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COMPARISON OF PINTLE AND POROUS INJECTOR FOR LIQUID ROCKET ENGINE

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Abstract**—** Injectors govern the fundamental processes of atomization and mixing in liquid rocket engines, directly influencing combustion efficiency, flow stability, and overall engine performance. This study presents a comprehensive comparative analysis of pintle and porous injectors using computational fluid dynamics (CFD) simulations under identical operating conditions. The investigation focuses on key performance parameters, including velocity distribution, pressure drop characteristics, atomization behavior, and flow uniformity.

The results reveal that porous injectors promote highly uniform flow distribution and fine-scale atomization due to the distributed injection through multiple micro-pores, resulting in enhanced mixing efficiency. However, this mechanism introduces a significant pressure drop across the porous medium, which influences flow regulation and system stability. In contrast, pintle injectors exhibit strong macroscopic mixing through impingement and recirculation, while maintaining a relatively constant pressure drop, making them highly suitable for deep throttling applications.

Further analysis highlights the dependence of combustion efficiency on droplet size and operating conditions, demonstrating that both injector types exhibit distinct instability mechanisms under extreme regimes. Pintle injectors are susceptible to atomization-driven instabilities at low momentum conditions, whereas porous injectors show sensitivity to low pressure drop and high momentum flux conditions.

Overall, the study provides a unified physical interpretation of the performance trade-offs between pintle and porous injectors, offering valuable insights for injector selection and the design of advanced liquid propulsion systems.

Keywords — Pintle injectors, porous injectors, liquid rocket engines, computational fluid dynamics (CFD), atomization, mixing efficiency.

I. INTRODUCTION

Liquid rocket engines (LREs) operate under extreme thermodynamic and fluid dynamic conditions, where efficient propellant preparation is essential for achieving high performance and stable combustion. Among the various subsystems, the injector plays a decisive role by controlling atomization, mixing, and the spatial distribution of heat release within the combustion chamber. Even minor variations in injector design can significantly influence combustion efficiency, pressure stability, and thermal loading.

Traditional injector configurations, such as shear coaxial and impinging injectors, have been widely used; however, they often face limitations in terms of combustion instability, limited throttling capability, and non-uniform mixing. To address these challenges, advanced injector concepts such as pintle and porous injectors have been developed, each offering fundamentally different approaches to propellant injection and atomization.

Pintle injectors utilize a central movable element to generate a radially expanding spray that interacts with an opposing flow, creating strong recirculation zones that enhance mixing and stabilize the flame. Their ability to maintain a nearly constant pressure drop through variable geometry makes them highly suitable for deep-throttling applications. In contrast, porous injectors employ a permeable faceplate through which gaseous propellant is distributed at a microscopic scale, promoting fine atomization and highly uniform mixing. This distributed injection mechanism enables improved combustion efficiency and inherent acoustic damping.

Despite their individual advantages, existing studies often treat pintle and porous injectors as inherently stable solutions and analyze them independently. However, recent experimental and numerical investigations suggest that both injector types exhibit distinct instability mechanisms under specific operating conditions. Pintle injectors can become unstable under low momentum conditions due to poor atomization and delayed vaporization, while porous injectors are sensitive to extreme pressure drop conditions and high momentum flux, leading to hydrodynamic and feed-coupled instabilities.

This gap in understanding highlights the need for a unified comparative analysis that not only evaluates performance differences but also interprets the underlying physical mechanisms governing their behavior. Therefore, the present study aims to systematically compare pintle and porous injectors using computational fluid dynamics (CFD) simulations under identical operating conditions.

The objectives of this work are:

(i) to analyze velocity and pressure distributions within both injector configurations.
(ii) to evaluate atomization and mixing characteristics.
(iii) to investigate pressure drop behavior and flow uniformity.
(iv) to identify stability trends and performance trade-offs between the two injector types.

By integrating simulation results with theoretical insights and graphical analysis, this study provides a comprehensive understanding of the advantages, limitations, and operational regimes of pintle and porous injectors, contributing to the design of more efficient and reliable liquid rocket propulsion systems.

