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Case Study on Oxidizer-Only Flow Through a Modified Bi-Swirl Injector

P.A. Chandru*, Kurella Alekhya†

Aeroin Space Tech Pvt. Ltd, Velachery Rd, Pallikaranai, Chennai, Tamil Nadu, India – 600100.

Abstract: An experimental simulation study was conducted to analyze oxidizer-only injection through a modified bi-swirl injector. This report aims to present the simulation process and findings in an accessible manner, while retaining the necessary technical detail. The oxidizer used for this study is liquid oxygen (LOX), and the simulation explores various flow conditions by varying inlet mass flow rates and outlet velocities. The objective is to evaluate the flow characteristics and potential backflow behavior, which are critical for optimizing the injector design and ensuring effective oxidizer delivery. The case study utilizes ANSYS Discovery for detailed computational fluid dynamics (CFD) simulations. Results include velocity profiles, pressure distributions, and flow gradients, all derived through a systematic ANSYS problem formulation workflow. These insights support the evaluation and potential modification of the bi-swirl injector to enhance its performance under single-propellant (oxidizer-only) injection conditions.

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1. Introduction

A thorough understanding of injector characteristics is essential for optimizing rocket engine performance through informed design modifications. Injectors play a crucial role in achieving efficient combustion by ensuring proper mixing of fuel and oxidizer—primarily through effective atomization of the propellants. Various types of injectors exist, each tailored to specific propellant combinations, atomization strategies, geometric configurations (such as angle of injection, mixing location), and material considerations. In this study, a case analysis of oxidizer flow through bi-swirl injectors was conducted to gain deeper insight into internal injector dynamics. This work builds on the foundational findings presented in [5]. The detailed characteristics of different injector types, including their respective performance parameters and design trade-offs, are extensively discussed in [2]. While most liquid rocket engines are designed to operate with cryogenic propellant systems, alternative fuel options—such as jet fuel—are also employed in specific configurations. To maintain simplicity and cost-effectiveness, this study relies entirely on virtual simulation techniques, including CAD modeling, flow simulation, analytical calculations, and results tabulation, to investigate the performance of bi-swirl injectors.

2. Literature Review

The development of high-performance rocket propulsion systems has increasingly focused on improving combustion efficiency, stability, and fuel utilization. One of the promising methods for achieving these improvements is the application of swirl injection technology in rocket engines. Swirl injectors impart angular momentum to the injected fluid, promoting enhanced mixing between oxidizer and fuel, thus contributing to more efficient combustion processes. The literature reviewed here

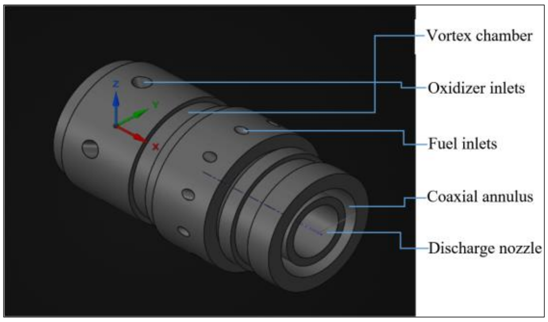

Figure-1 Bi-Swirl Injector

* Aeroin SpaceTech Private Limited, Chennai, Tamil Nadu, India – 600100. **Contact:** chandrupa.aeroin@gmail.com.
† Aeroin SpaceTech Private Limited, Chennai, Tamil Nadu, India – 600100.
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provides a comprehensive understanding of how swirl injectors affect combustion characteristics in hybrid and liquid rocket engines.

Zhang et al. (2022) conducted an in-depth experimental investigation into the effects of swirl injection on a novel composite hybrid rocket fuel grain. The study revealed that aligning the swirl flow with the helical structure of the fuel grain significantly enhanced the regression rate and combustion efficiency. Among the injector configurations tested, the Swirl-Direct (SD) injector was identified as the most effective, delivering the highest performance in terms of fuel regression and stability. These findings suggest that swirl injection can be a transformative solution for hybrid rocket engines, leading to more predictable and efficient performance, especially when carefully integrated with grain geometry (Zhang et al., 2022).

