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Experimental and numerical investigation of coaxial swirl injector

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Abstract

Coaxial swirl injectors are used in liquid rocket engines to ensure proper propellant mixing[2] . This study examines liquid-liquid interactions in coaxial injectors using liquid nitrous oxide as the oxidiser and a methanol-nitromethane mixture as fuel, a combination offering promising performance. Experiments were performed on a 700 N-class injector included hot-fire and cold-flow tests with water as an oxidiser substitute. The spray cone was analysed using a circumferential patternator. Transient CFD simulations using Ansys Fluent 2024R2 and the Volume of Fluid (VOF) model[4] validated experimental results, assessing swirl chamber geometries. The results confirm the validity of the numerical setup in designing coaxial injectors by assessing the spray angle and discharge coefficient.

1. Introduction

The swirl injectors are the class of flow-shaping devices, used for atomisation of fluid flow. It is accomplished by breaking the liquid film at the end of the injector. The film is shaped as a cone due to the tangent placement of the circumferential holes that deliver flow to the prechamber of the injector. Accurate modelling and experimentation of this device is crucial because this type of device is a critical part of gas turbines and liquid rocket engines[7] . They are an interesting choice, because with a mediocre machining accuracy the resultant mixing and atomisation is high.[2] With an accurate solution of flow, there is the possibility of obtaining a preliminary assessment of the combustion process, which is vital in the preparation of low-emission and highly efficient devices. The main analytical theory of steady swirl injector operation is the work of Bazarov[3] . Other works related to the analytical solution of swirl atomisers that are worth mentioning are Orzechowski[1] and Taylor[8] studies. In this theory, there are many assumptions because of the complex nature of fluid flow in the swirl injector. Firstly, the implementation of fluid viscosity is typically modelled as a coefficient to the inviscid flow solution to capture friction losses in injector chambers.[9] Another simplicity is neglecting the angular momentum of the fluid flow in the entrance holes to the injector chamber that caused additional movement in the axis. Both of these reasons need to be studied with the help of experiment and CFD analysis.

In this study as an example, the coaxial rocket swirl injector is assessed. The purpose of coaxial injectors in liquid rocket engines is to get an efficient mix of the fuel with the oxidiser in the combustion chamber. Good design should be able to get good atomisation and mixing in a wide range of mass flow rates.[10] During a decrease in flow rate, there is a risk of a lack of mixing that can cause low-frequency combustion instabilities and oxidiser reach points in the combustion chamber. The second failure is critical in terms of the possibility of liner damage, and is the main concern during studies.

2. Design layout

2.1 Propellant choice and flow requirements

First calculation for included various fuels such as Methanol, Ethanol and Propan as a first choice and RP-1 substitute as comparison and liquid oxygen and N_2O as oxidisers. As the reference design propellant the Methanol+N_2O combination was chosen. Further analysis of fuel library showed better performance of mixtures with Nitromethane due to higher density and its high oxygen balance with low oxygen concentration oxidiser like N_2O allows much higher fuel flows for regenerative cooling with low oxidiser-to-fuel (O/F) ratios while keeping the mixture close enough to stoichiometry for performance. The final mixture of 30-70 ratio of Nitromethane to Methanol was chosen due o lowest chamber temperature and legal reasons for future tests in UK static fire competition Race2Space. Analysis was constrained to 40 960 seconds total impulse (for sea level conditions) as a US limit for rocket motors and to 160 mm rocket diameter. Implemented automatic design optimization for propellants amount and configuration showed better performance for designs with lower thrust but with longer burnt-time and lower chamber pressure (thus lower tank pressure and required tank mass and Composite Overwrapped Pressure Vessel size). The changes to design O/F ratio had samller impact within optimization loop and the designed O/F ratio of 2 was chosen in order to lower the maximal expected temperature in the chamber. The engine burn-time is designed to be approximately 60 seconds with implemented regenerative cooling and film cooling system. The engine parameters are listed in Table 1.

Parameter	Current design	Future flight configuration
Fuel composition w/w	30% Nitromethane, 70% Methanol	40% Nitromethane, 60% Methanol
Oxidiser	N_2O	N_2O
Thrust	750 N	800 N
Tank pressure	40 bar	28 bar
Chamber pressure	18 bar	18 bar
Designed O/F ratio	≈ 2	≈ 2
Fuel flow rate	135 $\frac{g}{s}$	$\approx 130\frac{g}{s}$
Oxidiser flow rate	270 $\frac{g}{s}$	$\approx 260\frac{g}{s}$

Table 1: Comparison of engine at its current development stage with future target flight engine

