500lbf flight version was developed for Vespula, targeting a summer 2025 launch to 100,000ft. This paper goes over the development process including waterflows, cold flows, and hotfire tests.

I. Nomenclature

A_h	=	area of tangential entry holes
R_n	=	radial distance from swirler center line to entry hole center line
β	=	ratio of R_n to swirler radius
K	=	swirler geometric constant; $\frac{r_n R_n}{n r_h^2}$
n	=	number of tangential entry holes
r_h	=	radius of tangential entry holes
r_n	=	swirler radius
φ	=	swirler filling coefficient; $\frac{\pi(r_n^2 - r_{gc}^2)}{\pi r_n^2}$
r_{gc}	=	swirler gas core radius
X	=	ratio of swirler gas core radius to swirler radius
d_s, d_n	=	diameter of swirl chamber and swirl nozzle for closed LOX swirlers
LOX	=	liquid oxygen
LN2	=	liquid nitrogen
Jet-A	=	commercial aviation-grade jet fuel
Cd	=	discharge coefficient
$\dot{m}$	=	mass flow rate
ρ	=	density
Δp	=	pressure drop
c^*	=	characteristic velocity
Nu	=	Nusselt Number
Re	=	Reynold's Number
Pr	=	Prandtl Number
k	=	thermal conductivity
h_c, h_g	=	coolant side and hot gas side convection coefficients
t	=	face plate thickness
T_c, T_g	=	coolant and hot gas temperatures
q	=	heat flux
p_c	=	chamber pressure
A_t	=	throat area

II. Introduction

The Yellow Jacket Space Program (YJSP) was founded by students at the Georgia Institute of Technology in 2015. YJSP is a liquid rocketry club with an eventual goal of launching a vehicle to the edge of space. Students develop skills not taught in traditional classrooms thus preparing them for the aerospace industry. Since its founding, YJSP has grown to over 200 members from multiple majors including Aerospace, Electrical, Mechanical, Business, and Computer Science.

A liquid rocket engine is an extremely important part of a launch vehicle and to reach space in the most efficient manner possible, the engine must be high performing and efficient. This is heavily determined by the mixing of the propellants through a device known as an injector. YJSP has previously designed, built and tested a pintle injector with relatively poor performance and poor reliability and thus a decision was made to explore other injector options, one of which was the Coaxial-Swirl Injector.

III. Design Process

There are two main parameters that must be known for a coaxial-swirl injector, the coefficient of discharge (Cd) and the spray angle. Unlike other types of injectors such as a pintle or impinging, a Cd value of around .6 (corresponding to a sharp-edged orifice) cannot be assumed as a swirl injector is much more complex. An injector's Cd value is directly related to the pressure drop across the injector, a critical design parameter for injector performance and stability. Therefore, much work was needed to try to find an accurate method to predict a discharge coefficient. Many different academic research papers were found all outlining different experimental or theoretical equations. These are listed in Table 1.

Table 1. List of discharge coefficient equations

Equation	Reference
$Cd = 0.19\left(\frac{A_h}{4R_n^2}\right)^{0.65} \beta^{-2.13}$ (1)	[1]
$Cd = \frac{1}{\sqrt{\frac{1}{\varphi^2} + \frac{K^2}{1-\varphi}}}$ (2)	[2]
$Cd = \frac{\varphi\sqrt{\varphi}}{\sqrt{2-\varphi}}$ (3)	[2]
$Cd = 0.474\left(\frac{A_h}{d_s d_n}\right)^{0.5}$ (4)	[3]
$Cd = 0.35\left(\frac{A_h}{d_s d_n}\right)^{0.5}\left(\frac{d_s}{d_n}\right)^{0.25}$ (5)	[3]
$Cd = \left[\frac{(1-X)^3}{1+X}\right]^{0.5}$ (6)	[4]
$Cd = 1.17\left[\frac{(1-X)^3}{1+X}\right]^{0.5}$ (7)	[4]
$Cd = \sqrt{0.225\frac{A_h}{d_s d_n}}$ (8)	[4]

Additionally, knowing the spray angle is important in defining what is known as the Recess Number (RN). A recess number is the ratio between the recess length (l_r) and the impact location (l_c) of the two swirler liquid sheets, and this determines if the injector is internal mixing (RN > 1), tip mixing (RN~1), or external mixing (RN < 1). Figure 1 shows the three different mixing locations of a bi-swirl injector.