In the domain of swirl injector design, (Rezende et al.2014) developed a mathematical model for the dimensioning of simplex swirl injectors. They highlighted the importance of accounting for separate discharge coefficients for both inlet and outlet orifices. This refinement led to significantly more accurate predictions of mass flow rates and spray angles. Their model was experimentally validated through nearly 100 tests across 15 injector designs, underscoring its practical reliability. The precision provided by this model aids in optimizing injector configurations for a wide range of propulsion systems, from small-scale thrusters to larger rocket engines (Rezende et al., 2014).

The impact of momentum ratio (MR) on combustion stability and efficiency was studied by So, (Han, and Kwon.et.al.2021), who examined multi-element swirl coaxial jet injectors. Three injector configurations with MRs of 3.0, 3.3, and 3.7 were analyzed under both cold-flow and hot-fire conditions. The MR 3.0 configuration achieved the highest combustion efficiency (98%) and demonstrated the most stable operation, with minimal pressure and temperature oscillations. Additionally, acoustic analysis and dynamic pressure measurements confirmed the injector's excellent performance, with RMS fluctuations consistently below 0.8%. These results emphasize the role of MR in fine-tuning combustion dynamics in swirl injectors (So et al., 2021).

(Goulart, Hinckel, and Bontempo,2020) expanded on traditional injector designs by developing non-uniform spray swirl injectors, using skewed cuts on injector nozzles to achieve directional spray control. Their experimental and analytical results showed that the skewed design led to a mass flow ratio (τ) of 3.17 between high- and low-flow sectors, demonstrating that propellant distribution can be strategically directed. Based on these findings, a conceptual injector plate design was proposed, featuring centrally skewed oxidizer-rich injectors surrounded by fuel-rich ones. This configuration aimed to optimize the mixture ratio and reduce thermal loading on chamber walls, offering practical design advantages for liquid rocket engines (Goulart et al., 2020).

(Wang, Wang, and Yang, 2017a) explored geometric effects on swirl injector performance by analyzing LOX/kerosene bi-swirl injectors under supercritical conditions. They introduced the concept of a “critical mixing line” to quantify mixing effectiveness. The study concluded that longer recess lengths, increased post thickness, and larger annulus widths significantly improved fuel-oxidizer mixing by increasing the spreading angle of the spray. However, this improvement came with trade-offs, including heightened thermal stress on injector walls due to reduced kerosene coverage, which typically acts as a thermal buffer. These findings highlight the complex interplay between injector geometry, combustion efficiency, and thermal management (Wang et al., 2017a).

In a follow-up study, (Wang et al. 2017b) conducted a comprehensive numerical investigation of cryogenic swirl injectors using Large Eddy Simulation (LES). This study was notable for capturing a wide range of flow instabilities, including helical, centrifugal, shear-layer, and acoustic modes. A key finding was that a dominant helical instability mode ($m = -3$) resonated with an acoustic wave at 4.8 kHz, leading to intensified flow disturbances. The application of Proper Orthogonal Decomposition (POD) revealed that the first six POD modes captured more than 80% of the oscillatory energy, providing critical insight into the dynamic behavior of swirl injector flows. These observations are essential for the design of injectors that must operate under extreme conditions with minimal instability (Wang et al., 2017b).

Together, these studies form a comprehensive body of knowledge that advances our understanding of swirl injector behavior in both hybrid and liquid propulsion systems. The integration of experimental methods, analytical modeling, and advanced simulations provides a solid foundation for developing more efficient and stable rocket engines. The research emphasizes the importance of geometry, momentum ratio, flow dynamics, and thermal considerations in designing next-generation swirl injectors.

3. Methodology

To predict the flow characteristics of the interested injector with limited time constraint, we have approached the ANSYS Discovery Solver for approximate results. First, the 3D CAD model of injector (Shown in Fig 1 and 2) was designed using Discovery and then by using volume extraction method the 2 different internal fluid regions have been assigned particularly for each propellant flow domain.