II. LITERATURE SURVEY

The design of propellant injectors significantly influences atomization behaviour, mixing characteristics, and combustion stability in liquid propulsion systems. Over the years, significant research has been carried out on both pintle and porous injector configurations, highlighting their individual advantages and limitations.

Studies on pintle injectors primarily emphasize their strong throttling capability and stable combustion behavior. Cha et al. [1] demonstrated that optimization of pintle geometry significantly improves spray characteristics, including Sauter Mean Diameter (SMD) and evaporation length. Similarly, Rios et al. [3] reported that increasing gas flow rate enhances atomization due to improved momentum exchange, while dimensionless parameters such as Weber and Ohnesorge numbers govern the breakup process. These findings indicate that pintle injector performance is highly dependent on momentum flux and geometric configuration.

In contrast, research on porous injectors highlights their ability to achieve fine atomization and uniform mixing through distributed injection mechanisms. Lux et al. [2,4] and Suslov et al. [7] showed that porous injectors can maintain stable combustion across a wide range of pressure conditions, owing to their inherent acoustic damping characteristics. Experimental and numerical studies by Kim et al. [5] and Lee et al. [10] further demonstrated that porous structures promote enhanced atomization through surface stripping and radial momentum exchange, resulting in improved mixing efficiency compared to conventional injectors.

Despite these advantages, several studies also report limitations associated with porous injector operation. Polyaeva et al. [11] identified clogging as a major challenge due to the small pore sizes, while Deeken et al. [8] observed that atomization mechanisms differ significantly from traditional injectors, requiring careful optimization of operating conditions. Furthermore, investigations on porous injector performance indicate that pressure drop and porous element geometry strongly influence atomization behavior and stability.

Although both injector types have been extensively studied, most existing research focuses on their performance in isolation. Direct comparative studies between pintle and porous injectors remain limited, particularly in terms of integrating flow dynamics, pressure behavior, atomization characteristics, and stability mechanisms within a unified framework. Additionally, the assumption that these injectors are inherently stable has been challenged by recent findings, which reveal the presence of distinct instability modes under extreme operating conditions.

Therefore, there is a need for a comprehensive comparative analysis that not only evaluates the performance differences between pintle and porous injectors but also provides a deeper understanding of the physical mechanisms governing their behavior. The present study addresses this gap by employing CFD-based analysis under consistent operating conditions, enabling a systematic comparison of velocity distribution, pressure characteristics, atomization behavior, and flow uniformity.

III. METHODOLOGY

The present study adopts a combined computational and literature-based approach to compare the performance characteristics of pintle and porous injectors in liquid rocket engines. While computational fluid dynamics (CFD) simulations are used to investigate flow behavior qualitatively, a comprehensive analysis of published research is incorporated to support and validate the observed trends.

3.1 Geometric Modeling

Three-dimensional models of both porous and pintle injectors were developed using CATIA V5. The porous injector geometry was constructed based on an existing design, incorporating a uniformly distributed pore structure. For the pintle injector, the geometry was created using available AutoCAD design data, ensuring accurate representation of the central pintle element and flow passages. Due to the axisymmetric nature of the pintle injector, a two-dimensional axisymmetric model was used for simulation to reduce computational cost while preserving flow characteristics.

The geometric parameters of the pintle injector were adopted from a validated numerical study available in the literature [1], ensuring consistency with established injector configurations. The selected dimensions correspond to a variable-area pintle injector operating with LOX/GCH_4 propellants, which has been widely used for spray and combustion analysis.

