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Computational study of injectors: Coaxial Swirl and Pintle configuration

Sanjay Nagesh[1, a)], Pramod B Kumar[2, b)], Tharini Naveen[3], Tejaswini A N[4]
[1,2,3]UG scholar, Department of Aeronautical Engineering, Global Academy Of technology, Adithya Layout, Rajarajeshwari Nagar, Bengaluru-560098, INDIA
[4]Asisstant Prof, Department of Aeronautical Engineering, Global Academy Of technology, Adithya Layout, Rajarajeshwari Nagar, Bengaluru-560098, INDIA

Abstract:
This study delves into the innovative realm of liquid rocket engine injector design, focusing on a novel hybrid configuration that amalgamates the strengths of coaxial swirl and pintle injectors. The primary objective is to meticulously analyze the intricate flow dynamics, atomization characteristics, and subsequent combustion performance of this hybrid design, providing a comprehensive comparison against conventional coaxial swirl and pintle injectors.
The impetus behind this hybrid approach stems from the inherent limitations of traditional injector designs. Coaxial swirl injectors, renowned for their superior oxidizer atomization through the generation of swirling flows, often struggle with precise fuel delivery and throttling capabilities. Conversely, pintle injectors excel in fuel control and throttling, enabling variable thrust, but may exhibit suboptimal atomization, especially at off-design conditions.
The proposed hybrid design strategically integrates a coaxial swirl outer injector to capitalize on enhanced oxidizer atomization. This outer injector induces a swirling motion in the oxidizer stream, fostering the formation of fine droplets, which is crucial for efficient combustion. Simultaneously, a central pintle injector is incorporated to ensure precise fuel delivery and facilitate effective throttling. The pintle's ability to modulate the fuel flow rate allows for dynamic adjustments to the engine's thrust, catering to the demands of varying mission profiles.
To rigorously evaluate the performance of this hybrid injector, advanced Computational Fluid Dynamics (CFD) simulations were employed. The complexity of the multiphase flow and droplet formation necessitated the utilization of sophisticated numerical models. Specifically, the Volume of Fluid (VOF) method was implemented to capture the interface between the liquid and gas phases, accurately representing the liquid breakup and spray formation. The Discrete Phase Model (DPM) was used to track the trajectories and sizes of individual droplets, providing insights into the atomization characteristics.
Keywords: *swirling motion, co-axial swirling, pintle, atomization, discrete phase model*

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I. INTRODUCTION

High performance in liquid rocket engines depends on steady and effective combustion, and the injector is a key factor in defining the combustion parameters. The injector has a major influence on the propulsion system's overall thrust, specific impulse, and stability by controlling the mixing, atomisation, and combustion efficiency of propellants. Coaxial swirl injectors and pintle injectors are two common injector designs seen in rocket engines. Every configuration has unique benefits and has been thoroughly researched for a range of space propulsion applications.

In addition to their better atomisation and increased mixing efficiency, coaxial swirl injectors are frequently used in liquid rocket engines. The liquid propellant is broken up into tiny droplets by swirling motion in these injectors, which speeds up vaporisation and burning. Increased combustion stability and a decrease in problems like high-frequency screeching or low-frequency chugging are the outcomes of this design. In bipropellant engines, where effective oxidiser and fuel mixing is crucial for optimising performance, the use of coaxial swirl injectors is very beneficial.

Conversely, pintle injectors have drawn a lot of interest because of their capacity to lessen combustion instability and provide throttling. The pintle injector, which was first created for the Apollo Lunar Module Descent Engine (LMDE), uses a central pintle element to guide the propellants outward in a radial direction, producing an annular impingement pattern that improves combustion and atomisation. This design is a popular option for reusable and throttleable propulsion systems, such as contemporary lunar and Mars landers, because it permits a broad range of throttling capabilities while maintaining stable combustion.

Integrating these two injector designs offers a viable way to increase stability, adaptability, and combustion efficiency. A hybrid injector design may be able to maximise performance in a variety of operating regimes by fusing the throttling and stability advantages of a pintle injector with the swirling properties of a coaxial swirl injector. However, sophisticated computational research is needed to comprehend the intricate fluid dynamics, spray generation, and combustion properties of such a hybrid injector.

A powerful means for examining the intricate flow mechanics and operation of rocket injectors is computational fluid dynamics, or CFD. Analysis of variables including velocity fields, pressure distribution, droplet size, and atomisation efficiency can be done by numerical simulations, which offer insightful information to support experimental research. The performance characteristics of a hybrid injector that combines pintle and coaxial swirl features are analysed computationally in this study. The purpose of the study is to assess this innovative injector configuration's overall performance, combustion stability, and better atomisation efficiency of the operating engine and propellants.