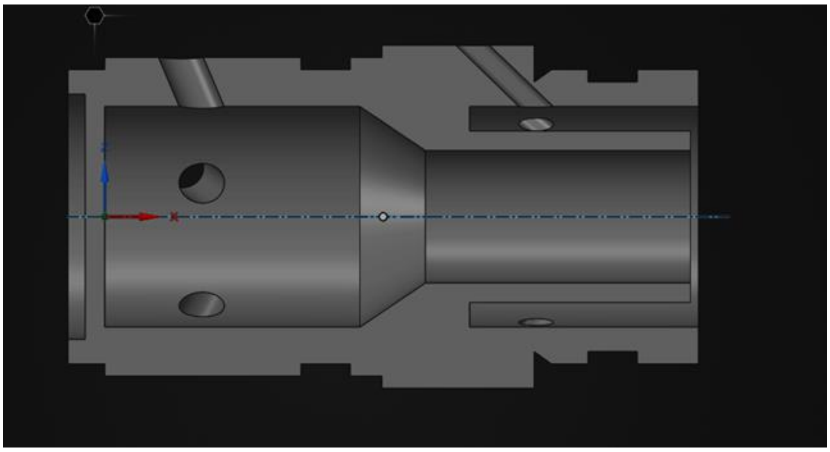

Figure-2 Cut-plane view of injector

Next, exactly the only oxidizer region is included in the simulation with boundary conditions (varies for each simulation). The relation between pressure and velocity is primarily considered to check the flow uniformity. The velocity and pressure contours are derived and presented below.

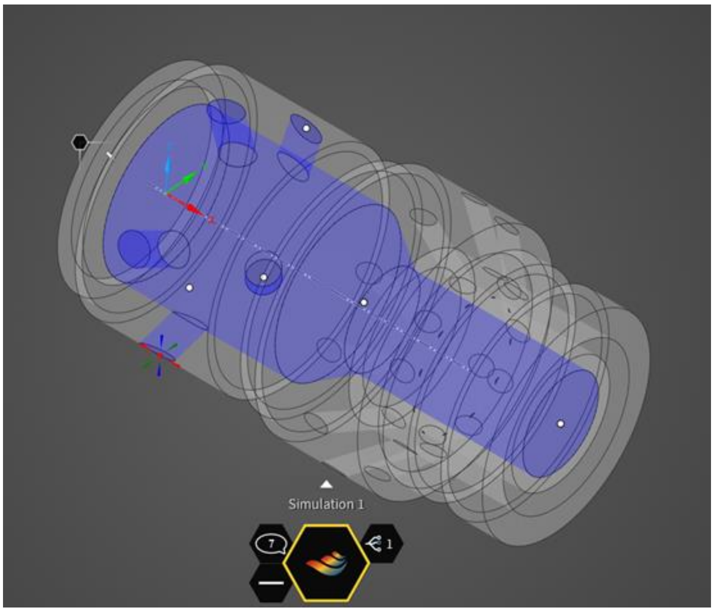

Figure-3 Propellant (Oxidizer) region (Included)

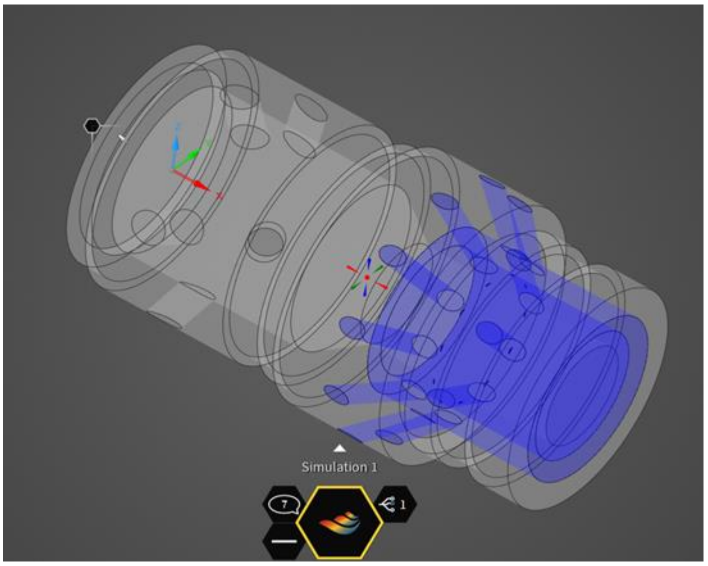

Figure-4 Propellant (Fuel) region (Excluded)