The key geometric parameters used in the present study are summarized in Table 1 and Table 2

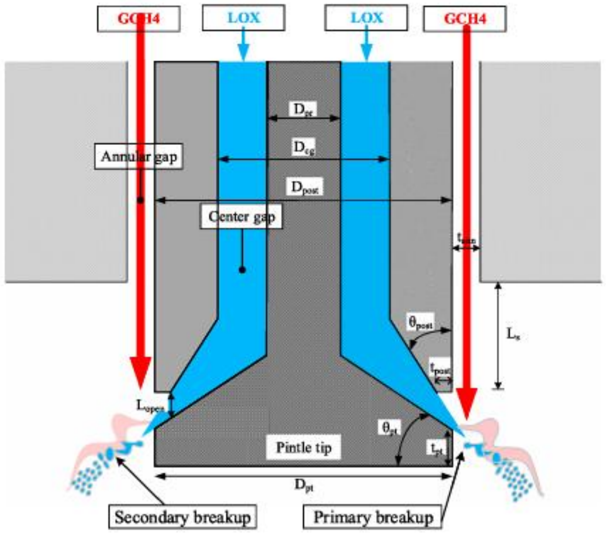

Fig. 1. Pintle injector sketch with flow mixing.

Table 1: Geometrical Parameters of Pintle Injector

Parameter	**Symbol**	**Value**	**Unit**
Annular gap thickness	t_ann	1.5	mm
Centre gas diameter	D_cg	4.55	mm
Pintle opening distance	L_open	0.05	mm
Pintle rod diameter	D_pr	3.0	mm
Pintle tip diameter	D_pt	11.2	mm
Post diameter	Dpost	11.2	mm
Pintle tip angle	θ_pt	30°	deg
Post angle	θ_post	30°	deg
Pintle tip thickness	t_pt	1.0	mm

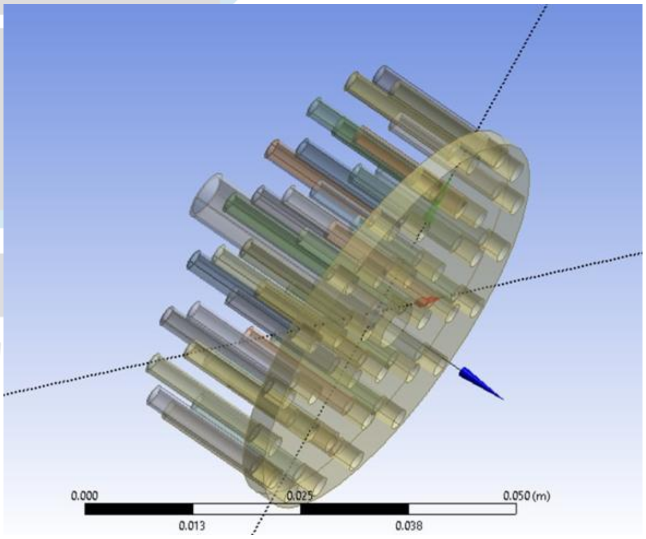

Fig. 2. Porous injector Catia 3d model.

Table 2: Geometrical Parameters of Porous Injector

Parameter	**Symbol**	**Value**	**Unit**
Injector outer diameter	Do	2.6	mm
Injector length	L	15	mm
Porous section length	Lp	3	mm
Number of pores	Np	36	—

3.2 Numerical Simulation

A hybrid meshing approach was employed to ensure a balance between computational accuracy and efficiency. Finer mesh elements were applied in regions of high velocity gradients, particularly near the injector exit and porous section, while relatively coarser elements were used in the bulk flow region. Boundary layer refinement was incorporated near solid walls to capture near-wall flow behavior. The mesh quality was verified to ensure numerical stability, and the grid resolution was selected to provide consistent flow predictions without excessive computational cost.

The CFD simulations were carried out using ANSYS Fluent. A cold-flow analysis was initially performed using air as the working fluid to study velocity and pressure distribution. Subsequently, a reactive flow case was implemented using species transport, with gaseous methane (CH_4) as fuel and liquid oxygen (LOX) as oxidizer.

The simulations were conducted primarily to capture qualitative trends in flow behavior, mixing patterns, and pressure variations within the injector configurations.