2.2 Co-swirl rationale

The injector is a coaxial, liquid-liquid type, preliminarily designed based on the analytical model proposed by Bazarov.[2] This type of injector was chosen due to some experience with similar designs for hybrid motor, compact sizes, possibility for in-house manufacturing on conventional machines such as lathe and milling machine and chances for adequate atomisation of propellants. The fuel is fed through the outer swirl chamber after chamber cooling role, while the fuel flows through the inner swirl chamber to ensure stable flow from the larger tank. The operational temperature of the nitrous oxide is maintained between -20 °C and -10 °C to ensure a liquid-liquid phase regime. As the result rocket can take higher volume of propellants and operate on gas phase in low dense atmosphere during further part of the flight. In the design phase three configurations of the injector were assessed. The first (Figure 1a) was designed for ignition and preliminary tests with a lower O/F ratio and as a proof of manufacturing capabilities. This version was compatible with various spacers in order to study impact of exit chamber offset on propellant cone behind injectors.

The second version (Figure 1b) was modified to operate on the designed O/F ratio ($\approx$ 2). The number and sizes of orifices was changed to ensure designed O/F ratio with 6 mm chamber exits offset.

The third design (1c) is a final geometry similar to second design with twelve 1.1 mm orifices in inner section and three 1.2 mm orifices in outer chamber. The outer swirl chamber were enlarged, to achieve higher circumferential velocity. More changes were introduced in the inner chamber, where the diameter was increased to 7 mm and was changed to an open type. These changes were inspired by a micro-coaxial injector design patented by XCOR Aerospacce in 2007[6] and our previous open type designs for self pressurized hybrid motors. Additionally, it is a measure of precaution in case the nitrous is under cooled, and extends operation range of oxidiser temperatures.

The results of analytic calculation and performed tests are given in Table 2. The dimensions of each configuration are given in Table 3.

2*TC	A geom		Cd		oxidiser mass flow [g/s]		Fuel mass flow [g/s]		OF	OF
	inner	outer	inner	outer	analytical	messured	analytical	messured	analytical	messured
A	2.03	14.07	0.29	0.06	311	265	226	260	1.38	1.02
B	2.03	22.69	0.29	0.04	311	260	146	150	2.13	1.73
C	1.68	32.59	0.19	0.03	415	TBD	126	110	3.28	2.6

Table 2: The results of analytical calculation of swirl injector, pressure drop = 22 bar, nitrous at -20 °C

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Configuration	Swirl chamber outlet diameter [mm]	Swirl chamber diameter [mm]	Inlet orifices diameter [mm]	Number of orifices
A - inner	5	7	1.5	6
A - outer	10	11	1.5	3
B - inner	5	7	1.1	12
B - outer	12	11	1.2	3
C - inner	7	7	1.1	12
C - outer	10	14	1.2	3

Table 3: Injector characteristic dimensions

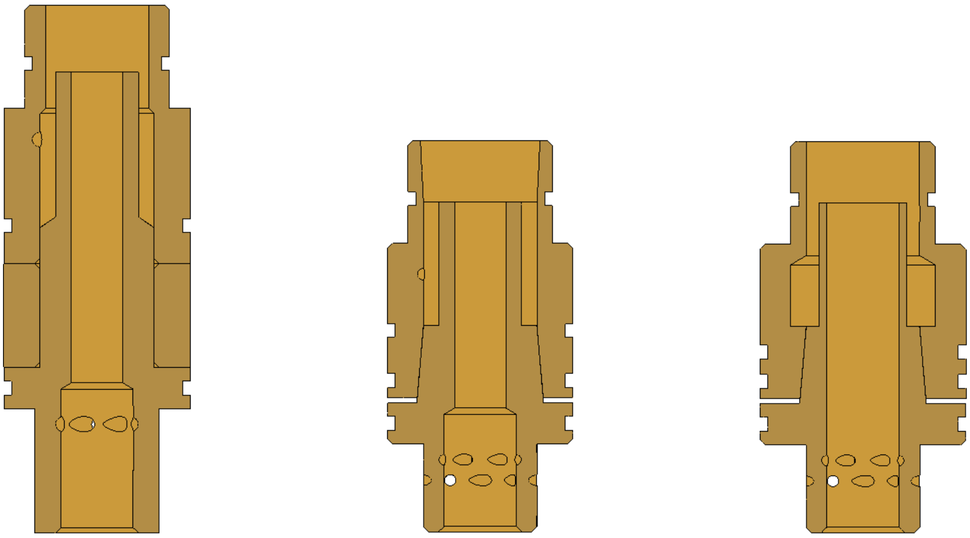
(a) First version with 10 mm spacer (b) Second version with 6 mm offset (c) Third version with 6 mm offset

Figure 1: Injectors design history

3. Preliminary numerical assessment

The injector is preliminarily designed based on the analytical model proposed by Bazarov. The design pressure drop of the injector is 22 bar and this value is used for all analysis. CFD calculations were performed for choosing the flow direction and the gap size between the ends of the swirl chambers (Figure 2). The studies have shown that better mixing and more stable performance in terms of spray pattern were shown for -6 mm gap and contr-swirl configuration.

