Review on Fuel Injectors with Different Components Configurations in a Semi-Cryogenic Rocket Engine

P A Chandru*, Prasanna Senthil, Rajesh R, Shristy Kumar, Shubham Shah, Simran kaur

*Corresponding Author Email: chandrupa.aeroin@gmail.com

AEROIN SPACETECH PRIVATE LIMITED

---***---

Abstract - Semi-cryogenic engines are a key advancement in the field of rocketry due to their potential capabilities. Fuel injectors are one of the significant components used in semi-cryogenic engines. This research paper aims to review different types of fuel injectors and their components. It is important to note that the selection of the fuel injector for a semi-cryogenic engine is based on many factors, such as mission profile, engine requirements, and other considerations. Thus, the best fuel injector may vary depending on these factors.

Key Words: fuel injector, rocket propulsion, injector components.

1. INTRODUCTION

Propulsion system is one of the most important pillars in the evolution of rockets. Advancements in propulsion systems lead to massive performance improvement and cost reduction. Ongoing research on propulsion systems in semi-cryogenic engines have enabled semi-cryogenic based rockets to compete with cryogenic and solid engine based rockets.

The semi cryogenic engine will facilitate applications for future space missions, such as the Reusable Launch Vehicle, Unified Launch Vehicle and vehicle for interplanetary missions. Semi-cryogenic engines use a combination of cryogenic oxidizers and liquid hydrocarbon fuels. Using hydrocarbon fuels like refined kerosene at room temperature, instead of cryogenic liquid hydrogen, has led to massive weight reduction, more payload capabilities, higher reliability and reduced complexity. Fuel injector is an important component of rocket engines; enhancing fuel injectors and optimising fuel injector configurations can lead to significant improvement in combustion efficiency and engine performance.

Fuel injectors are responsible for mixing fuel and oxidizer in appropriate proportions to ensure that the engine operates according to its mission profile with highest possible efficiency. An engine's mission requirements are the primary factor in deciding the appropriate fuel injector, such as pintle, shear coaxial,impinging injectors, etc. Each injector offers unique advantages and challenges based on operational conditions and mission requirements. For example, pintle injectors are known for their simplicity and robust performance, while shear coaxial injectors are preferred for their excellent atomization and mixing capabilities under high-pressure conditions.

This research paper aims to review the different fuel injector configurations and their functioning in a semi-cryogenic rocket engine.

FUEL INJECTORS

1. WORKING OF FUEL INJECTORS

Semi cryogenic engines run on cryogenic oxidizer (usually liquid oxygen, LOX) and liquid hydrocarbon fuel such as refined kerosene (RP-1). These engines operate at very high pressures and temperatures. The task of the fuel injector is to ensure that the propellant is distributed and mixed in proper proportion before the exhaust escapes out from the throat and nozzle of the rocket engine. The higher the combustion efficiency of the engine, the better is the fuel injector system.

The basic principle of fuel injector is to maximize the surface area to mass ratio of the propellant in the combustion chamber of the engine. This is achieved by spraying the liquid propellant through tiny holes (injectors). These injectors not only increase the propellant velocity but also atomize the propellant, leading to better combustion. [Refer to reference 1,14,15]

2. TYPES OF FUEL INJECTORS

Different types of fuel injectors are used depending on their operating conditions and mission requirements. For example, a throttleable engine may opt for a pintle injector, while a single-use engine might prefer a coaxial swirl injector. Some of the common types of fuel injectors are:

1) Pintle Injectors
2) Shear Coaxial Injectors
3) Impinging Injectors
4) Swirl Injectors
5) Multi-Element Injectors
6) Triplet Injectors

Multi-element injectors and triplet injectors are beyond the scope of this research paper.