3.3 Boundary Conditions

The simulations were performed under steady-state conditions. Velocity inlet boundary conditions were applied at the propellant inlets, with an inlet velocity of 50 m/s. A pressure outlet condition was specified at the exit to represent combustion chamber conditions. All walls were treated as no-slip and adiabatic.

For the reactive case, species transport modeling was applied based on reference conditions from previous studies to simulate fuel–oxidizer interaction.

3.4 Numerical Approach and Limitations

Due to computational constraints and model simplifications, the CFD results are primarily used for qualitative analysis rather than precise quantitative prediction. The simulations provide insight into general flow trends such as velocity distribution, pressure drop behavior, and mixing characteristics.

To overcome these limitations, the numerical results are supplemented with an extensive review of experimental and high-fidelity computational studies from the literature. This combined approach ensures a more reliable and comprehensive comparison of pintle and porous injector performance.

3.5 Comparative Framework

The comparison between pintle and porous injectors is based on integrating CFD observations with established findings from the literature. Key parameters considered include atomization behavior, pressure drop characteristics, combustion efficiency trends, and stability mechanisms.

This hybrid methodology enables a balanced evaluation of injector performance while accounting for both computational insights and validated experimental evidence.

IV. RESULTS AND DISCUSSION

4.1 Flow Field Characteristics

The CFD simulations provide insight into the fundamental differences in flow behavior between pintle and porous injectors. The pintle injector exhibits strong recirculation zones near the injector exit due to the interaction between the radial jet and opposing flow streams. These recirculation zones enhance mixing and contribute to flame stabilization. In contrast, the porous injector produces a more uniform and distributed flow field, with reduced large-scale recirculation and improved spatial homogeneity.

As shown in Fig. 1, the pintle injector exhibits strong recirculation zones…

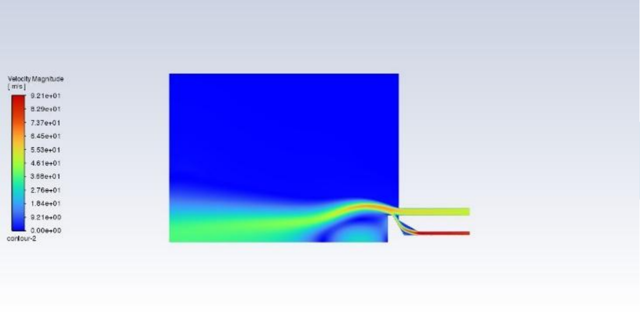

Fig. 3. Velocity magnitude contour of the pintle injector obtained from CFD simulation, illustrating high-velocity jet interaction and formation of recirculation zones near the injector exit.

The velocity contour (Fig. 3) reveals the formation of a high-velocity jet emerging from the injector, which interacts with the surrounding fluid and generates recirculation zones near the injector exit. These recirculation regions play a significant role in enhancing mixing by increasing residence time and promoting turbulence.

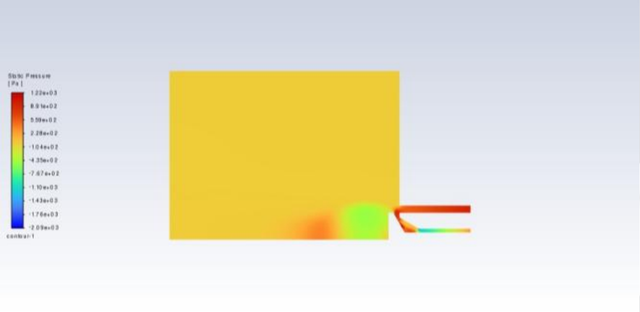

Fig. 4. Static pressure distribution within the pintle injector showing pressure gradients and localized pressure variations near the flow outlet or injection region at pintle tip.

The pressure distribution (Fig. 4) indicates a localized pressure drop near the injection region, followed by gradual recovery downstream. This pressure gradient drives the flow acceleration and contributes to jet breakup and mixing processes.

This difference in flow structure plays a critical role in determining atomization behavior and combustion performance.