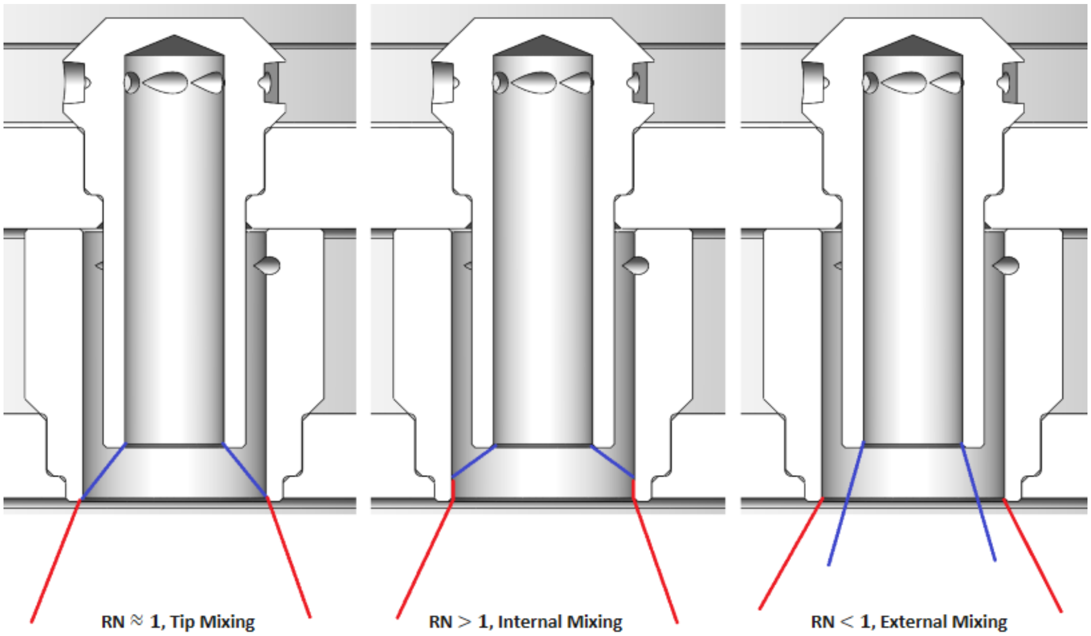

Fig 1. Mixing location

As part of the design process, a decision had to be made on the recess number. An externally mixed injector would be more stable but would provide lower performance. This is because the fuel and oxidizer liquid sheets either never impinge on each other or impinge inside the combustion chamber thus decreasing the effective L* of the chamber. This is not true for an internally mixing injector, as the liquid sheets impinge inside the swirlers. This comes with the downside of a more unstable combustion process as there are multiple distinct mixing regions in the case of a multi-element combustor. The theoretical analysis from Ref. [5] is used to predict the spray angles of a swirler. Now that the tools have been established to size a swirler, it can be designed, built, and flow tested with water in a single element style injector which is described in the following section. Following this, a subscale combustor was designed and hotfired on YJSP's engine testing stand (HETS). Finally, using all the lessons learned from the single element and subscale testing campaigns, a flight injector was designed and hotfired to support Vespula on its flight to 100,000ft.