The objectives of this study include:

- Conducting CFD simulations to analyze the flow characteristics and atomization behavior of the hybrid injector.

- Comparing the performance metrics of the hybrid injector against traditional coaxial swirl and pintle injectors.

- Investigating the impact of design parameters such as swirl strength, pintle geometry, and injection pressure on mixing efficiency and combustion stability.

- Assessing the potential advantages and limitations of the hybrid injector for various space propulsion applications.

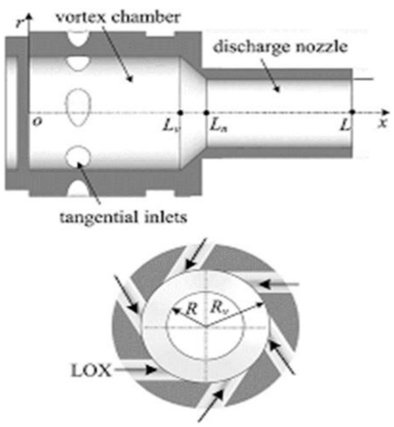

Fig-1: Co-axial configuration

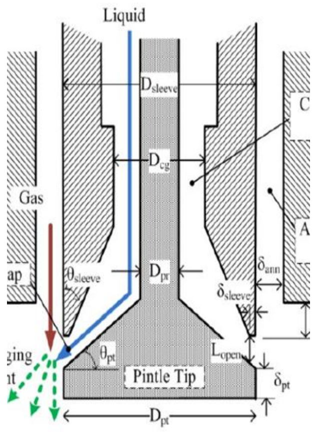

Fig-2: pintle configuration

II. METHODOLOGY

1. **Hybrid Injector Design:**

- The core innovation lies in the synergistic combination of two distinct injection mechanisms. The coaxial swirl outer injector is designed to impart a tangential velocity component to the oxidizer flow, creating a swirling motion. This swirling action induces centrifugal forces, leading to the formation of a thin liquid sheet that breaks up into fine droplets, enhancing atomization. The swirl angle, a critical design parameter, directly influences the intensity of the swirl and the resulting droplet size distribution.
- Concurrently, the central pintle injector provides precise control over the fuel delivery. The pintle, a movable central stem, allows for precise adjustment of the fuel flow rate and distribution. The pintle diameter and its axial position are crucial parameters that determine the fuel spray pattern and penetration. The controlled fuel delivery from the pintle injector complements the enhanced atomization from the coaxial swirl injector, ensuring optimal fuel-oxidizer mixing.
- The design parameters, including swirl angle, pintle diameter, injection velocity, and mass flow rates of both the oxidizer and fuel, are meticulously chosen based on the desired performance characteristics of the rocket

engine. These parameters are often optimized through iterative simulations and experimental testing to achieve the desired thrust, combustion efficiency, and stability.

2. **Computational Fluid Dynamics Setup:**
- ANSYS Fluent, a widely used CFD software, was employed to simulate the complex multiphase flow and combustion processes within the hybrid injector. The Volume of Fluid (VOF) model was utilized to capture the interface between the liquid and gaseous phases, accurately representing the atomization and spray formation processes.
- The Discrete Phase Model (DPM) was incorporated to track the trajectories and size distribution of individual fuel droplets. This model provides valuable insights into the droplet evaporation, dispersion, and mixing characteristics.
- Turbulence modelling is essential for accurately predicting the flow behavior within the injector. The k-ϵ turbulence model, a Reynolds-averaged Navier-Stokes (RANS) approach, was initially used to provide a computationally efficient solution. For more detailed analysis of turbulence effects, Large Eddy Simulation (LES) was employed. LES resolves the large-scale turbulent eddies while modelling the smaller scales, providing a more accurate representation of the turbulent flow field, especially in regions of high shear and mixing.

3. **Boundary Conditions:**
- The inlet boundary conditions, including the mass flow rates, temperature, and velocity profiles of the oxidizer and fuel, were carefully defined based on typical bipropellant rocket engine operating conditions. These conditions were varied to analyse the injector performance under different thrust levels and operating regimes.
- The chamber pressure and temperature, which significantly influence the combustion process, were also varied to investigate the injector's performance under different environmental conditions. The sensitivity of the injector's performance to variations in these parameters was assessed to determine its robustness and adaptability.