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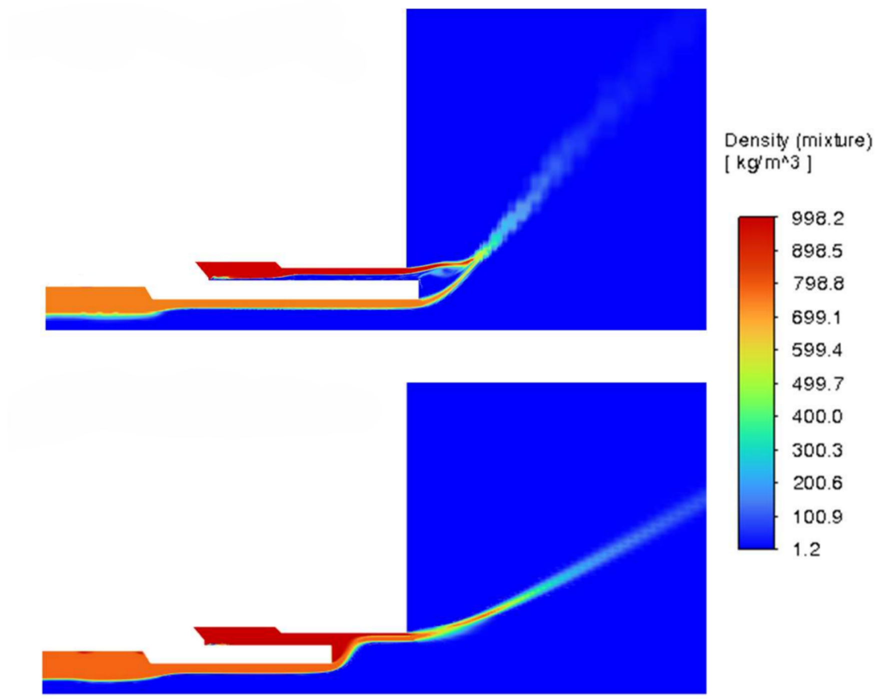

Figure 2: Results of density field in different gap configuration +1 mm vs -6 mm

4. Experiment description and preliminary results

In experimental studies of injectors the main goal is to get data on droplets. The crucial properties of droplets are droplet size and flow rate in a specific location, also called spray pattern. In case of rocket coaxial swirls, equally important in terms of combustion stability and temperature distribution is mixing. During hot-fires mixing properties can be evaluated.

Nitrous oxide handling has great safety requirements during cold-flow and hot-fire tests. In addition, it is difficult to study the mixing properties when methanol and nitrous oxide are used. To encounter this difficulty, an experiment was designed based on flow similarity and as analogue to nitrous oxide water was chosen. Methanol wasn't change, because it is relatively safe to handle, cost effective To study this property, the difference in mixture density is used.

For the initial phase, tests were carried out to verify the analytical design procedures. This was followed by a hot-fire test of the engine to assess its performance under operational conditions. Subsequently, a series of flow characterization experiments using Venturi tubes were conducted to determine the discharge coefficient as a function of Reynolds number and to evaluate the injectors behavior. To investigate the influence of dual-phase operation, measurements were performed separately for fuel flow, oxidiser flow, and then with both propellants injected simultaneously.

4.1 Initial tests

For initial tests that verified analytical design procedures, water flow tests were performed. The water was pressurized with nitrogen to approximately 15 bar (expected pressure drop on injector) and sprayed into a 3D printed patternator (Figure 4). During those studies, the influence of the gap size on the shape of the cone and stability of discharge coefficient were studied. The results have shown a good correlation for inner swirl, and a high susceptibility of fuel injector on assembly mistakes. The CdA for outer swirl varied in range of 50 % with consecutive tests, due to different placements of inner and outer swirl chamber as well as unevenness of their axes. The example results of cold flow are shown in Figure 3. To address that issue, consecutive designs of the injector use cones connection between inner and outer swirl for a better coaxial placement.