IV. Single Element Testing Campaign

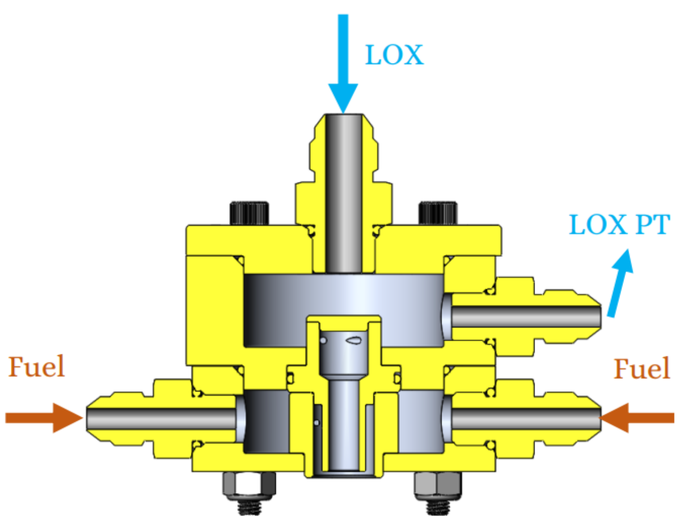

Fig. 2. Single element swirler assembly.

To determine which discharge coefficient model was accurate for this application, a single element swirler and manifold assembly was designed and is displayed in Fig. 2. The inner and outer swirlers are swapable to test different geometries. All parts were machined in-house on manual mills and lathes. The injector was flowed with water at an inlet pressure equal to the predicted injector pressure drop. This pressure drop was calculated using Eq. (9), also known as the CdA equation. After 8 waterflow tests, a model was found for each swirler that exhibited an error of less than 10% on discharge coefficient, which was deemed acceptable. Results of these waterflow tests are listed in Table II.

$$Cd = \frac{\dot{m}}{A\sqrt{2\rho\Delta p}} \tag{9}$$

Table II. Single element waterflow discharge coefficients

Test Number	Swirler (s) Tested	Measured Cd	Predicted Cd	% Error
1	Fuel	0.031	0.0182	70%
	Open LOX	0.201	0.111	81.6%
2	Fuel	0.0197	0.0246	19.9%
	Open LOX	0.153	0.168	9.2%
	Closed LOX	0.185	0.158	17.1%
3	Fuel	0.0205	0.0269	23.9%
4	Fuel	0.0252	0.0294	14.3%
	Closed LOX	0.156	0.158	1.2%
5	Fuel	0.0272	0.032	14.9%
	Open LOX	0.139	0.136	2.4%
6	Fuel	0.0241	0.0265	8.9%
	Closed LOX	0.143	0.131	9%
7	Closed LOX	0.126	0.134	5.7%
8	Fuel	0.0245	0.0265	7.4%
	Open LOX	0.140	0.136	3.3%
	Closed LOX	0.122	0.134	8.9%

On the other hand, spay angle predictions were consistently within 5 degrees of reality. However, when the entry holes were between 0.042” to 0.046” in diameter, errors of up to 30 degrees were observed along with a visibly poor spray behavior compared to other swirlers. A comparison of the spray is shown in Fig. 3 with the good spray on the left and the bad spray on the right. This was considered for future combustor designs, with a bottom limit of 0.048” holes on the outer swirlers.

Fig. 3. Spray comparison

V.Subscale Combustor Design and Hotfires

With the lessons learned from the single element campaign, a 7-element combustor was designed with LOX as the inner element, and Jet-A as the outer element. Two versions were developed, one with “open” style LOX swirlers, and one with “closed” style. Open style swirlers have a constant diameter nozzle, whereas closed style swirlers have a swirl chamber with a larger diameter before the rest of the swirl nozzle. This was done to evaluate the performance differences between the types of swirlers. The fuel swirlers were open style for both versions. Both injectors were designed with internal mixing swirlers (RN>1). The engine operating parameters along with the swirler geometry are listed in Table III, and a cross-section view of the engine and injector is shown in Fig. 4.