MATERIAL PROPERTIES FOR THE INJECTOR:

Table-1: Material properties of Graphite

PROPERTIES	VALUES	UNITS
Elastic Modulus	4800	N/mm^2
Poisson's Ratio	0.28	N/A
Mass Density	2240	kg/m^3
Tensile Strength	100.826	N/mm^2
Yield Strength	120.594	N/mm^2
Thermal Expansion Coefficient	1.3e-05	/K
Thermal Conductivity	168	W/(m·K)
Specific Heat	712	J/(kg·K)

Table-2: Material properties of Inconel 625

PROPERTIES	VALUES	UNITS
Elastic Modulus	205000	N/mm^2
Poisson's Ratio	0.29	N/A
Mass Density	8440	kg/m^3
Tensile Strength	930	N/mm^2
Yield Strength	460	N/mm^2
Thermal Expansion Coefficient	1.28e-05	/K
Thermal Conductivity	9.8	W/(m·K)
Specific Heat	410	J/(kg·K)

THEORETICAL CALCULATIONS

Kerosene (RP-1) and Liquid Oxygen (LOX)

Given Parameters (per engine - assuming similar values to the Vikas for comparison):

- Propellants: RP-1/LOX
- Chamber Pressure: ~6.9 MPa

- O/F Ratio: Typical range is ~2.2-2.6. Let's use 2.4 for this example.
- Combustion Temperature: ~3000-3700 K. Let's use 3500 K.
- Mass Flow Rate: ~147.5 kg/s

1. Simplified Chemical Equation:

Since RP-1 is a mixture of hydrocarbons, we'll use a representative average formula of $C_{12}H_{23}$ (a common approximation) for simplification:

$C_{12}H_{23} + 17.75\ O_2 \rightarrow 12\ CO_2 + 11.5\ H_2O$

2. Theoretical Heat Release (per kg of RP-1):

- ΔHf°($C_{12}H_{23}$(l)): ~ -300 kJ/mol (estimated)
- ΔHf°(O_2(g)): 0 kJ/mol
- ΔHf°(CO_2(g)): -393.5 kJ/mol
- ΔHf°(H_2O(g)): -241.8 kJ/mol

ΔH°rxn = [12(-393.5) + 11.5(-241.8)] - [-300]

ΔH°rxn ≈ [-4722 - 2780.7] + 300

ΔH°rxn ≈ -7202.7 kJ/mol of RP-1

Molar mass of $C_{12}H_{23}$ ≈ (12 * 12.01) + (23 * 1.01) ≈ 167 g/mol = 0.167 kg/mol

Heat release per kg of RP-1 ≈ -7202.7 kJ/mol / 0.167 kg/mol ≈ **-43.1 MJ/kg**

3. Calculating RP-1 Mass Flow Rate:

Considering with an O/F of 2.4:

Total mass per unit of RP-1 = 1 kg RP-1 + 2.4 kg LOX = 3.4 kg

Therefore, the total RP-1 mass fraction is = 1/3.4

RP-1 mass flow rate = (1/3.4) * 147.5 kg/s ≈ 43.38 kg/s

4. Theoretical Heat Release Rate (Power):

Theoretical Power = 43.38 kg/s * -43.1 MJ/kg ≈ **-1.87 GW**

5. Estimating Actual Heat Release Rate (Power) using Combustion Temperature:

- Actual Temperature Rise = 3500 K - 298 K = 3202 K
- Theoretical Temperature Rise = 3700 K - 298 K = 3402 K

Actual Power ≈ -1.87 GW * (3202 K / 3402 K) ≈ **-1.76 GW**

6. Combustion Efficiency:

Combustion Efficiency = (-1.76 GW / -1.87 GW) * 100% ≈ **94%**

7. Thrust calculation:

The force that drives a rocket forward is called thrust, and it is produced when high-speed exhaust gases are released through the nozzle. It is a rocket engine's primary output and is controlled by Newton's Third Law, which states that "for every action, there is an equal and opposite reaction."

F=$\dot{m}\cdot V_e$

where,
F= Momentum thrust
$\dot{m}$= mass flow rate
V_e= Exit velocity

Exit velocity can be calculated by the below formula,

V_e=Isp·g_0
Where,
Isp= specific impulse
g_0 = gravity constant (9.81m/s^2)

V_e=300×9.81 m/s ≈ 2943 m/s
F=147.5 kg/s × 2943 m/s ≈ 434.09 kN

Results Summary for RP-1/LOX:

- Theoretical Heat Release (per kg of RP-1): ≈ -43.1 MJ/kg
- Theoretical Heat Release Rate (Power): ≈ -1.87 GW
- Estimated Actual Heat Release Rate (Power): ≈ -1.76 GW
- Combustion Efficiency: ≈ 94%
- Thrust Generated: 439.09 kN
- Specific Impulse: 300 seconds