2.1 Pintle Injectors

Pintle injectors are the most common type of fuel injector used in the modern rocket engines. Pintle injector works on the principle of a central pintle that moves axially within an annular orifice, which allows for variable propellant flow and better atomization of propellant, leading to higher combustion efficiency. The fuel is injected through the central pintle, while the oxidizer flows through the annular orifice. They're known for their combustion stability and reliability. One of their unique features is that these injectors prevent the leftover propellant in the pipes from mixing once the engine has been turned off. Pintle injectors have gained popularity due to the rise of reusable launch vehicles, which usually require throttleable engines. [Refer reference 7,11,12]

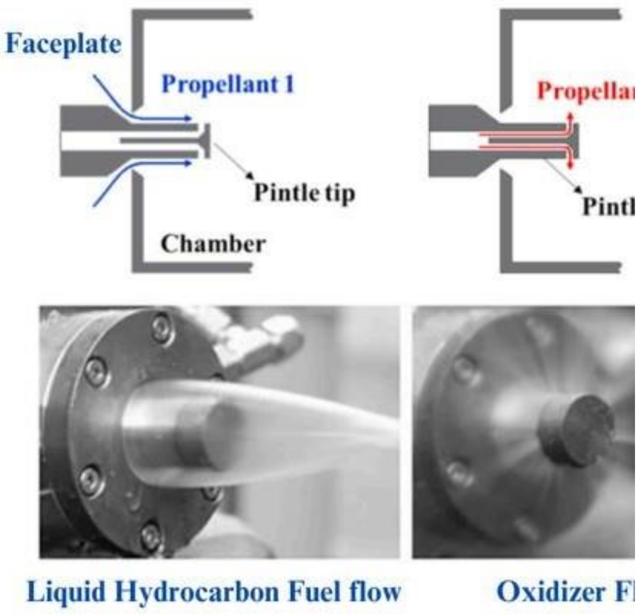

Figure 2.1 : Design of a Pintle fuel injector [refer to reference 15,16]

Components of Pintle injectors are:

1) Pintle: This moves axially to provide variable thrust by controlling the flow of the propellant into the combustion chamber. It gives precision over propellant mixture ratio and flow rate.
2) Annular Orifice : It surrounds the central pintle and is the main passageway for the oxidizer to flow into the combustion chamber.
3) Actuator : It moves the central pintle and can be hydraulically/electrically actuated.
4) Fuel and Oxidizer Manifolds

Advantages of Pintle injectors:

- Variable Mixture Ratio Control
- Stable Combustion
- Reliability
- Versatility

Disadvantages of Pintle Injectors

- Potential for Flow Separation
- Limited Applicability for High-Pressure System
- Thrust Oscillations
- Complex Control Requirements

Methodology:

Pintle injectors are used to inject cryogenic liquid propellants into the combustion chamber. They exhibit a greater throttling range than others by creating a self-stabilized stream pattern along with some rare acoustic ignition instabilities. The flow characteristics of pintle injector is studied by proposing a spray model based on previous works, and then a model of discharge coefficient is also derived. Result shows that the pintle injector forms an arch cloak-like spray. The pintle injector has demonstrated its effectiveness in atomizing and mixing propellant in rocket engines. It has also inherent protection from combustion instability(an investigation shows that total momentum ratio has never experienced combustion instability in any of its pintle injector equipped engines). Pintle injectors are one of the excellent injector for liquid rocket engines. Generally, the thrust chamber has only one pintle injector. Therefore, the flow rate in the combustion chamber is not uniform, which differs from the thrust chamber equipped by traditional injector. Previous investigations suggest that recirculation of flow pattern inside combustion chamber is extremely important for combustion, it also maintains stability in combustion. Spray pattern also plays a crucial role. It determines both recirculation zones and flame structure. Accordingly, the characteristics of flow and spray are key features dominating the combustion process inside pintle injector engines.