Table III. Engine parameters and swirler geometry

	Value	**Units**
Chamber Pressure	261	psia
LOX mass flow rate	1.19	kg/s
Fuel Mass Flow Rate	0.663	kg/s
Mixture ratio	1.8	
Number of elements	7	
	Fuel Swirler	
Nozzle Diameter	0.535	in
Entry Hole Diameter	0.05	in
Number of Entry Holes	3	
Nozzle Length	0.55	in
	Open LOX Swirler	
Nozzle Diameter	0.29	in
Entry Hole Diameter	0.054	in
Number of Entry Holes	5	
Nozzle Length	1.1	in
	Closed LOX Swirler	
Nozzle Diameter	0.29	in
Nozzle Length	0.85	in
Swirl Chamber Diameter	0.4	in
Swirl Chamber Length	0.3	in
Entry Hole Diameter	0.05	in
Number of Entry Holes	6	

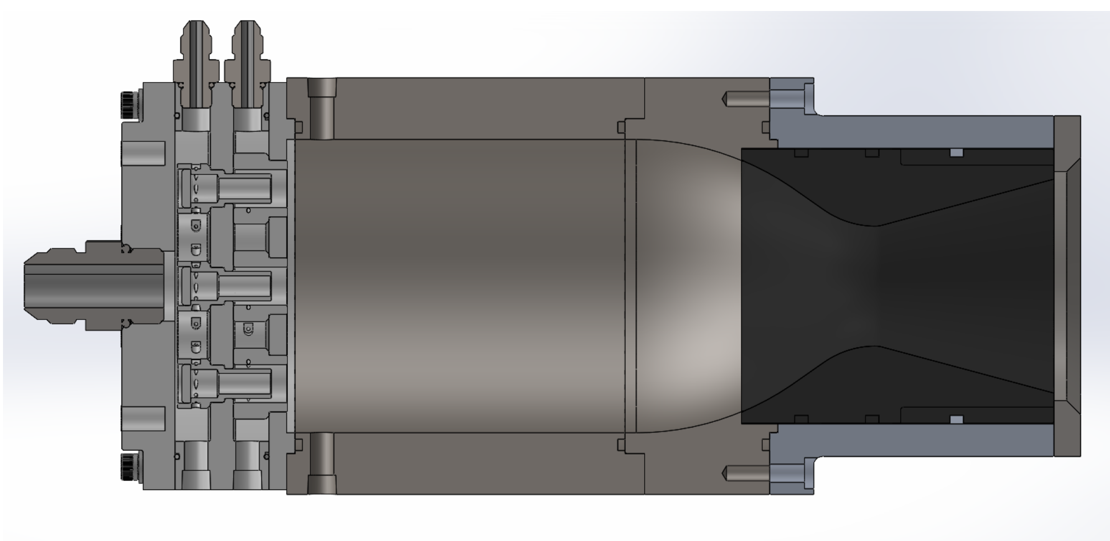

Fig. 4. Subscale combustor CAD cross section

The design features an AS5202 -12 boss port for the LOX Inlet, -04 ports for pressure and temperature measurements, and 2 -04 ports for the fuel inlets. The swirlers are vacuum furnaced brazed to the manifolds. The engine is a heatsink style combustor with 4140 steel walls and a graphite insert for the throat and nozzle. The injector was machined out of 303 Stainless Steel on a CNC mill and CNC lathe. 303 Stainless Steel was chosen for its ease of machinability compared to 304 or 316. It was then waterflowed on the waterflow stand to gather Cd data and visualize the spray pattern. A picture of the spray pattern is shown below in Fig. 5. Table IV lists the predicted and measured Cd values.

Fig. 5. Subscale injector spray visualization

Table IV. Subscale injector measured versus predicted discharge coefficients

Injector Side	Measured Cd	Predicted Cd	% Error
Fuel	0.0265	0.0265	0%
Open LOX	0.107	0.136	21.3%
Closed LOX	0.104	0.134	22.3%

As shown in the table, there is a large error between the predicted and measured Cd values for the LOX manifold, compared to a 0% error on the fuel side. At the time, it was believed this was due to the manifolding differences between the single element and multi-element combustors. The true reason was only discovered when the Vespula injector was waterflowed. This is discussed in the next section. A total of 10 hotfire tests were conducted with the subscale combustors. A video still from one of the hotfires is shown in Fig. 6, while Fig. 7 shows the corresponding engine data.