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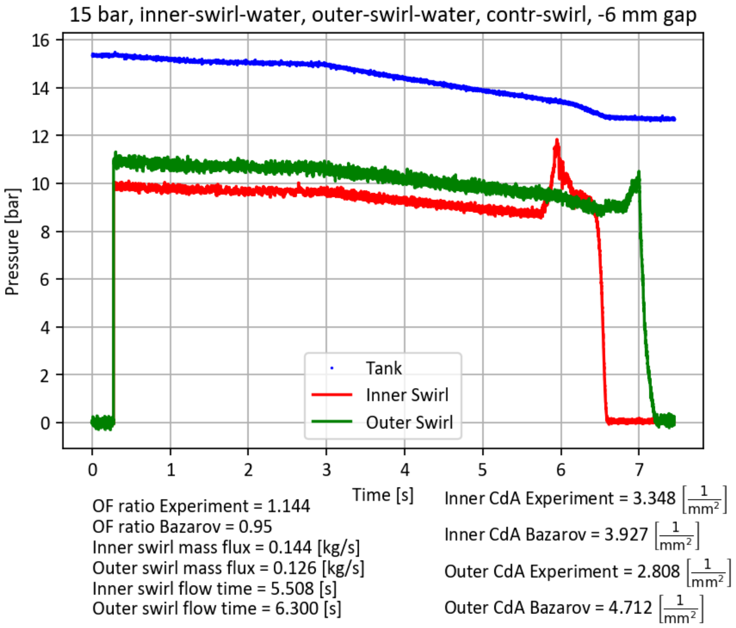
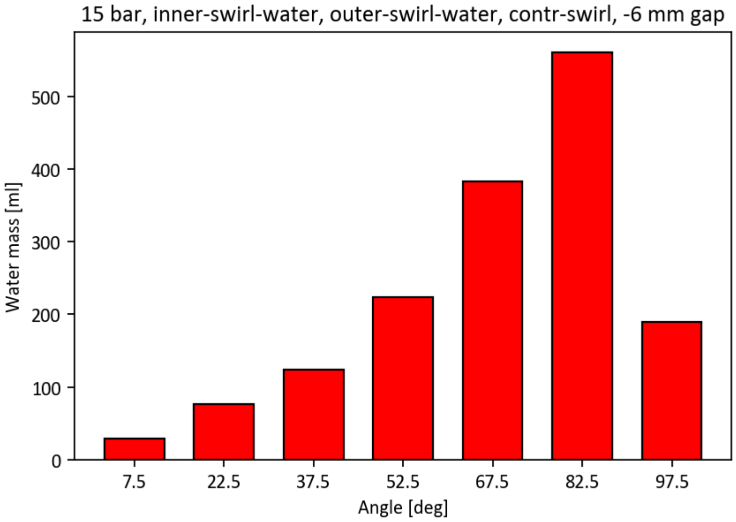


(a) Water flow results



(b) Paternator results

Figure 3: Injectors test results

4.2 Discharge coefficient verification

To further investigate the injector's hydraulic behavior, a series of experiments was conducted using Venturi flow measurements. The primary aim was to characterize how the presence of a second propellant stream affects the injector's performance, with measurements carried out for fuel-only, oxidiser-only, and combined flow conditions. This allowed for a direct evaluation of interaction effects between the two streams. Additionally, the tests enabled analysis of the discharge coefficient as a function of Reynolds number. Experimental data were also compared with predictions based on Bazarov's theoretical model to assess its applicability. Particular attention was paid to potential differences in model accuracy between the inner (oxidizer) and outer (fuel) swirl flows.

To enable these tests, a set of custom Venturi tubes was designed and manufactured in accordance with the ISO 5167-4:2022 standard[5] for flow measurement. The final geometry is presented in Figure 9a. To characterize the Venturi tubes, a series of tests was conducted using water as the working fluid. The objective was to determine the discharge coefficient by comparing the mass flow rate calculated from the pressure drop, based on the ISO 5167-4:2022