Design parameters:

- Fuel Inlet diameter = 0.98mm
- Oxidizer inlet diameter =1.7mm
- Discharge nozzle diameter = 9mm

The Problem discretization (Meshing) involves fidelity adjustments of local Sizing (0.1m) of entire domain which leads to following

Table-1 Mesh Statistics

Elements	**Nodes**
237166	81019

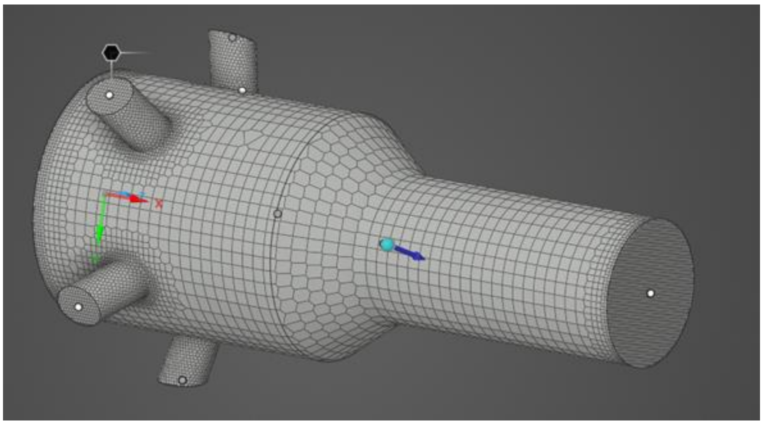

Figure-5 Fluid domain discretization

The Physics of the problem formulation contains

Table-2 Material properties of LOX at desired inlet conditions

Characteristics	**Values**
Density	$1080\ kg/m^3$
Viscosity	$0.0001458400622\ Pa \cdot s$
Thermal Conductivity	$6.94\ W/m \cdot K$

Specific Heat	$1280\ J/kg.K$
Operational Temperature	$106\ K$
Thermal Expansion Coefficient	$9.53 \text{ x } 10\hat{}-3\ /c^{0}$

These properties remain the same as we perform multiple case simulations by LOX as Oxidizer. Only the inlet and out flow boundary conditions of the specific fluid region may change for each case until 4 cases as below

Boundary Conditions

1. Adiabatic Thermal Expansion and Contraction
2. Mass Flow Rate Inlet
3. Velocity Outlet

Table-3 Case 1

Boundary	**Velocity**	**Mass flow rate**
Inlet (5 Inlets are Identical)	-	$0.1\ kg/s$
Outlet (Common Outlet)	$50\ m/s$	-

Table-4 Case 2

Boundary	**Velocity**	**Mass flow rate**
Inlet (5 Inlets are Identical)	-	$0.1\ kg/s$
Outlet (Common Outlet)	$60\ m/s$	-

Table-5 Case 3

Boundary	**Velocity**	**Mass flow rate**
Inlet (5 Inlets are Identical)	-	$0.05\ kg/s$
Outlet (Common Outlet)	$50\ m/s$	-

Table-6 Case 4

Boundary	**Velocity**	**Mass flow rate**
Inlet (5 Inlets are Identical)	-	$0.05\ kg/s$
Outlet (Common Outlet)	$60m/s$	-

Table V. Liquid Properties of Commonly Used LOX Simulants

	Temperature K(°R)	Pressure MPa(psia)	Surface Tension N/m(lb/ft)	Density $kg/m^3(lb/ft^3)$	Viscosity kg/m·s(lb/ft·s)
Liquid Oxygen	106 (190)	5.51 (800)	.0097 (6.7 E-4)	1080 (67.2)	1.5 E-4 (9.8 E-5)

Figure-6 Liquid properties of LOX simulant [1]