4.2 Atomization Characteristics

The variation of Sauter Mean Diameter (SMD) with momentum flux ratio highlights the distinct atomization mechanisms of the two injector types. For the pintle injector, droplet size decreases significantly with increasing momentum due to enhanced shear interaction and jet breakup. This indicates a strong dependence on operating conditions, particularly momentum ratio.

In contrast, the porous injector maintains relatively consistent droplet sizes across a range of operating conditions. This behavior is attributed to the distributed injection through multiple micro-pores, where atomization is governed by surface stripping and localized shear rather than bulk momentum interaction.

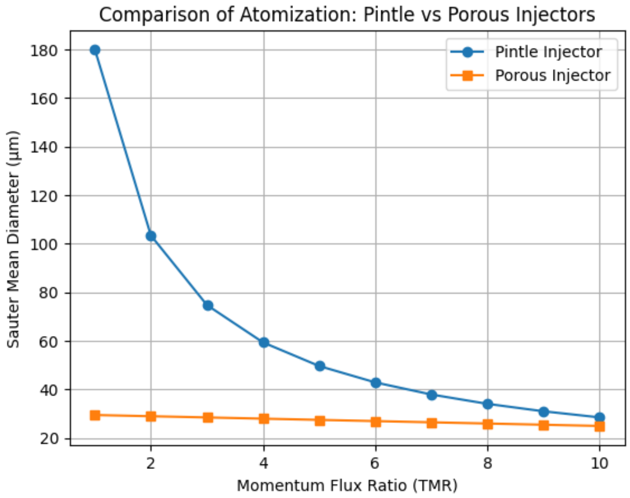

Fig. 5. Variation of Sauter Mean Diameter (SMD) with momentum flux ratio for pintle and porous injectors.

As shown in Fig. 5, the Sauter Mean Diameter (SMD) decreases with increasing momentum flux ratio for the pintle injector, indicating improved atomization at higher momentum conditions. This behavior is primarily due to enhanced aerodynamic shear between the interacting streams, which promotes breakup of the liquid jet into finer droplets. At lower momentum values, the atomization is weaker, resulting in larger droplet sizes and reduced mixing efficiency.

In contrast, the porous injector exhibits relatively uniform droplet sizes across the operating range, showing weak dependence on momentum flux. This can be attributed to the distributed injection mechanism through multiple micro-pores, where atomization is governed by localized shear forces rather than bulk momentum interaction. As a result, porous injectors provide more stable atomization, while pintle injectors offer controllable atomization through variation in operating conditions.

4.3 Pressure Drop Characteristics

The pressure drop behavior further distinguishes the two injector types. The porous injector exhibits a strong dependence of droplet size on pressure drop, following an inverse relationship ($d \propto \Delta P^{-2/3}$). Increased pressure drop enhances gas–liquid interaction and promotes finer atomization

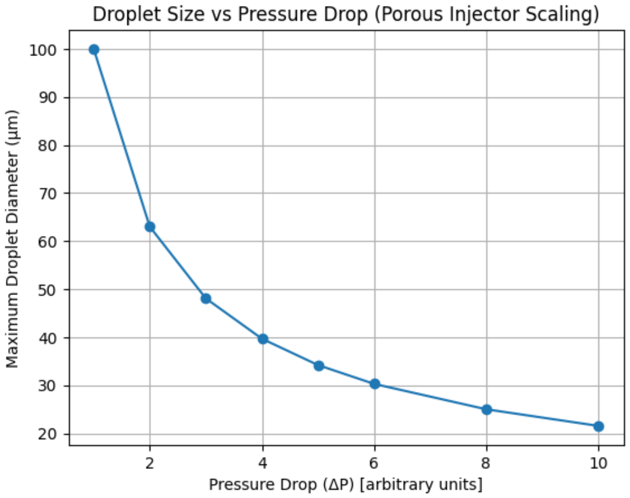

Fig. 6. Effect of pressure drop on droplet size showing inverse relationship ($d \propto \Delta P^{-2/3}$).