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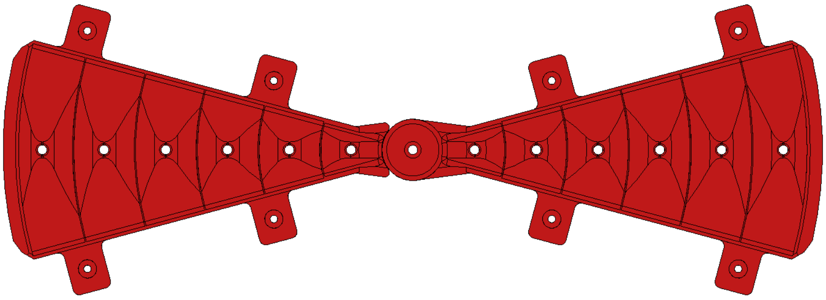
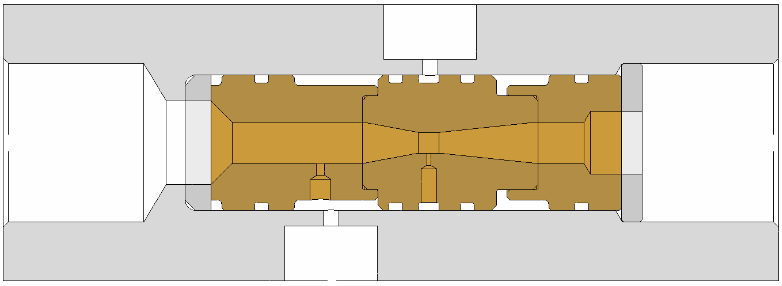
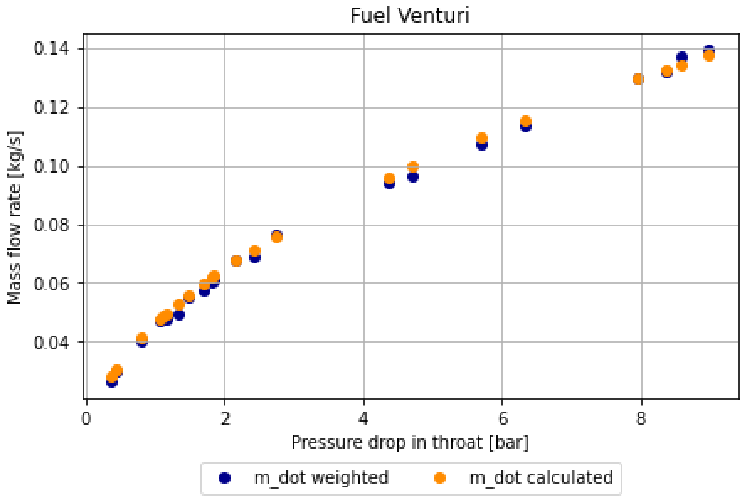


Figure 4: Visualisation of paternator used in this study

formulation, with the reference mass obtained by weighing the total amount of water collected after each test. The test stand was equipped with two Kulite ETM-500-375M-80barA absolute pressure transducers, installed upstream and at the throat of the Venturi.



(a) Venturi Tube design



(b) Venturi tube testing

Figure 5: Venturi Tube

The test stand used for final injector characterization is shown in Figure 6. Both the fuel and oxidiser lines were pressurized using a single nitrogen supply bottle. Water was loaded into the oxidiser tank, while methanol was used as

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the fuel. The temperature of both liquids was measured before each test. Downstream of the tanks, servo-actuated ball valves were used to initiate the flow. Each line was equipped with a dedicated Venturi tube, with pressure transducers installed at three key locations: at the inlet of the Venturi, at the throat, and downstream of the restriction, corresponding to the injector inlet. This configuration enabled accurate measurement of pressure losses and mass flow rates through the injector under different flow conditions. A detailed list of all pressure transducers used during these tests, including their measurement ranges and installation points, is provided in Table 4.