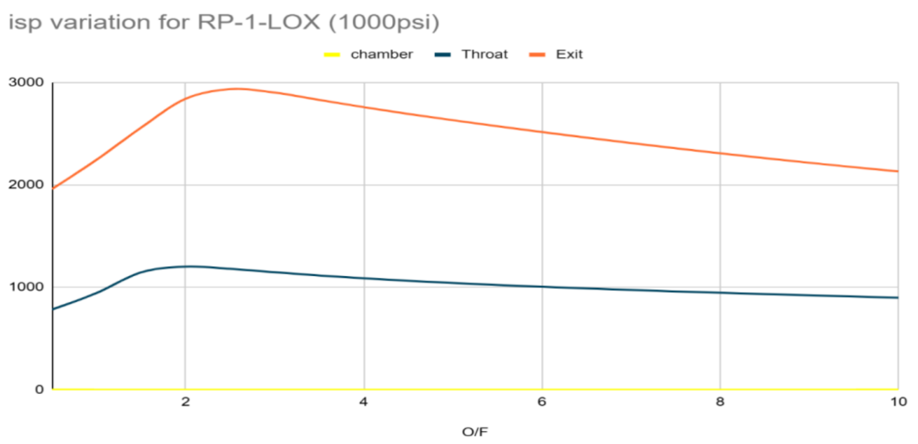

Fig-1: Above is the graph showing the variation for RP-1/LOX propellant at chamber pressure 1000psi

Hydrazine and Nitrogen Tetroxide (NTO)

Given Parameters:

- Propellants: N_2H_4/N_2O_4
- Chamber Pressure: ~6.9 MPa
- O/F Ratio: Typical range is ~0.8-1.4. Let's use 1.5 for this example.
- Combustion Temperature: ~3000-3500 K. Let's use 3250 K.
- Mass Flow Rate: ~147.5 kg/s

1. Balanced Chemical Equation:

2 N_2H_4 + N_2O_4 → 3 N_2 + 4 H_2O

2. Theoretical Heat Release (per kg of Hydrazine):

- ΔHf°(N_2H_4(l)): 50.6 kJ/mol
- ΔHf°(N_2O_4(g)): 9.16 kJ/mol
- ΔHf°(N_2(g)): 0 kJ/mol
- ΔHf°(H_2O(g)): -241.8 kJ/mol

ΔH°rxn = [3(0) + 4(-241.8)] - [2(50.6) + 1(9.16)]
ΔH°rxn = [-967.2] - [101.2 + 9.16]
ΔH°rxn ≈ -1077.56 kJ/2 moles of N_2H_4

Molar mass of N_2H_4 = (2 * 14.01) + (4 * 1.01) ≈ 32.06 g/mol = 0.03206 kg/mol [1]

Heat release per kg of N_2H_4 ≈ (-1077.56 kJ / 2 mol) / 0.03206 kg/mol ≈ **-16.8 MJ/kg**

3. Calculating Hydrazine Mass Flow Rate:

With an O/F of 1.5:

- Total mass per unit of N_2H_4 = 1 kg N_2H_4 + 1 kg N_2O_4 = 2 kg
- N_2H_4 mass fraction = 1.5/2
- N_2H_4 mass flow rate = (1.5/2) * 147.5 kg/s = 110.63 kg/s

4. Theoretical Heat Release Rate (Power):

Theoretical Power = 110.63 kg/s * -16.8 MJ/kg ≈ **-1.85 GW**

5. Estimating Actual Heat Release Rate (Power) using Combustion Temperature:

We'll assume a theoretical adiabatic flame temperature of around 3300-3500 K for Hydrazine/NTO. Let's use 3400K as an average.

- Actual Temperature Rise = 3250 K - 298 K = 2952 K
- Theoretical Temperature Rise = 3400 K - 298 K = 3102 K

Actual Power ≈ -1.85 GW * (2952 K / 3102 K) ≈ **-1.76 GW**

6. Combustion Efficiency:

Combustion Efficiency ≈ (-1.76GW / -1.85 GW) * 100% ≈ **95%**

Assume specific impulse to be 280 seconds

$F=\dot{m}\cdot ve$

$ve=Isp\cdot g$

v_e= 280x9.81 =2747 m/s
F=147.5 x 2747 = 405.15 kN

Results Summary for Hydrazine/NTO:

- Theoretical Heat Release (per kg of N_2H_4): ≈ -16.8 MJ/kg
- Theoretical Heat Release Rate (Power): ≈ -1.85 GW
- Estimated Actual Heat Release Rate (Power): ≈ -1.76 GW
- Combustion Efficiency: ≈ 95%
- Thrust Generated: 405.15 KN
- Specific Impulse: 280seconds

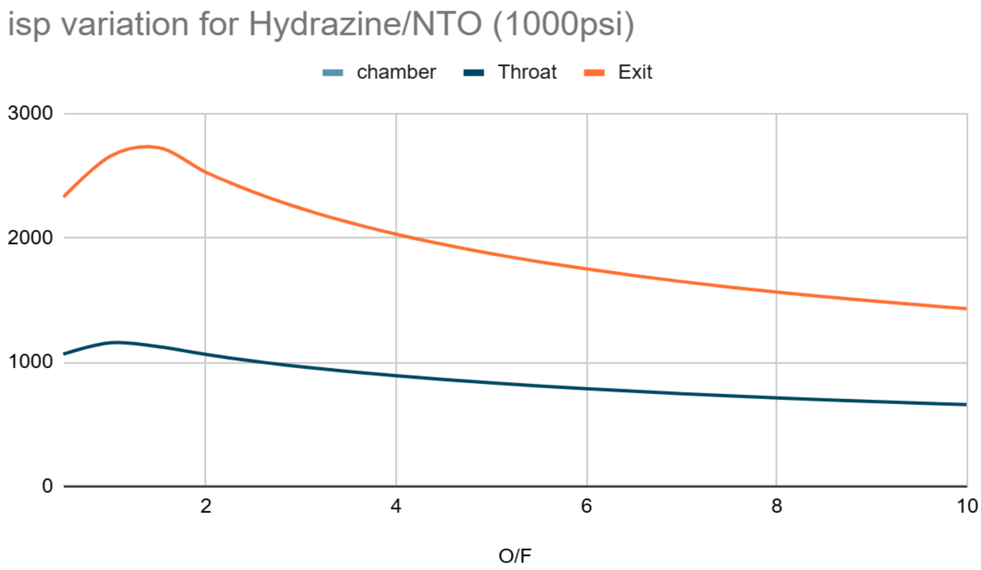

Fig-2: Above is the graph showing the variation for Hydrazine/NTO propellant at chamber pressure 1000psi

Monomethyl Hydrazine (MMH) and Nitrogen Tetroxide (NTO)

Given Parameters (per engine - for comparison):

- Propellants: MMH/NTO
- Chamber Pressure: ~6.9 MPa
- O/F Ratio: Typical range is ~0.6-2. Let's use 2.0 for this example.
- Combustion Temperature: ~3000-3500 K. Let's use 3250 K.
- Mass Flow Rate: ~147.5 kg/s

1. Balanced Chemical Equation:

4CH3NHNH2+5N2O4→9N2+4CO2+12H2O

2. Theoretical Heat Release (per kg of MMH):

- ΔHf°(CH_3NHNH_2(l)): 21 kJ/mol (approximately)
- ΔHf°(N_2O_4(g)): 9.16 kJ/mol
- ΔHf°(N_2(g)): 0 kJ/mol
- ΔHf°(CO_2(g)): -393.5 kJ/mol
- ΔHf°(H_2O(g)): -241.8 kJ/mol

ΔH°rxn = [2.5(0) + 1(-393.5) + 3(-241.8)] - [1(21) + 1.5(9.16)]
ΔH°rxn = [-393.5 - 725.4] - [21 + 13.74]
ΔH°rxn ≈ -1118.9 - 34.74
ΔH°rxn ≈ -1153.64 kJ/mol of MMH

Molar mass of CH_3NHNH_2 = (1 * 12.01) + (5 * 1.01) + (2 * 14.01) ≈ 46.07 g/mol = 0.04607 kg/mol

Heat release per kg of MMH ≈ -1153.64 kJ/mol / 0.04607 kg/mol ≈ **-25.04 MJ/kg**

3. Calculating MMH Mass Flow Rate:

With an O/F of 2.0:

- Total mass per unit of MMH = 1 kg MMH + 1 kg N_2O_4 = 2 kg
- MMH mass fraction = 2/2 = 1
- MMH mass flow rate = (2/2) * 147.5 kg/s = 147.5 kg/s

4. Theoretical Heat Release Rate (Power):

Theoretical Power = 147.5 kg/s * -25.04 MJ/kg ≈ **-3.7 GW**

5. Estimating Actual Heat Release Rate (Power) using Combustion Temperature:

We'll assume a theoretical adiabatic flame temperature of around 3200-3400K for MMH/NTO. Let's use 3300K as an average.x