Figure 6 illustrates the relationship between pressure drop and droplet size for porous injectors. It can be observed that droplet diameter decreases significantly with increasing pressure drop, following an inverse power-law trend. This behavior is consistent with shear-driven atomization, where higher pressure differences enhance the velocity gradient across the liquid–gas interface, leading to increased surface stripping and breakup.

At lower pressure drops, insufficient aerodynamic interaction results in larger droplets and incomplete atomization. As the pressure drop increases, the liquid jet becomes more unstable, producing finer droplets and improving mixing efficiency. This highlights the critical role of pressure-driven mechanisms in controlling atomization performance in porous injectors.

On the other hand, the pintle injector maintains a relatively constant pressure drop across operating conditions due to its variable-area geometry. This characteristic enables stable operation during throttling and ensures consistent flow delivery.

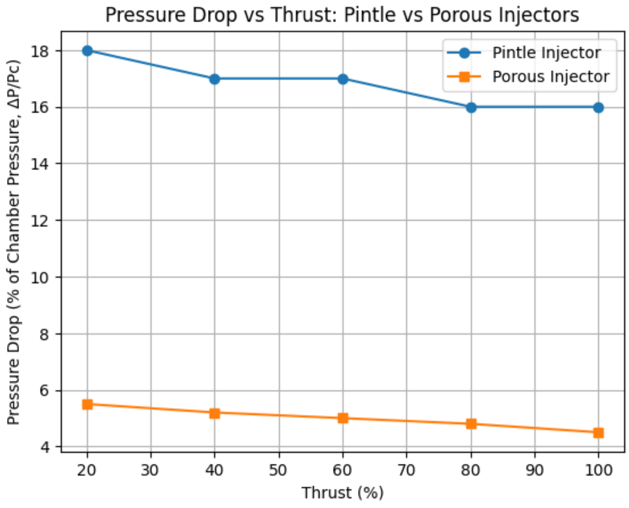

Fig. 7. Comparison of normalized pressure drop with thrust level for pintle and porous injectors.

As shown in Fig. 7, the pressure drop variation with thrust differs significantly between pintle and porous injectors. The pintle injector maintains a nearly constant pressure drop across the operating range, which is a direct consequence of its variable-area geometry. This feature enables stable operation during throttling and ensures consistent flow delivery even at varying thrust levels.

In contrast, the porous injector operates at comparatively lower pressure drops, with only minor variation as thrust increases. This behavior is attributed to the distributed injection and inherent flow resistance offered by the porous medium. While this reduces the energy requirement for flow delivery, it also introduces sensitivity to operating conditions, particularly at very low pressure drops where feed-system coupling may occur.

Overall, the results indicate that pintle injectors are better suited for applications requiring stable throttling, whereas porous injectors offer efficiency advantages under steady operating conditions.

Thus, while porous injectors rely on pressure-driven atomization, pintle injectors depend more on geometric and momentum-based control.

4.4 Combustion Efficiency and Droplet Size

The combustion process is highly sensitive to droplet size, as it directly affects evaporation rates and fuel–oxidizer mixing within the chamber. This relationship is illustrated through the efficiency–diameter trend. High efficiency is maintained for droplet sizes below approximately 80 µm, where rapid evaporation ensures effective mixing and combustion.

As droplet size increases beyond 90 µm, the evaporation time increases significantly, leading to incomplete combustion and reduced efficiency. Extremely large droplets (>110 µm) may result in combustion instability or flame quenching.

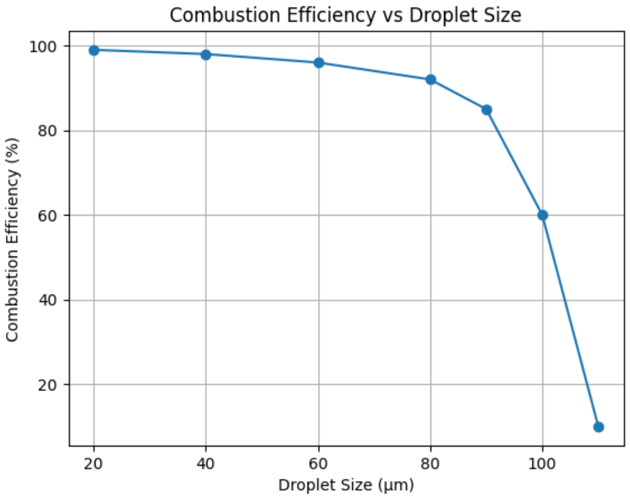

Fig. 8. Variation of combustion efficiency with droplet diameter showing efficiency decline at larger droplet sizes.