Fig. 6. Subscale engine hotfire picture

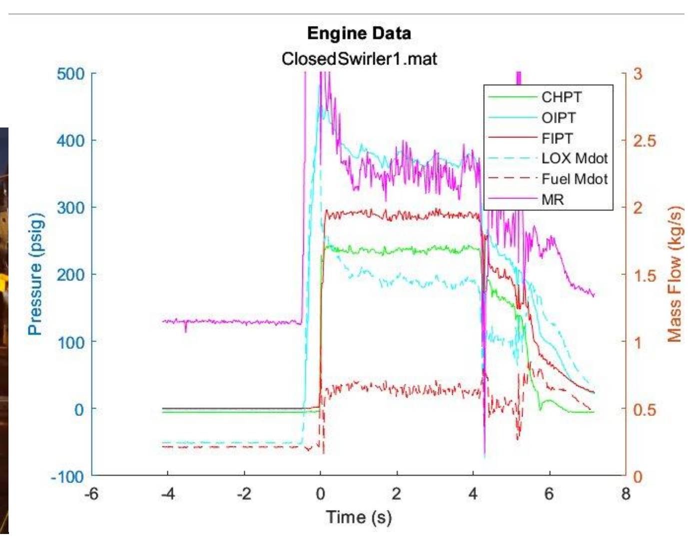

Fig. 7. Subscale engine hotfire data

C*-efficiency was calculated by dividing the measured c* by the theoretical c*. The measured c* is calculated using Eq. (10), while the theoretical (ideal) c* was calculated using NASA's CEA program [6][7]. Figure 8 is a typical plot of the calculated c*-efficiency using two different mass flow rate measurement methods for the LOX side. A turbine flow meter was used on the fuel side, and this tended to agree well with the fuel side injector Cd measured during waterflows. For the LOX side, a custom venturi was designed and built, however it frequently measured data that was incorrect and very different from the injector CdA. For this reason, the c*-efficiency value was calculated using the LOX side injector Cd value measured from waterflow. Table V lists the calculated c*-efficiency for each hotfire test conducted.