2.2 Impinging Injectors

Impinging injectors have been utilized in many classic rocket engines, particularly in the early era. These injectors work on the principle of collision of multiple propellant jets at high speed in the combustion chamber. This leads to enhanced atomization and improved mixing of propellants. Impinging injectors have many different variations and geometry, such as unlike Impinging Injectors, like Impinging Injectors, doublet Impinging Injectors,etc., but they are generally considered to be simpler than other types of injectors. [Refer reference 1,9,14]

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 08 Issue: 07 | July - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

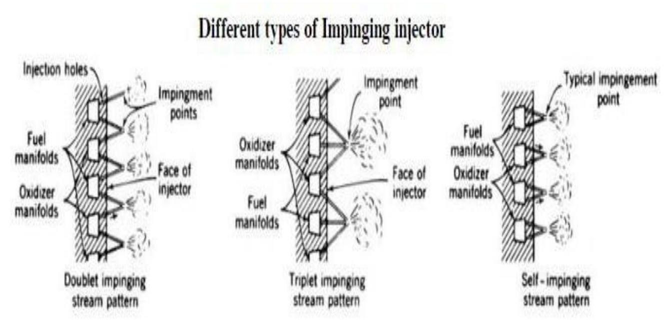

Figure 2.2 : Different types of impinging injector [Refer to reference 1,20]

Components of Impinging Injectors are

1) Fuel and Oxidizer jets : They provide a path to the propellant before they mix
2) Injector Faceplate : The faceplate is designed with precise holes and angles to ensure that the fuel and oxidizer jets collide at the optimal point for mixing and atomization.

Advantages:

- Scalability
- Cost-Effectiveness
- Design Flexibility

Disadvantages:

- Complex Manufacturing
- Potential for Clogging
- Thermal Management Issues
- Design Complexity for Optimal Performance:
- Propellant Compatibility

Methodology:

Impinging injectors are tested to observe jet collision and atomization. Flow rate, pressure drops, and thermal management parameters are measured to evaluate performances. Analysing impinging injector is often modelled using momentum conservation equations and turbulence theories. In the design of experiments, key parameters such as injector orifice size, impingement angle, and fluid properties are varied within a controlled test rig equipped with precise measurement instruments. Experimental procedures include executing trials under defined conditions, and safely collecting data on spray characteristics. Data analysis encompasses processing raw measurements, employing statistical techniques to assess droplet size distributions, and visualising spray patterns. Results are interpreted by comparing experimental data with theoretical predictions and previous studies, identifying potential sources of error, and conducting sensitivity analyses to understand the impact of parameter variations on injector performance.

2.3 Swirl Injector

Many semi-cryogenic engines employ swirl injectors, which works on the principle of providing a tangential velocity to the propellant flow. The propellant retains its tangential flow until it exits the injector throat, thus forming a cone-like structure.This swirling motion enhances the mixing of propellants, atomization, and uniform distribution of propellants, earning the injector its name.

[Refer reference 1, 2,10]

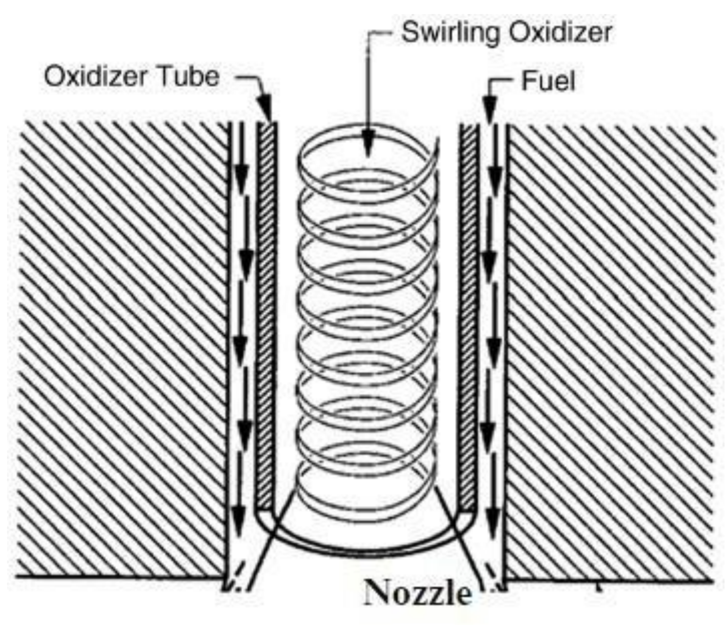

Figure 2.3 : Schematic of swirl injector [Refer to reference 21]