- Actual Temperature Rise = 3250 K - 298 K = 2952 K
- Theoretical Temperature Rise = 3300 K - 298 K = 3002 K

Actual Power ≈ -3.7 GW * (2952 K / 3002 K) ≈ **-3.64GW**

6. Combustion Efficiency:

Combustion Efficiency ≈ (-3.64 GW / -3.7 GW) * 100% ≈ **98%**

Assume that specific impulse to be 288 seconds
$F=\dot{m}\cdot ve$

$ve=Isp\cdot g_0$

Ve=288 x 9.81 =2825 m/s
F= 147.5 x 2825 = 416.72 kN

Results Summary for MMH/NTO:

- Theoretical Heat Release (per kg of MMH): ≈ -25.04 MJ/kg
- Theoretical Heat Release Rate (Power): ≈ -3.7 GW
- Estimated Actual Heat Release Rate (Power): ≈ -3.64 GW
- Combustion Efficiency: ≈ 98%
- Thrust Generated: 416.72 kN
- Specific Impulse: 288 seconds

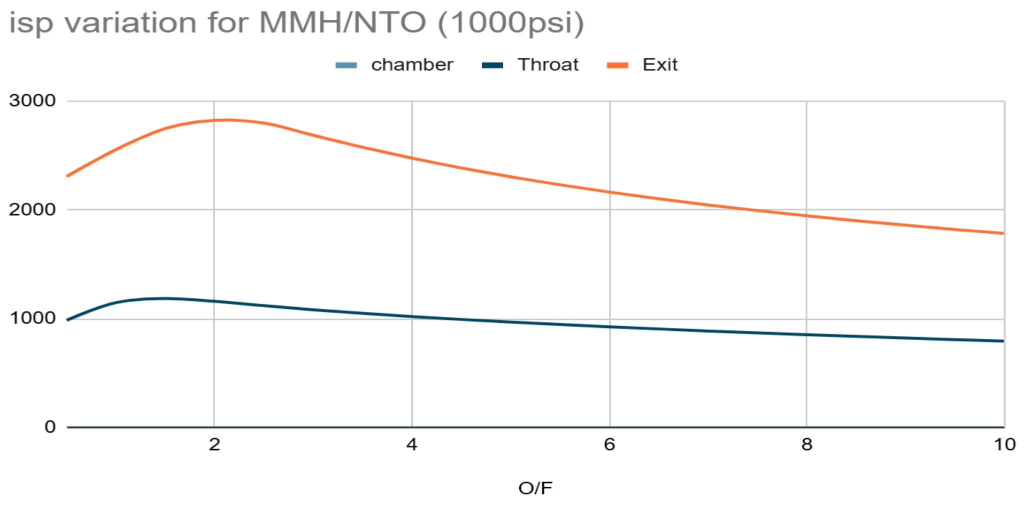

Fig-3: Above is the graph showing the variation for MMH/NTO propellant at chamber pressure 1000psi

Comparison of all propellant combinations:

Propellant Combination	Theoretical Heat Release rate (power GW)	Estimated Actual Power (GW)	Combustion Efficiency (%)
RP-1/LOX	-1.87	-1.76	94
Hydrazine/NTO	-1.85	-1.76	95
MMH/NTO	-3.7	-3.64	98

Designed geometry:

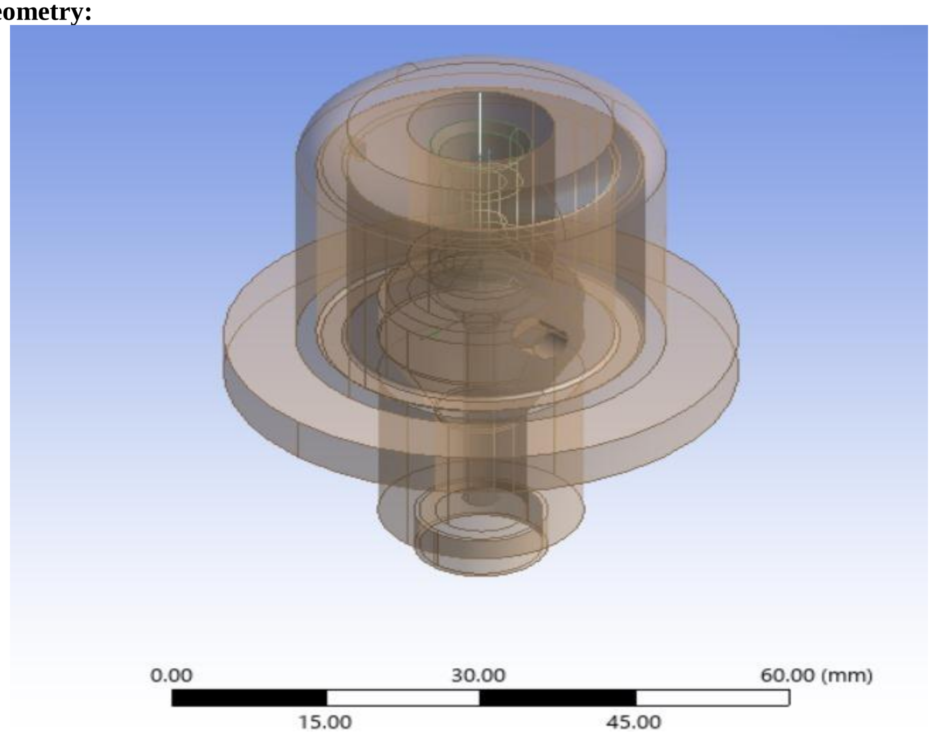

Fig-4: 3D model of the injector

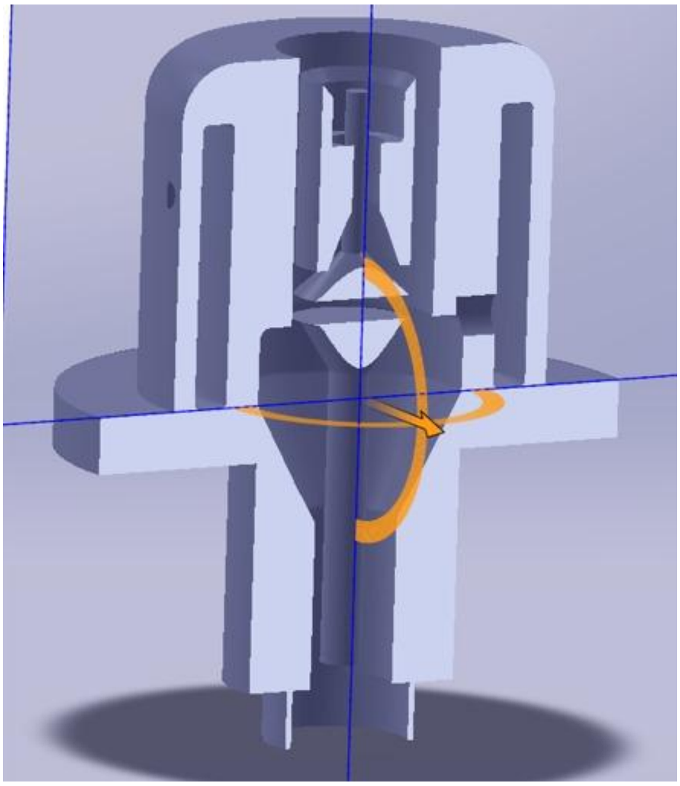

Fig-4: sectional view of the injector

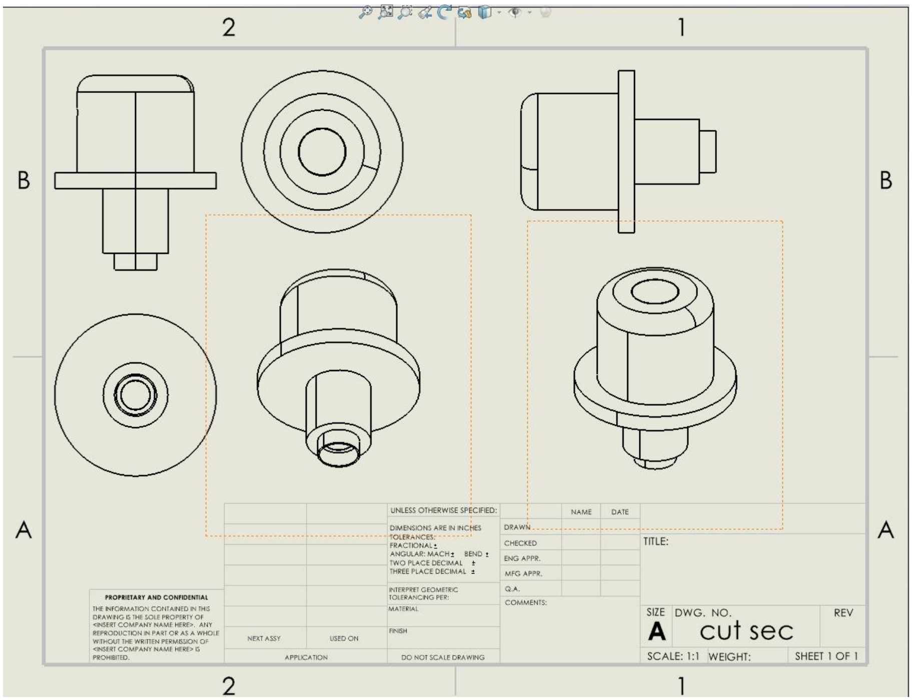

Fig-5: Draft sheet of the injector

III. Results and Discussion

- **Flow Dynamics and Atomization:**
  - The velocity contours revealed the complex flow patterns generated by the hybrid injector. The swirling motion induced by the coaxial swirl injector created a strong centrifugal force, leading to the formation of a thin liquid sheet that rapidly disintegrated into fine droplets. The pressure distribution within the injector provided insights into the pressure drop and flow resistance, which are critical factors in injector design.

    - Compared to standalone coaxial or pintle injectors, the hybrid configuration produced a more uniform spray pattern, characterized by a more homogeneous droplet size distribution and improved spatial distribution. This uniformity is crucial for achieving efficient and stable combustion. The reduction in droplet size, achieved through enhanced atomization, increased the surface area-to-volume ratio, promoting rapid evaporation and mixing.

- **Combustion Stability and Mixing Efficiency:**
    - The hybrid injector demonstrated improved combustion stability, which is a critical requirement for reliable rocket engine operation. The combined effects of swirl-induced atomization and pintle-controlled fuel distribution contributed to this enhanced stability. The swirl motion stabilized the combustion process, preventing the formation of large-scale instabilities. The pintle injector ensured a consistent and controlled fuel supply, minimizing fluctuations in the fuel-oxidizer ratio.
    - The mixing efficiency was quantified using fuel-oxidizer equivalence ratio contours, which revealed the degree of homogeneity in the mixture formation. A more homogeneous mixture, characterized by a uniform equivalence ratio, leads to more complete and efficient combustion. The hybrid injector exhibited a more homogeneous mixture formation compared to traditional injector configurations, indicating improved mixing efficiency.
- **Performance Comparison:**
    - The computational results demonstrated that the hybrid injector achieved higher combustion efficiency and reduced combustion instabilities compared to traditional injector designs. The improved atomization and mixing characteristics of the hybrid injector led to more complete combustion, resulting in higher thrust and specific impulse.