Table III. LOX/Hydrogen Injection Parameters

Injection Parameters	LeRC Modular Injector Configuration No. 1	No. 2	No. 3
D_o, cm (in)	.132 (.052)	.132 (.052)	.132 (.052)
A_g, cm^2 (in^2)	.198 (.0307)	.130 (.0201)	.0710 (.0110)
W_L, kg/s (lb/s)	.0838 (.185)	.0873 (.192)	.0898 (.198)
W_g, kg/s (lb/s)	.0210 (.0462)	.0179 (.0395)	.0159 (.0350)
ρ_L, kg/m^3 (lb/ft^3)	1080 (67.2)	1080 (67.2)	1080 (67.2)
ρ_g, kg/m^3 (lb/ft^3)	4.47 (.279)	4.47 (.279)	4.47 (.279)
ΔP_L, MPa (psi)	1.75 (254)	1.90 (275)	2.01 (291)
V_L, m/s (ft/s)	57.0 (187)	59.4 (195)	61.1 (200)
V_g, m/s (ft/s)	237 (777)	308 (1010)	502 (1650)
V_r, m/s (ft/s)	180 (591)	249 (817)	441 (1450)
σ, N/m (lb/ft)	9.72 E-3 (6.66 E-4)	9.72 E-3 (6.66 E-4)	9.72 E-3 (6.66 E-4)
μ_L, kg/m·s (lb/ft·s)	1.46 E-4 (9.84 E-5)	1.46 E-4 (9.84 E-5)	1.46 E-4 (9.84 E-5)
μ_g, kg/m·s (lb/ft·s)	8.99 E-6 (6.04 E-6)	8.99 E-6 (6.04 E-6)	8.99 E-6 (6.04 E-6)

Figure-7 Characteristics of LOX simulant [1]

Only the range of values for the boundary conditions and materials characteristics are chosen from the above table reference for each case of simulation, but not the exact value.

4. Result

Case 1

To allow an efficient space economy space infrastructures must be built that would support all activities.

Inlet (5 Inlets are Identical)-Mass flow rate (0.1 kg/s)

Outlet (Common Outlet)-Velocity (50 m/s).