Components of Swirl Injector are

1) Swirl Chamber: The propellant holes are drilled at an incline, so as to provide them with the necessary tangential velocity. This chamber provides the flow with a swirling motion.
2) Orifice: It allows the swirling propellant flow into the combustion chamber
3) Injector Faceplate: It supports the orifice and swirl chamber

Advantages

- Improved Mixing
- Efficient Cooling
- Compact Design
- Fuel Flexibility
- Improved Ignition

Disadvantages

- Precision Requirements
- Increased Pressure Drop
- Thermal Stress
- Sensitivity to Flow Variations
- Combustion Instability

Methodology:

Swirl injectors are analyzed using computational fluid dynamics (CFD) simulation to optimise the swirl chamber and orifice design. Experimental validation involves measuring atomization quality, pressure drop and combustion efficiency. These injectors reduce the thickness of boundary layers. Swirl injectors in semi-cryogenic rocket engines involve a methodical approach aimed at enhancing combustion efficiency and stability. Swirl is induced either through injector head design or pre-chamber configurations, aiming to promote better mixing of propellants within the combustion chamber. Experimental validation through hot-fire tests is crucial to validate CFD predictions, assessing parameters like combustion stability, temperature profiles, and thrust characteristics. Iterative refinement based on experimental data allows for fine-tuning of swirl injector performance, optimizing specific impulse and overall engine efficiency. Ultimately, this integrated approach advances understanding and application of swirl injectors in semi-cryogenic rocket engines.Swirl injectors are used in oxidizer-rich staged combustion cycle engines. A pressure swirl injector with tangential inlet flow is widely used in liquid rocket engines.

2.4 Shear Coaxial Injector

Shear Coaxial injector are quite unique in their functioning compared to other injectors mentioned above. The working principle of these injectors is to create a velocity difference between the fuel and oxidizer flows, generating the shear force between the two streams, forcing the propellant to break into fine droplets. This leads to better atomization and thorough mixing of fuels. The injector consists of a central orifice and an annular orifice. Generally, oxidizer flows through the central orifice while fuel flows through annular orifice.

It should be noted that in shear coaxial injector, there is no tangential velocity given to the propellant, unlike swirl injector. [Refer reference 1,2,9]

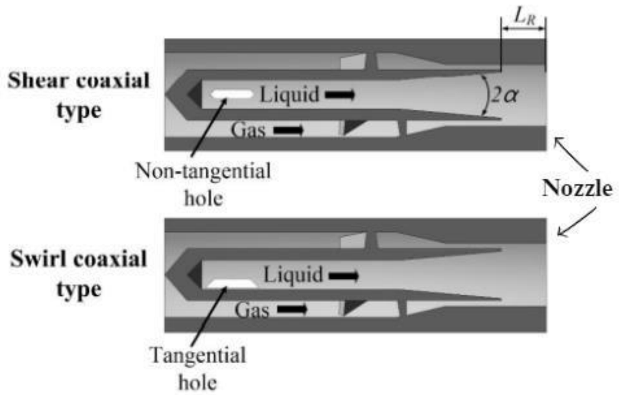

Figure 2.4 : Schematic of a shear coaxial injector [Refer to reference 22]

Components of Shear Coaxial Injector are :

1) Central Orifice: Helps the oxidizer to reach till the combustion chamber
2) Annular Orifice: Helps the liquid hydrocarbon fuel to reach till the combustion chamber
3) Injector Faceplate: Provides structural integrity and holds the orifice
4) Cooling Chamber

Advantages

- Variable Thrust Capabilities
- Stable combustion
- Reduced coking

Disadvantages

- Sensitivity to Flow Variations
- Thermal stress

Methodology:

Shear coaxial injectors are tested using both experimental setup and numerical simulation. The velocity profile for fuel and oxidizer streams are measured, along with droplets sizes and spray pattern. Combustion tests are conducted to measure stability and efficiency. Advantages of shear coaxial injectors are in their simplicity, rather good atomization and uniformity of combustible mixtures. In the hydrogen temperature ramping test one or more injectors are placed in a combustion chamber and hot fired while the temperature of the gaseous hydrogen being injected is slowly reduced until a spontaneous instability occurs. The physical significance of the hydrogen temperature ramping technique comes from the atomization process occurring in coaxial injector where the high velocity outer gaseous hydrogen flow strips droplets from the lower velocity inner liquid oxygen flow. Experiments at ONERA using water as a liquid oxygen simulant have shown that a higher relative velocity between the two flows, one gaseous and other liquid, results in smaller droplets. Lowering the gaseous hydrogen temperature increases its density, thus lowering its injection velocity relative to the liquid in order to maintain the same mass flow and therefore the same fuel-to-oxidizer ratio. Wanhainen et al have shown that it is not the hydrogen temperature itself causing the transition to instability but the ratio of the gas to liquid injection velocity. From this one might infer that the instability resulted from a decline in droplet burning efficiency because of an increase in the liquid oxygen drop size along with an extension in the length of the atomization zone. A primary purpose of the experiment is to identify what effect the velocity ratio has on atomization and pressure drop across the injector to provide a better understanding of this common stability rating technique.

2. RESULT

The following important conclusions are drawn from the examination of fuel injectors in various configurations in a semi-cryogenic rocket engine:

Pintle Injectors:

Benefits: They provide consistent combustion, adaptability, dependability, and control over the mixture ratio. Their design makes them appropriate for reusable launch vehicles by preventing leftover propellant from mixing after engine shutdown.

Cons: The drawbacks of pintle injectors include the possibility of flow separation, their restricted suitability for high-pressure systems, thrust oscillations, and intricate control specifications.

Adjacent Injectors:

Benefits: Adjacent injectors provide flexible design, scalability, and affordability. They work well with a lot of vintage rocket engines because of their straightforward operating principle.

Cons: They can be difficult to manufacture, clog easily, have trouble with heat management, and require complicated designs for best results. Furthermore, they need the propellant compatibility to be carefully considered.

Injectors with swirls:

Benefits: better mixing, effective cooling, small size, flexible fuel, and better ignite. Better atomization and uniform propellant dispersion are guaranteed by their distinctive swirling motion.

Cons: They are more sensitive to flow changes, thermal stress, greater pressure dips, and possible combustion instability. They also demand precision in manufacture.

3. CONCLUSION

The review shows that mission-specific criteria and operating conditions play a major role in fuel injector selection for a semi-cryogenic rocket engine. Every type of injector has particular benefits and drawbacks.

Because of their ease of use, dependability, and compatibility with throttleable engines—particularly in reusable launch vehicles—pintle injectors are preferred.

Although impinging injectors are known for being easy to use and reasonably priced, they need to be carefully designed to prevent clogging and problems with heat control.

Although swirl injectors provide better mixing and cooling, there are production challenges including the possibility of combustion instability.

It is imperative to take into account many elements such as performance, reliability, and design complexity when choosing a fuel injector configuration, as they must be in line with the mission profile and engine requirements.

4. REFERENCES

1. Sutton, G. P., & Biblarz, O. (2010). Rocket Propulsion Elements. John Wiley & Sons.

https://archive.org/details/rocket-propulsion-elements

2. Huzel, D. K., & Huang, D. H. (1992). Modern Engineering for Design of Liquid-Propellant Rocket Engines. AIAA. https://arc.aiaa.org/doi/book/10.2514/4.866197

3. Sforza, P. M. (2016). Theory of Aerospace Propulsion. https://books.google.co.in/books/about/Theory_of_Aerospace_Propulsion.html?id=GNYCDAAAQBAJ&redir_esc=y

4. Heister, S. D. (2003). "Modeling Liquid Rocket Engine Atomization and Swirl/Coaxial Injectors," *Progress in Astronautics and Aeronautics*, 200, 125-150. https://apps.dtic.mil/sti/tr/pdf/ADA494724.pdf