$$c^* = \frac{p_c A_t}{\dot{m}} \tag{10}$$

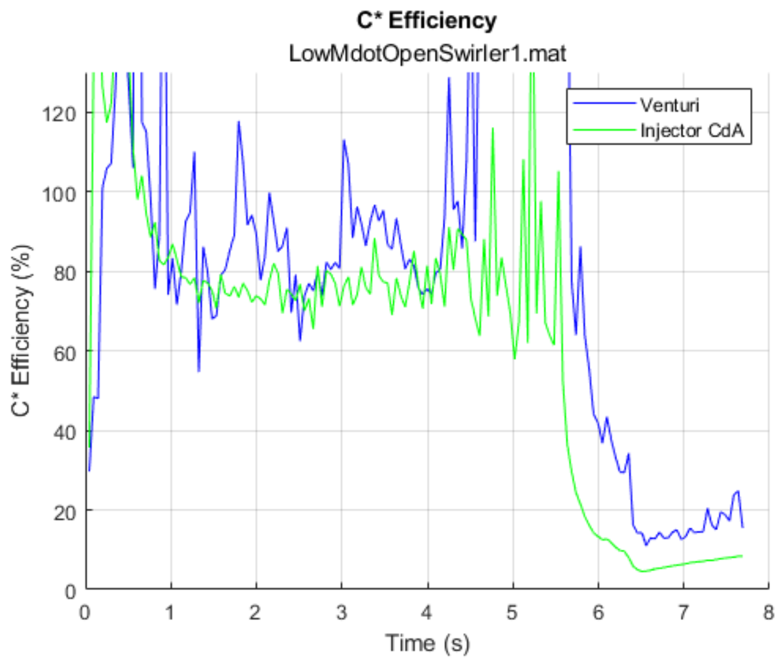

Fig. 8. Typical c*-efficiency plot

Table V. c*-efficiency for each hotfire

Hotfire Number	Calculated c*-efficiency (%)
1 (Open LOX)	75%
2 (Open LOX)	75%
3 (Closed LOX)	70%
4 (Open LOX)	78%
5 (Open LOX)	79%
6 (Open LOX)	79%
7 (Open LOX)	79%
8 (Open LOX, internal mixing)	84%
9 (Closed LOX, internal mixing)	77%
10 (Open LOX, internal mixing)	83%

As seen in the table, tests 8 and 10 had a 4-5% higher efficiency value. This was due to a slight injector modification where the LOX swirler tips were machined down. It was theorized that the injector was in fact not internal mixing and instead was external mixing. While it was visually confirmed in the waterflow tests that the injector was internal mixing, there was some doubt that the LOX spray angles were not the same as the waterflow spray angles. To confirm this, LN2 was flowed through the injector and the spray angle is shown in Fig. 9.

Fig. 9. LN2 injector cryo flow

The reduced spray angle when flowing a cryogenic liquid was enough to change the injector to external mixing, therefore by machining down the LOX posts, the recess length was increased. This made the injector internal mixing and explains why the performance increased. It should be noted that test 9 had an engine anomaly where combustion gases were escaping through the injector/engine interface causing poor performance.

While performance barely increased compared to the pintle injector, it was not a major concern. Future flight injectors were going to have more elements which generally increases the mixing efficiency. Most importantly, after 12 hotfires, including a long duration 8 second burn, no melting was ever observed on the injector face plate or LOX posts. This was a huge success compared to the pintle injector, which typically exhibited melting problems after 5 seconds [8]. Post hotfire pictures are shown below in Fig. 10 and 11.

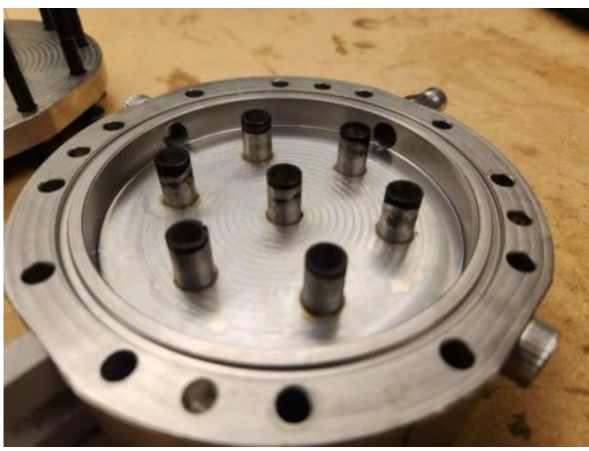

Fig. 10. LOX posts after hotfire

Fig. 11. Injector faceplate after hotfire

VI. Vespula Flight Injector Design and Hotfires

With a successful subscale hotfire campaign, work began on a 2500lbf flight injector to be used on the Vespula vehicle flying to 100,000ft. The injector is once again made from 303 Stainless Steel, with 18 total swirler elements brazed to the manifold plates. A solid rocket motor is integrated directly into the face plate to make the ignition process more reliable. Table VI lists the engine and swirler geometric parameters, and Fig. 12 shows a cross-section view of the injector. This injector was once again tested on a heatsink style engine. The discharge coefficient model was adjusted reflecting the high error seen on the subscale injector. As Vespula would have to burn for 35s, it was extremely important for the injector to not experience any melting throughout the burn. A 1D thermal resistance model across the faceplate was created and validated with Ansys Steady State Thermal FEA analysis. The coolant side Nusselt Number was found using the turbulent flow relationship shown in Eq. (11), and the convection coefficient was found with Eq. (12) with the plate radius as the characteristic length [9].