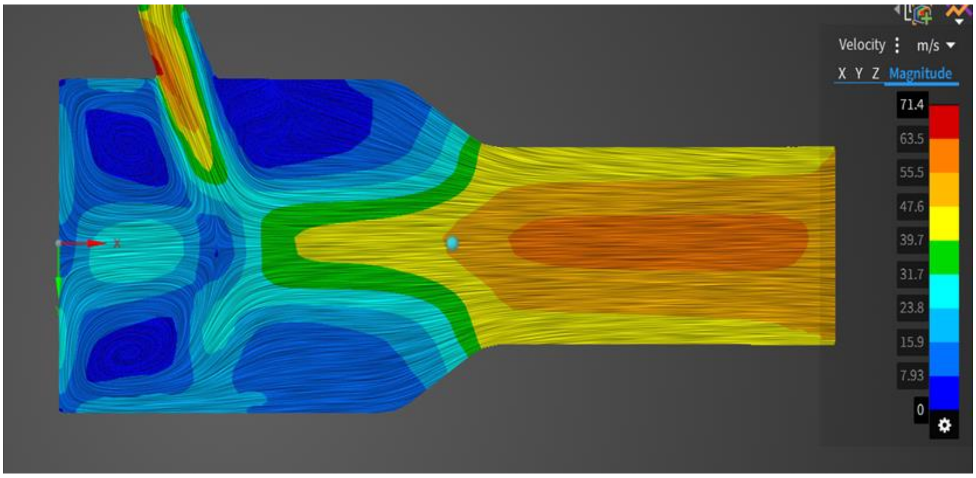

Figure-8 Case 1 Velocity Contour

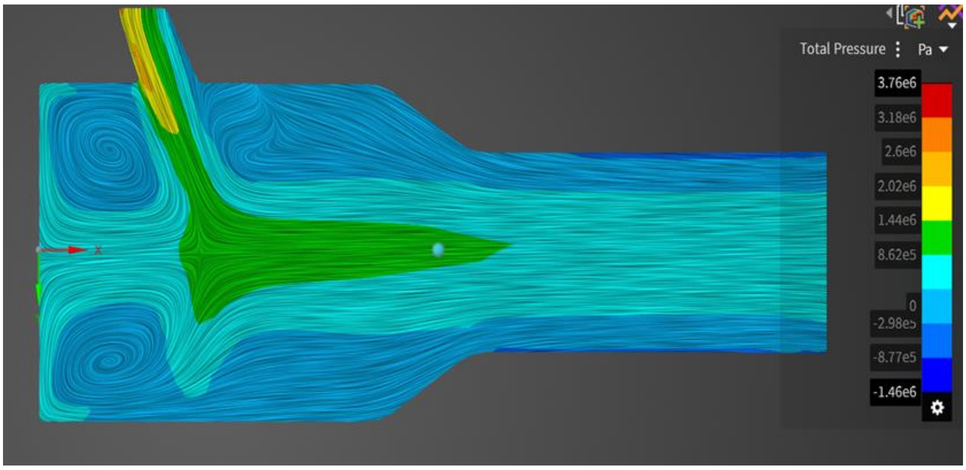

Figure-9 Case 1 Pressure Contour

Case 2

Conditions

Inlet (5 Inlets are Identical)-Mass flow rate (0.1 kg/s)

Outlet (Common Outlet)-Velocity (60 m/s)

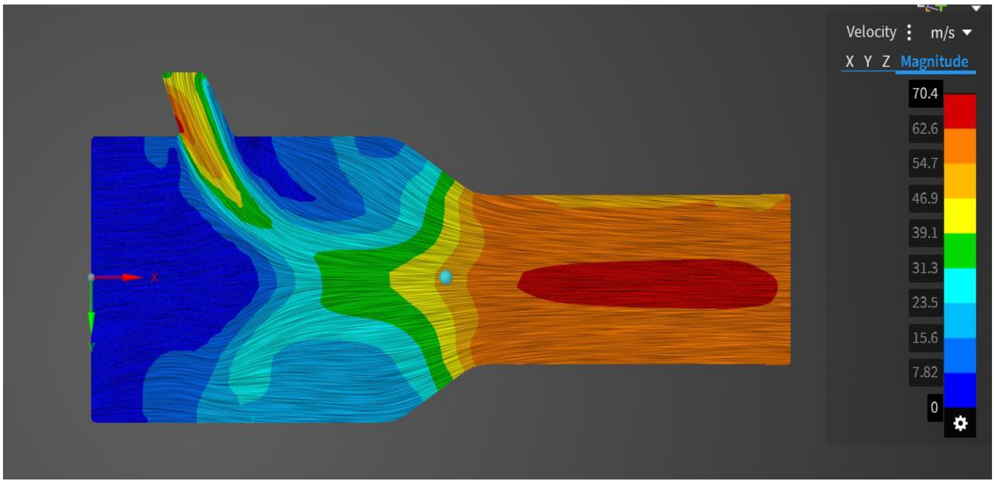

Figure-10 Case 2 Velocity Contour

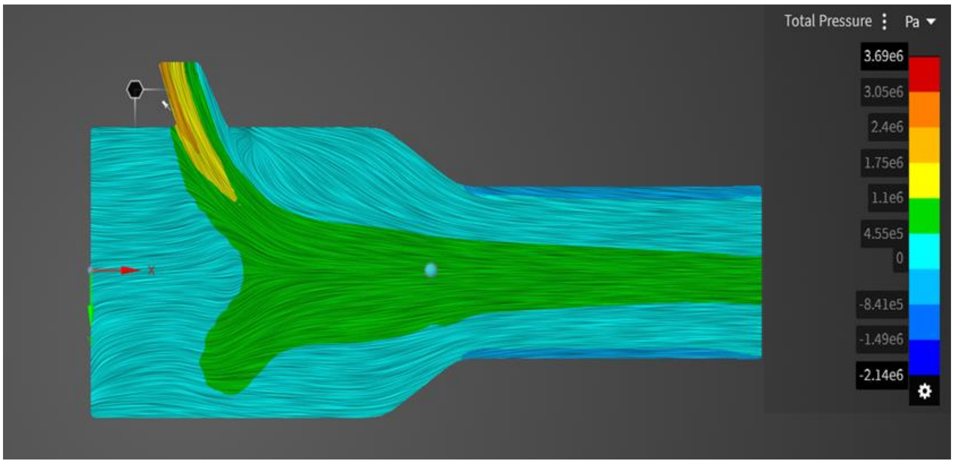

Figure-11 Case 2 Pressure Contour

Case 4

Conditions

Inlet (5 Inlets are Identical)-Mass flow rate (0.05 kg/s)