5. Turns, S. R. (2012). An Introduction to Combustion: Concepts and Applications. McGraw-Hill. https://books.google.co.in/books/about/An_Introduction_to_Combustion.html?id=idM8twAACAAJ&redir_esc=y

6. Gruber, M. R., & Nejad, A. S. (1995). New supersonic combustion research facility ,11(6), 1222-1229.

https://doi.org/10.2514/3.23940

7. Fisher, S. R., & Ahrens, R. A. (1990). "Combustion stability characteristics of pintle injectors." *AIAA Journal*.

8. M. Thirupathi, N. Madhavi, K. Simhachalam Naidu (2015). Design and Analysis of a Fuel Injector of a Liquid Rocket Engine, 2249-8958. https://www.ijeat.org/wp-content/uploads/papers/v4i5/E4105064515.pdf

9. Heister, S. D. (2002). "Atomization and sprays in combustion systems." *Progress in Energy and Combustion Science*.

10. S.Candel, (2002). "Combustion dynamics and control: Progress and challenges." *Proceedings of the Combustion Institute*. https://www.sciencedirect.com/science/article/abs/pii/S1540748902800074

11. Hulka, J. R., & Hutt, J. J. (1991). "Pintle engine history, development, and design considerations." *AIAA/SAE/ASME/ASEE 27th Joint Propulsion Conference and Exhibit*.

12. Mueller, T. J., & McConaghy, T. R. (2003). "Pintle injector rocket engine performance, stability, and testing." *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*.

13. AKHIL GARG, KARTIK JAKHU, KISHAN SINGH, ABHINAV MAURYA (2015). Cryogenic Technology & Rocket Engines. https://www.ijamejournals.com/pdf/rps145063.pdf

14. Wu, X., & Chen, Y. (2018). "Numerical simulation of cryogenic liquid jet impingement in a rocket engine injector." Aerospace Science and Technology.

15. Ficarella, A., & Laforgia, D. (2001). "Aerodynamic design of injectors for liquid-propellant rocket engines." Journal of Propulsion and Power.

16. Ankit Kumar Mishra1, Janani Kavipriya. (2020). "A Technical Review on Effect of Spray Angles and Characteristics for a Pintle Injector." Journal of Advanced Engineering Research.

17. Fan Zhao, Hao Zhang, Haibin Zhang, Bofeng Bai, Liang Zhao (2022) "Review of atomization and mixing characteristics of pintle injectors" Acta Astronautica https://doi.org/10.1016/j.actaastro.2022.08.042

18. Kazuki Sakaki, Tomokazu Funahashi, Shinji Nakaya, Mitsuhiro Tsue, Ryuichiro Kanai, Kyohei Suzuki, Takahiro Inagawa, Tetsuo Hiraiwa (2018). "Longitudinal combustion instability of a pintle injector for a liquid rocket engine combustor'' https://doi.org/10.1016/j.combustflame.2018.04.017

19.Wingen, L (1990) "Coaxial Injector Spray Characterization for the Ariane 5 Vulcain Engine," 6th Annual Confer0ence "Liquid Atomization and Spray Systems - Europe,"

19940018574.pdf (nasa.gov)

20. M. Rajadurai, Nishanth. P, Mohan Kumar (2018). "Design and Analysis of Fuel Injector Nozzle for Rocket Engines" International Conference on Aeronautics, Astronautics and Aviation(ICAAA) https://www.ijraset.com/fileserve.php?FID=16278

21. Li-jun Yang, Qing-fei Fu (2011). "Theoretical Investigation on the Dynamics of a Gas-Liquid Coaxial Swirl Injector" Journal of Propulsion and Power 27(1):144-150

22. JongHyeon Ahn, Cheolwoong Kang, Dain Lee, Gijeong Jeong, Kyubok Ahn, Ha Young Lim (2021). "Experimental Study on the Spray Characteristics of Shear Coaxial/Swirl Coaxial Injectors Manufactured by SLM Process" 15th Triennial International Conference on Liquid Atomization and Spray Systems