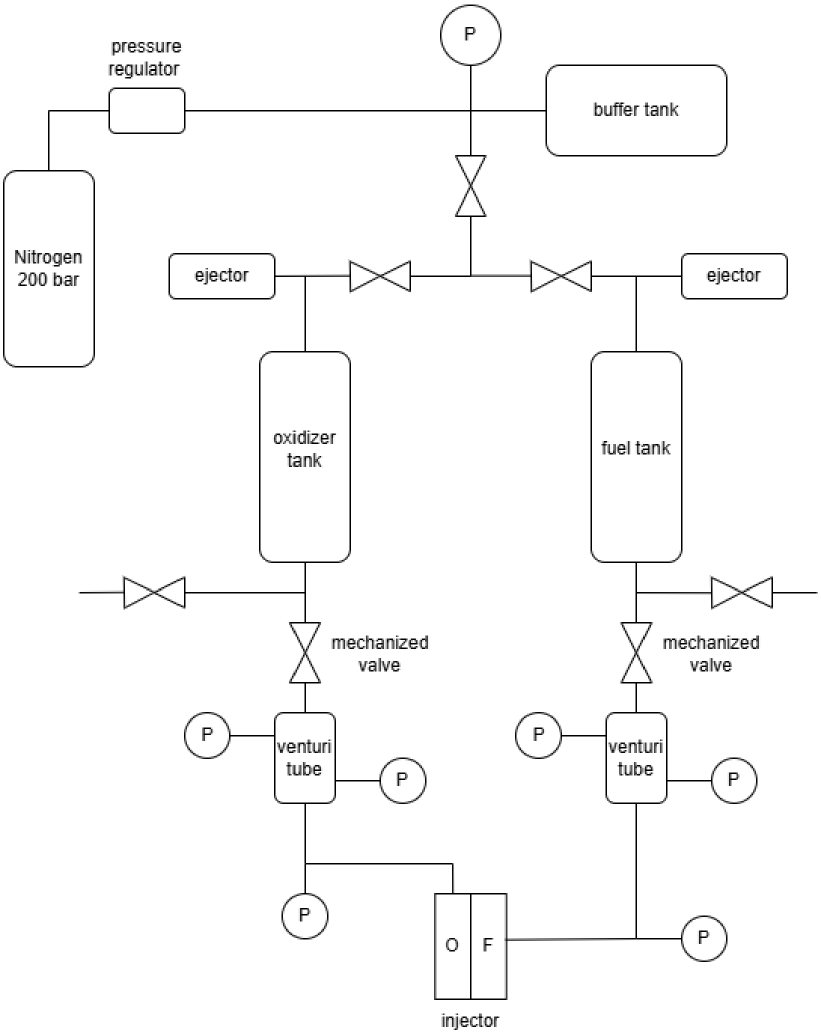

Figure 6: Test stand diagram

Table 4: Pressure transducers summarization

	Measurement Place	Pressure range - abs [bar]	Accuracy [%]
IFM PU5402	pressurization tank	1-101	+/- 0.5
IFM PU5402	oxidiser line venturi inlet	1-101	+/- 0.5
IFM PU5423	fuel line venturi inlet	1-61	+/- 0.5
Kulite ETM-500-375M-35barA	oxidiser line venturi throat	1-36	+/- 0.1
Kulite ETM-500-375M-35barSG	fuel line venturi throat	0-35	+/- 0.1
Kulite ETM-500-375M-80barA	oxidiser line injector inlet	1-81	+/- 0.1
Kulite ETM-500-375M-80barA	fuel line injector inlet	1-81	+/- 0.1

Figure 7 shows the calculated mass flow rates of oxidizer and fuel as a function of pressure drop across the injector for each of the combined (fuel + oxidizer) tests. For Injector A, the resulting O/F ratio was approximately 1.5,

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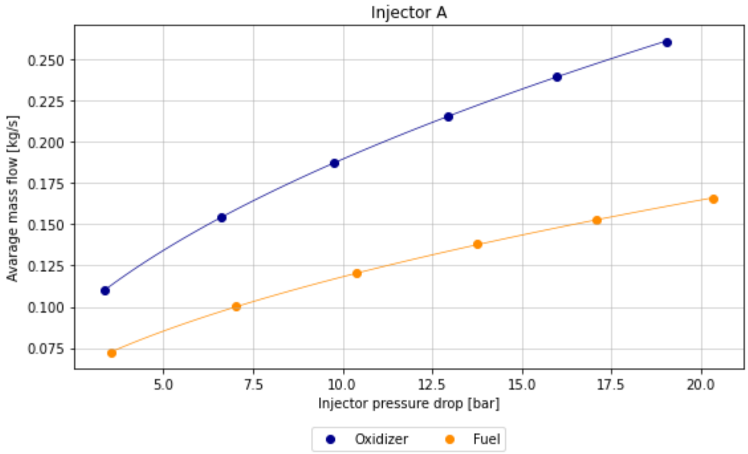
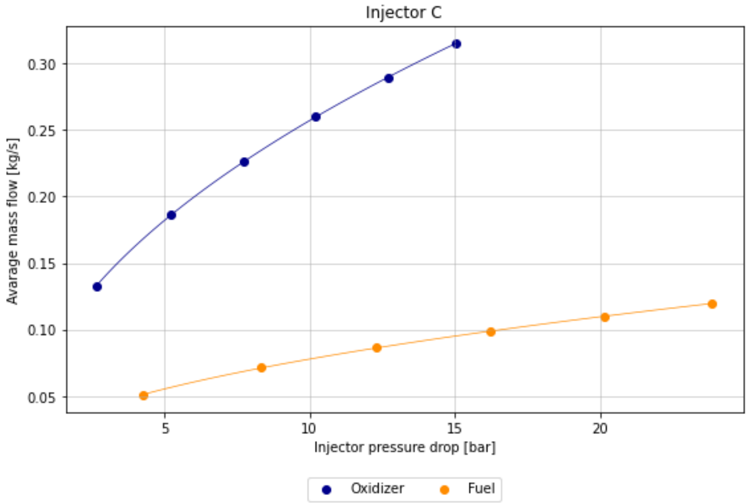
while for Injector C it reached around 2.6. These values reflect the differing internal geometries and flow resistance characteristics of the two injector designs. It should be noted that the O/F ratios measured during the cold-flow tests do not directly reflect the target engine configuration. In the final design, the oxidizer (N_20) is expected to be partially vaporized and cavitating, which will exhibit significantly lower mass flow compared to water under the same pressure drop. The presented results therefore reflect an intentional expansion of the injector's operating envelope. The elevated O/F ratio observed for Injector C is consistent with the design intent, which assumes a more modest oxidizer flow in the actual engine, potentially bringing the operational O/F closer to the target value of 2.0.