Outlet (Common Outlet)-Velocity (50 m/s)

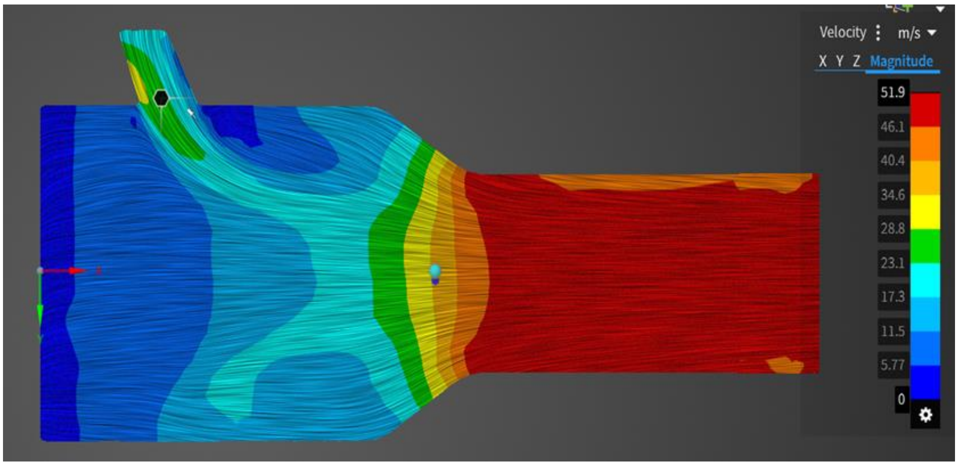

Figure-12 Case 3 Velocity Contour

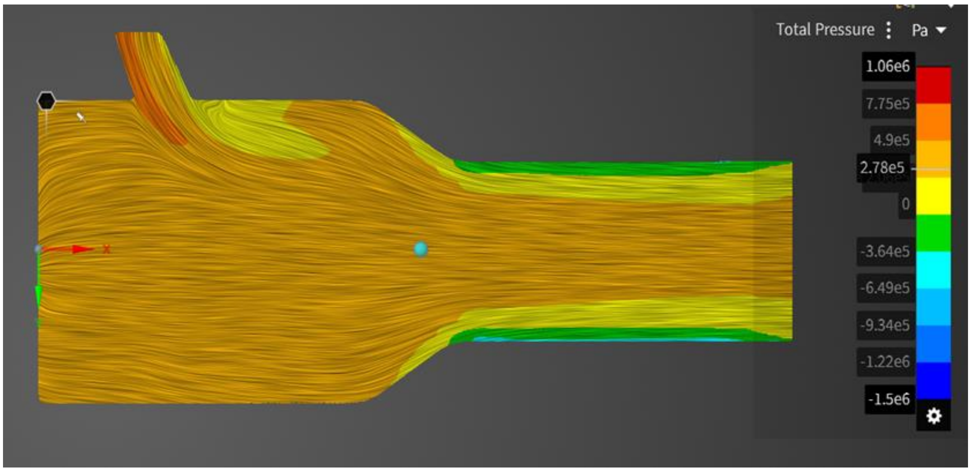

Figure-13 Case 3 Pressure Contour

Case 4

Conditions

Inlet (5 Inlets are Identical)-Mass flow rate (0.05 kg/s)

Outlet (Common Outlet)-Velocity (60 m/s)