    - The reduction of combustion instabilities, that can cause damage to the engine, is a very important improvement. The results indicate that hybrid injectors have significant potential for application in next-generation rocket propulsion systems, where high performance and reliability are paramount.

IV. Conclusion

- This computational study highlights the significant advantages of hybrid injectors that integrate coaxial swirl and pintle configurations. The CFD simulations provide compelling evidence of improved atomization, enhanced fuel-oxidizer mixing, and better combustion stability.
- These findings suggest that hybrid injectors can offer a significant performance boost for rocket propulsion systems. However, further research is needed to optimize the design parameters for specific rocket engine applications.
- Future work will focus on experimental validation of the computational results. Conducting hot-fire tests with prototype hybrid injectors will provide valuable data on the actual performance characteristics and validate the CFD predictions.
- Optimization of design parameters, such as swirl angle, pintle geometry, and injection velocities, will be conducted to maximize the performance of the hybrid injector for specific rocket engine requirements

References:

[1]. a-numerical-approach-to-optimize-the-design-of-a-pintle-1j5rgobf
[2]. design-and-optimization-of-pintle-injector-for-liquid-rocket-26ykgj4t1p
[3]. Effect of Injector Geometry on Atomization of a Liquid-Liquid
[4]. Effects of Momentum Ratio and Weber Number on Spray Half Angles of Liquid
[5]. Experimental and Theoretical Analysis of the Combustion
[6]. REVIEW-ON-FUEL-INJECTORS-WITH-DIFFERENT-COMPONENTS-CONFIGUARATIONS-IN-A-SEMI-CRYOGENIC-ROCKET-ENGINE
[7]. analyzing-combustion-efficiency-according-to-spray-118rgncs
[8] driving-and-damping-mechanisms-for-transverse-combustion-5brqpfc3fm
[9] self-coupling-an-effective-method-to-mitigate-thermoacoustic-24nweckl
[10] cfd-based-prediction-of-combustion-dynamics-and-nonlinear-3cn2r7aj
[11] experimental-investigation-on-enhanced-combustion-of-28gcv9iwxi
[12] flame-acceleration-and-detonation-transition-in-premixed-and-48vrg683wxad
[13] the-effects-of-fuel-distribution-on-exit-temperature-3mf3426m