(a) Injector A - mass flow characterization



(b) Injector C - mass flow characterization

Figure 7: Injector pressure drop versus mass flow rate for two injector geometries

Figure 8 shows a comparison of the discharge coefficient obtained from standalone oxidizer tests and combined fuel-oxidizer tests. The Reynolds number was calculated separately for the oxidizer and fuel sides, based on the hydraulic diameter at the respective outlet sections of the injector. Dynamic viscosity was determined individually for each measurement point using the corresponding measured fluid temperature. The resulting Reynolds numbers reflect actual test conditions and allow for accurate flow regime identification. In the plotted results, the discharge coefficient Cd is presented with respect to both the effective outlet flow area and the inlet orifice area, allowing for comparison of different reference definitions and highlighting the sensitivity of interpretation to geometric assumptions.

The results demonstrate strong agreement between the two test conditions, indicating that the presence of the second flow stream has a limited effect on the oxidizer-side discharge behavior. For Injector A, the theoretical discharge coefficient calculated using Bazarov's model was Cd=0.2140, which closely matches the experimentally determined values. When averaged over the entire Reynolds number range, the relative error remains about 1% - +1.2% for the standalone oxidizer tests and +0.9% for the combined fuel-oxidizer configuration. Similarly, for Injector C, the measured discharge coefficient agrees well with the theoretical prediction of Cd = 0.1735, with a relative error of -1.1%

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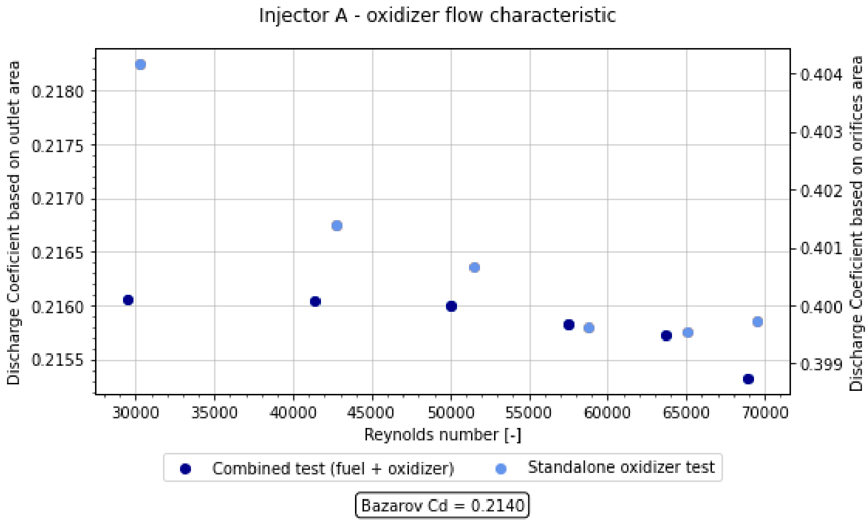
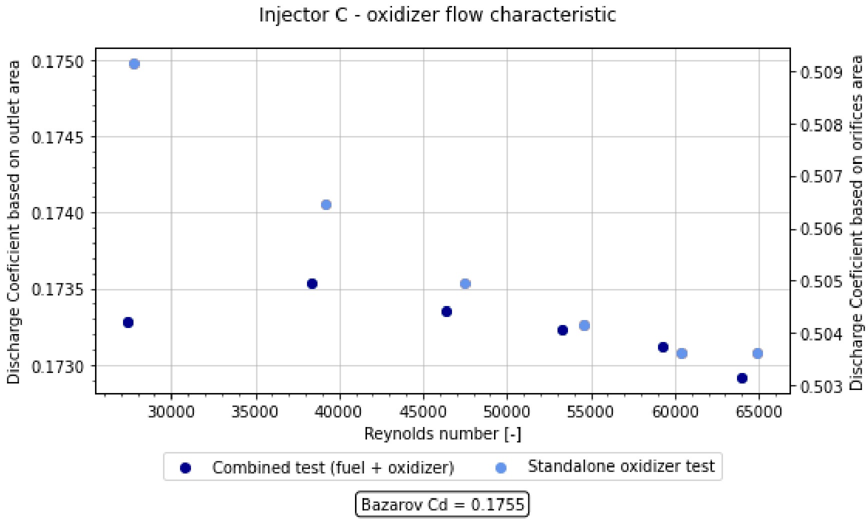
for the standalone case and -1.3% for the combined tests. Although the error trends differ-Bazarov's model slightly underpredicts the discharge coefficient for Injector A and slightly overpredicts it for Injector C-the overall agreement further confirms the applicability of the model for predicting oxidizer flow behavior in both injector geometries.