$$Nu = 0.037 Re^{\frac{4}{5}} Pr^{\frac{1}{3}} \tag{11}$$

$$h_c = \frac{kNu}{L} \tag{12}$$

Table IV. Vespula Engine parameters and swirler geometry

	Value	Units
Chamber Pressure	300	psia
LOX mass flow rate	3.23	kg/s
Fuel Mass Flow Rate	1.62	kg/s
Mixture ratio	2	
Number of elements	18	
	Fuel Swirler	
Nozzle Diameter	0.535	in
Entry Hole Diameter	0.048	in
Number of Entry Holes	3	
Nozzle Length	0.7	in
	Open LOX Swirler	
Nozzle Diameter	0.29	in
Entry Hole Diameter	0.058	in
Number of Entry Holes	6	
Nozzle Length	1.1	in

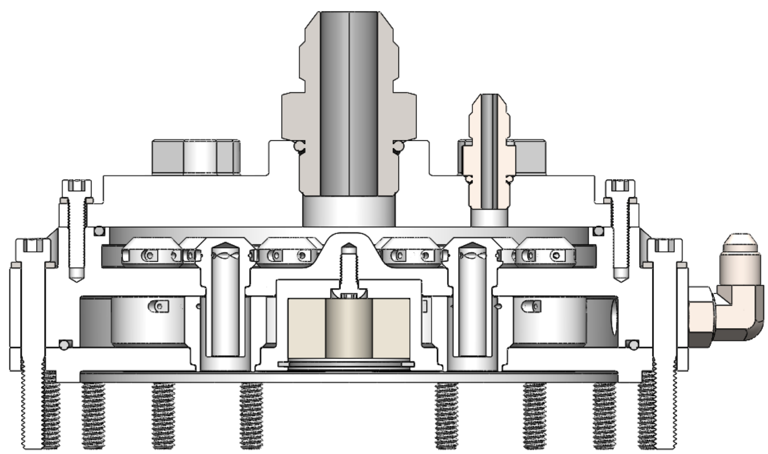

Fig. 12. Vespula injector CAD cross section

For the hot gas side, the heat transfer convection coefficient and hot gas temperature were an average of the values given in Table 1 from Ref. [10]. The values used are shown in Table VII.

Table VII. Heat transfer coefficient and temperature used for thermal analysis

Heat Transfer Coefficient (W/m^2-K)	1347
Hot Gas Temperature (°K)	2350

The thermal resistance model is a simple convection-conduction-convection in series and can be treated like circuit resistors. The total thermal resistance can be found by adding the individual resistances of each section as shown below in Eq. (13).

$$R_{total} = \frac{1}{h_g} + \frac{t}{k} + \frac{1}{h_c} \tag{13}$$

The total heat flux can then be found by dividing the temperature difference by the total resistance as shown in Eq. (14). Since the heat flux is constant throughout the entire circuit, the face plate temperatures can be found after some rearrangement of the convection and conduction equations. The predicted temperatures from the thermal resistance model along with the FEA model are listed in Table VIII.

$$q = \frac{T_g - T_c}{R_{total}} \tag{14}$$

Table VIII. 1D thermal resistance model versus FEA

	1D Thermal Resistance Model	Steady State Thermal FEA
Hot Gas Side Surface Temperature (K)	1194	1365
Coolant Side Surface Temperature (K)	575	587

Once the injector was machined and brazed, it was then waterflowed to determine the actual Cd values and spray distribution. As shown in Table IX, the fuel side had a huge error compared to the LOX side. The fuel side injector pressure drop was 14 psi compared to the predicted 58 psi. Not only is this bad for stability, but the spray behavior on the fuel side was very poor which would decrease mixing efficiency. After some investigation, it was determined that a manufacturing error left a small gap of around 0.005" between the top of each fuel swirlers and the manifold. In fact, if a discharge coefficient of 0.8 is assumed, the total area (gap area and current entry hole area) would result in an injector pressure drop of approximately 10 psi.