Figure 8 shows the variation of combustion efficiency with droplet size. It is evident that high combustion efficiency is achieved when the droplet diameter remains below approximately 80 µm. In this range, rapid evaporation of droplets promotes efficient mixing between fuel and oxidizer, resulting in near-complete combustion.

As droplet size increases beyond this threshold, the evaporation time increases significantly, leading to incomplete mixing and reduced combustion efficiency. Larger droplets (>90 µm) tend to persist longer within the combustion chamber, causing localized fuel-rich regions and reduced heat release. At extremely large droplet sizes, the combustion process may become unstable or incomplete, potentially leading to flame quenching.

This trend emphasizes the importance of fine atomization in achieving high-performance combustion in liquid rocket engines.

4.5 Stability Characteristics

The stability map provides a comprehensive view of injector performance across different operating conditions. Pintle injectors are prone to instability at low momentum flux ratios due to poor atomization and insufficient mixing. At higher momentum conditions, improved atomization enhances stability.

Porous injectors, while generally more stable due to distributed injection, exhibit instability at very low pressure drops due to feed-system coupling. Additionally, at excessively high momentum flux, hydrodynamic instabilities such as super-pulsation may occur.

This indicates that both injector types have distinct instability regimes and optimal operating ranges.

4.6 Comparative Analysis

A direct comparison between pintle and porous injectors reveals that neither configuration is universally superior. Pintle injectors provide excellent throttling capability and controlled atomization but are sensitive to low-momentum conditions. Porous injectors offer uniform flow distribution and stable atomization but are influenced by pressure drop and potential clogging issues.

The results suggest that the choice of injector depends on application requirements. Pintle injectors are better suited for variable thrust and deep throttling applications, whereas porous injectors are advantageous for systems requiring stable combustion and uniform mixing.

Overall, the combined CFD and literature-based analysis provides a comprehensive understanding of the trade-offs between the two injector configurations.

V. CONCLUSION

A comparative evaluation of pintle and porous injectors has been carried out using a combined computational and literature-driven approach to understand their performance characteristics. The results highlight that the two injector configurations exhibit fundamentally different atomization, pressure, and stability characteristics.

The pintle injector demonstrates strong dependence on momentum flux, where increased momentum significantly enhances atomization and reduces droplet size. Its variable-area geometry allows it to maintain a nearly constant pressure drop across a wide range of operating conditions, making it highly suitable for deep throttling applications. However, at low momentum conditions, poor atomization leads to larger droplets and increased susceptibility to combustion instability.

In contrast, the porous injector provides uniform flow distribution and consistent atomization due to its distributed injection mechanism. The atomization process is primarily governed by pressure-driven surface stripping, resulting in fine droplet formation even at lower momentum conditions. However, its performance is strongly influenced by pressure drop, and instability may arise under very low or excessively high operating conditions.

The analysis of combustion efficiency confirms that droplet size plays a critical role in determining performance, with optimal efficiency achieved at smaller droplet diameters. The stability assessment further indicates that both injector types operate effectively within specific regimes, and neither configuration is universally superior.

Overall, the study demonstrates that pintle injectors are more suitable for applications requiring throttling flexibility and controlled flow behavior, whereas porous injectors are advantageous for systems emphasizing uniform mixing and stable combustion. Future work may focus on high-fidelity simulations and experimental validation to further refine the understanding of multi-phase interactions and instability mechanisms in advanced injector designs.

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