(a) Injector A - oxidizer Cd vs. Reynolds number



(b) Injector C - oxidizer Cd vs. Reynolds number

Figure 8: Comparison of measured oxidizer discharge coefficient with Bazarov's theoretical prediction

For the fuel side, the discharge coefficient and Reynolds number was calculated using the same methodology as for the oxidizer. As shown in Figure 9, no comparison with Bazarov's model is provided in this case, since the model applies only to single-swirl injectors without a central insert. In the coaxial geometry tested here, the outer swirl flow is significantly affected by the presence of the central oxidizer post, making Bazarov's assumptions invalid for the fuel-side prediction. The results from both standalone fuel tests and combined fuel-oxidizer tests show strong agreement, indicating consistent flow behavior across different operating conditions.

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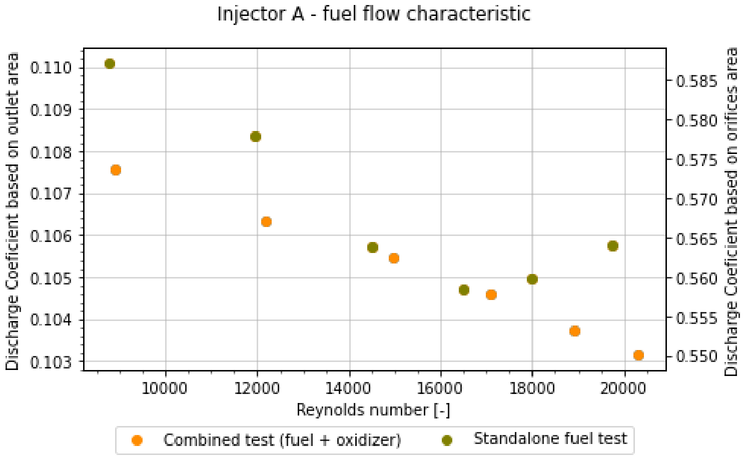
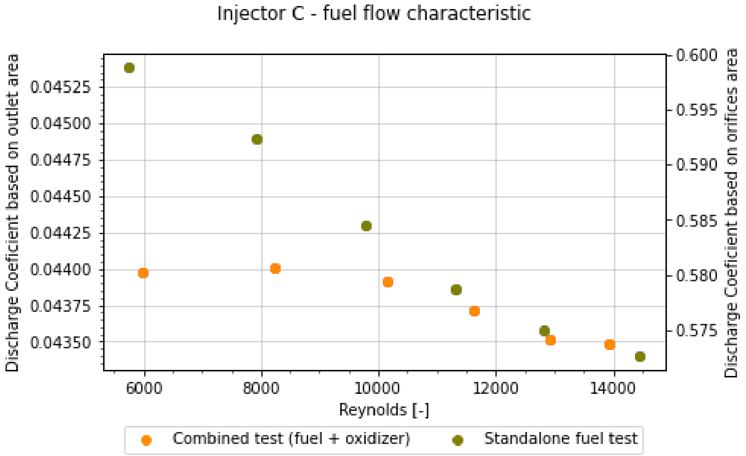


(a) Injector A - fuel Cd vs. Reynolds number



(b) Injector C - fuel Cd vs. Reynolds number

Figure 9: Comparison of measured fuel discharge coefficient

5. Conclusions

This study presented a comprehensive experimental and numerical investigation of coaxial swirl injectors designed for a bipropellant liquid rocket engine. The work included analytical design, cold-flow verification, CFD simulations, and experimental testing across multiple injector configurations.

Numerical results confirmed the importance of geometric parameters such as chamber gap and swirl direction for ensuring stable flow patterns and effective atomization. Preliminary CFD analysis supported the selection of an optimized configuration with a -6 mm offset and contr-swirl layout.

Experimental cold-flow tests, including standalone and combined propellant operation, were used to determine the discharge coefficient as a function of Reynolds number. High agreement was found between those tests, indicating minimal mutual interference between propellant streams in the tested conditions.

Comparison with Bazarov's theoretical model showed good agreement for the oxidizer-side swirl flow in both injectors A and C, with relative errors below 1.3%. This validates the model's applicability for inner swirl flows in coaxial injectors. As expected, the model was not applicable to the outer (fuel) swirl flow due to the presence of a central insert, but the experimental results remained consistent across all test cases.

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