Table IX. Vespula injector measured versus predicted Cd

Injector Side	Measured Cd	Predicted Cd	% Error
Fuel	0.05	0.0244	105%
Open LOX	0.150	0.1355	10.8%

The injector went through machining operations to try to remove the gap, however it proved unsuccessful. The next solution involved putting a gasket between the top of the fuel swirlers and the upper manifold and while it did help, the injector pressure drop was still too low. The final fix was to once again machine down the swirlers, but this time, only the outer ring of the fuel swirlers were machined. This allowed the gasket to conform to the height differences and thus sealing on all 18 swirlers. Not only did this completely solve the problem, but the injector pressure drop increased to 90psi, which corresponds to a stiffness value of 30% compared to the predicted 20%. The final discharge coefficient of the fuel was 0.0194. Having learned this, the weird behavior seen during the subscale waterflow test can be explained. The subscale injector was inspected for a similar gap at the top of fuel swirlers, and a gap was present. So, while the discharge coefficient did indeed increase when going from a single element version to a multi-element version (as observed in the LOX manifold), the increase in the fuel manifold Cd just happened to be cancelled out by the fuel swirler gap.

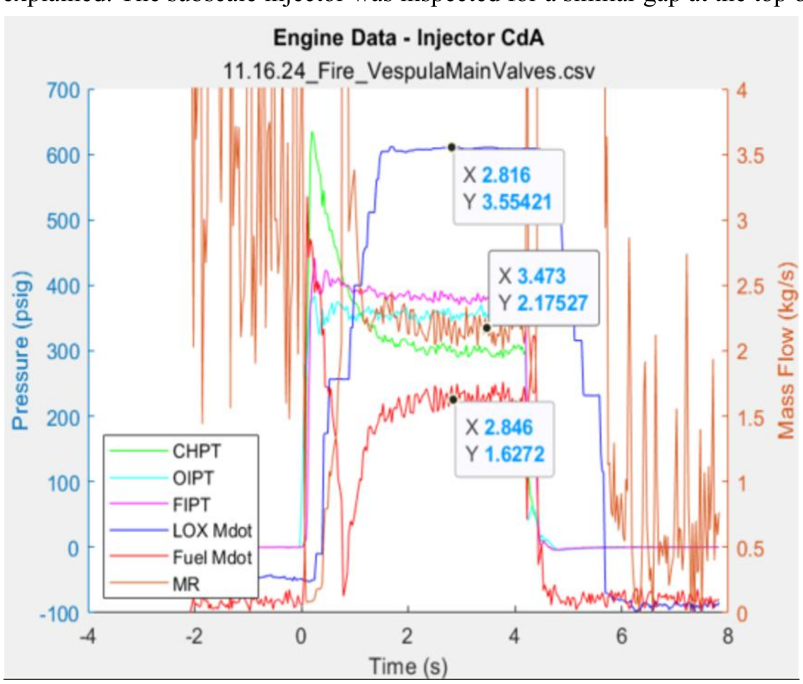

Fig. 16. Vespula injector hotfire data.

The injector was then hotfired twice. Figure 16 shows the engine data plot for the second hotfire, and a corresponding hotfire picture is shown in Fig. 17. A post hotfire picture of the injector face plate is shown in Fig. 18. The injector achieved a c*-efficiency of 92%, the highest in YJSP history, and overshooting the design target of 85%.

Fig. 17. Vespula injector hotfire picture.

Fig. 18. Vespula injector faceplate post hotfire.

VII. Conclusions

Over the course of 2 years, YJSP fully developed a LOX/Jet-A coaxial swirl injector that met the original goals of high performance and high reliability. All work was done in-house except for the vacuum furnace brazing process. Many lessons were learned throughout the development process including design, analysis, test, data review, and more. The lessons learned and experience gathered here will be extremely valuable for YJSP's future space-shot injector designs.

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