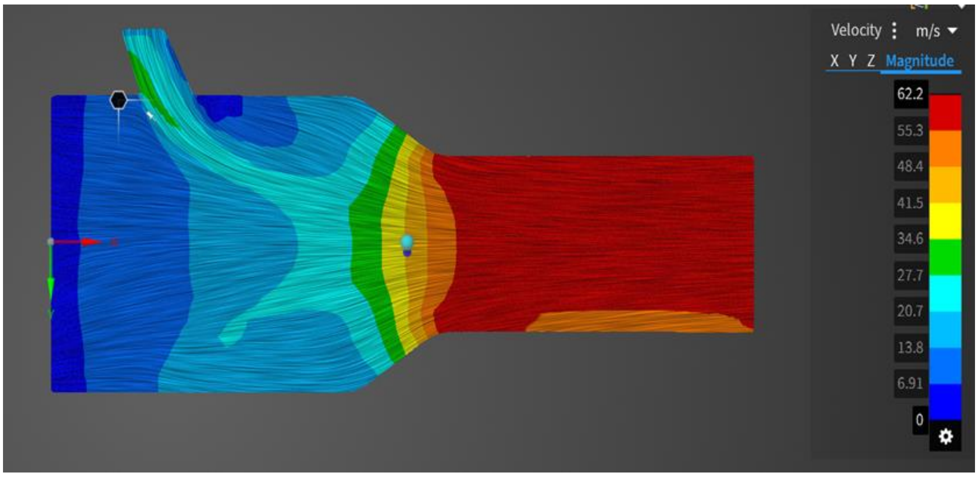

Figure-14 Case 4 Velocity Contour

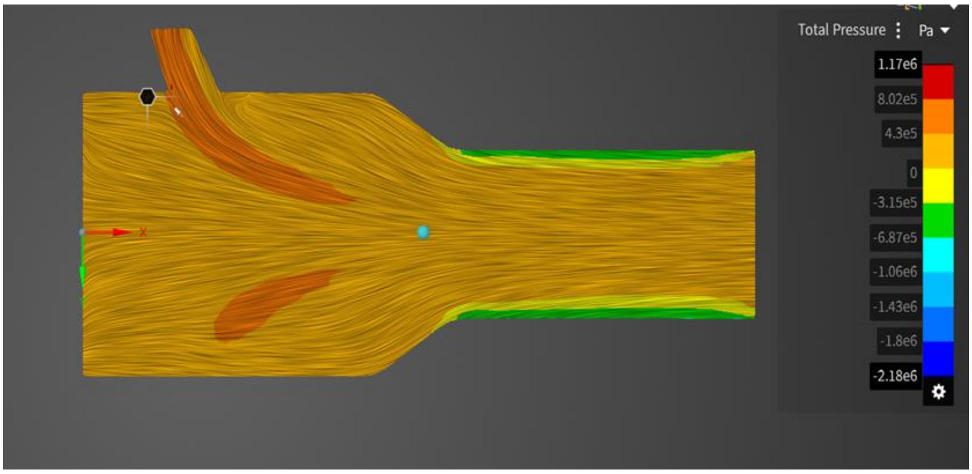

Figure-15 Case 4 Pressure Contour

5. Conclusion

In cases 2 and 4 (where the outlet velocity was set to 60 m/s), the oxidizer flow (acc. to Figure 8,9,14 &15) is parallel to the injector axis, with noticeably less signs of recirculation anywhere near the input region or walls. This suggests that higher exit velocities help to stabilize and guide the oxidizer stream, perhaps maintain the total pressure in actual injection process. While comparing cases 1 and 3 (both having an exit velocity of 50 m/s), lowering the mass intake flow rate from 0.1 kg/s to 0.05 kg/s significantly decreased turbulent recirculation zones and backflow tendencies, particularly near the injector core. The dual-region fluid separation and structured mesh allowed for sufficient spatial resolution of the data, validating the geometric integrity of the model. This is crucial in real-world injection system characteristics because backflow can negatively affect combustion efficiency, may lead to catastrophic failure or degenerated hardware. Even though flow conditions were the main determinant of flow characteristics, the simulated results often show how crucial it is to design the injector acc. to desired flow conditions to predict fluid behaviour.

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7. Conflict of Interest

The author declares no competing conflict of interest.

8. Funding

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