



Research Paper

Nano-Orifice Based Fuel Injector Design for Enhanced Combustion Efficiency and Reduced NOx Emissions in Aero Engines

N. V. S. Raju^{1*}, Danne Manikanta², Dharavath Venkatesh², Posani Rakesh², N. Dinesh², Shankari Chandu²

¹*Professor & Principal, ²UG Student, ^{1,2}Department of Mechanical Engineering
JNTUH College of Engineering Wanaparthy, Narsingaipalli, Gopalpet Rd, Wanaparthy, 509103, Telangana

*Correspondence: N. V. S. Raju (enviousraju@jntuh.ac.in)

ABSTRACT

Fuel injection systems constitute the core of diesel engine operation, where the injector serves as a critical component responsible for delivering fuel under extremely demanding conditions involving cyclic hydraulic, mechanical, and thermal stresses. The injector nozzle, in particular, governs combustion efficiency by atomizing fuel at very high pressures into the combustion chamber, ensuring proper air–fuel mixing. In this study, a novel modification to the conventional nozzle design is proposed by transitioning from micro-scale orifice geometries to nano-scale openings. This dimensional refinement is intended to enhance spray characteristics, improve atomization quality, and potentially reduce harmful emissions such as nitrogen oxides (NOx). The injector considered in this work is derived from a twin-cylinder agricultural tractor engine, and its geometric parameters including nozzle dimensions and orifice specifications—are carefully referenced for accurate modeling. During operation, the injector is subjected to fluctuating fluid pressures, variable mechanical loads due to the repetitive motion of the needle valve, and elevated thermal conditions, with surface temperatures often reaching 200–300°C or higher. These combined loading conditions significantly influence the structural durability and fatigue behavior of the injector. To evaluate these effects, a detailed three-dimensional model of the fuel injector is developed using CATIA V5. Subsequently, fatigue analysis is conducted to assess the structural integrity under complex cyclic loading. The results enable identification of potential failure regions and estimation of safety factors, thereby providing insights into the injector’s reliability and performance under prolonged operational conditions.

Keywords: Aero Engine Combustion, Fuel Atomization, Nano-Orifice Nozzle, Spray Breakup Mechanism, Low-Emission Combustion.

1. INTRODUCTION

Modern aero engines are engineered to operate with high efficiency and ultra-low emissions across a wide range of operating conditions, from idle to full thrust. This performance is achieved through the integration of advanced technologies such as turbocharging, exhaust gas recirculation (EGR), and charge air cooling, all of which optimize the thermodynamic cycle and combustion stability. Among these, the fuel injection system plays a pivotal role in determining engine performance, fuel efficiency, and emission characteristics. Precise control over

fuel delivery such as timing, pressure, and spray pattern is essential to ensure optimal mixing of fuel and air, which directly influences combustion quality and pollutant formation.

Within the combustion process, the injector must atomize the fuel into fine droplets and facilitate rapid vaporization to enable efficient mixing with compressed air. This process is particularly critical in modern high-pressure injection systems, where the fuel is delivered through micro-scale nozzle orifices at extremely high pressures. Under such conditions, complex internal flow phenomena arise, including

turbulence and cavitation. Cavitation occurs when local pressure within the nozzle drops below the vapor pressure of the fuel, leading to the formation of vapor bubbles. These bubbles subsequently collapse as pressure recovers, significantly affecting the internal flow structure, discharge coefficients, and ultimately the external spray characteristics.

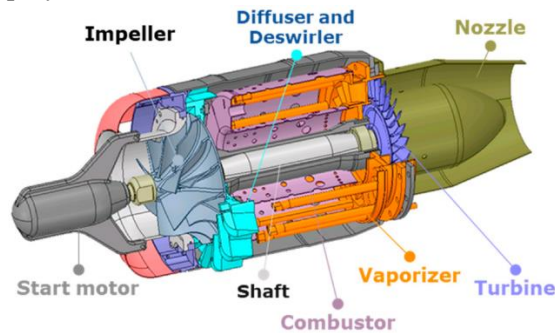


Fig 1. Integrated analysis model of turbojet engine

The presence of cavitation within injector nozzles has both beneficial and detrimental effects. On one hand, controlled cavitation can enhance fuel atomization by promoting spray breakup, improving air-fuel mixing, and even helping to prevent deposit formation within nozzle holes. On the other hand, excessive cavitation can lead to material degradation such as hole erosion, which compromises nozzle integrity and long-term reliability. Furthermore, erosion and uneven wear across nozzle holes can result in variations in spray parameters, including mass flow rate, spray penetration, and impulse, thereby affecting combustion uniformity and emission formation. Understanding and managing cavitation phenomena is therefore critical for the design and durability of advanced aero engine fuel injection systems

2. LITERATURE REVIEW

Mohan B. et al. in [1] discuss the method of measurement based on gauging the momentum flow of the atomized fuel stream from each injector nozzle opening and determining the coefficient of the outflow share from a given opening in relation to the others. In work [2], the authors applied conducted tests, a combination of

qualitative imaging techniques and quantitative techniques for the determination of the drop size, such as laser diffraction and Doppler anemometry (PDA). In paper [3], a nozzle concept consisting of orifices with convergent-divergent shapes was investigated. Three nozzles, characterized by different degrees of conicity, were compared to a nozzle with cylindrical orifices, which acts as a baseline. Karra and Kong 2010 [4] observed the 10-hole nozzle geometry hole nozzle had the best performance in the engine at full-load conditions. The number and cone of hole variations in the nozzle injector lead to better engine performance and reduced emissions.

In paper [5], simulated performance at different load conditions for a constant speed self-ignition engine was determined using GT-Power software. The critical parameters were optimized for achieving the desired fuel nozzle hole diameter. A very close validation with less than 1% difference is achieved at full load. In comparison, a less than 10% difference is achieved at part loads. The simulation model predicts the power, torque, brake specific fuel consumption, in-cylinder pressure, outlet temperature and NOx with very good accuracy at different loads. The optimized spray hole diameter of the testing engine was validated with the experimental results and compared with the baseline model.

Hooper et al. [6] have presented the methods of cold starting a UAV engine based on the experimental experience.

Hasan et al. [7] have studied a diesel engine-powered electrical generator by a series of experiments. They obtained the variations in different gas emissions with the engine power. Furthermore, Pankaj et al. [8] analyzed the effects of a bio-fuel of different proportions on a single cylinder, and confirmed that a dual fuel blend can be a promising source of biodiesel production. But there is still a lack of the aircraft engine model analysis for a fuel-powered UAV, causing difficulty in the optimization of the

engine power characteristics. Shamekhi et al. [9] improved the mean value model by using neural networks based on a thermodynamics model. Furthermore, they calculated the pollutant emissions precisely. However, the thermodynamics modeling is highly dependent on the business software, and the calculation time is extremely long. Kamyar et al. [10] investigated a new block-oriented modeling method to predict the engine performance and emissions. However, model research on an entire UAV power unit is still lacking. Lu. et al [11] has conducted research on a two-stroke aircraft engine for a fuel-powered UAV. He obtained the relationship between the output engine power and propeller pulling force from experiments and calculations.

3. PROPOSED SYSTEM

The proposed system focuses on the design, modification, and performance evaluation of an advanced fuel injection nozzle by transitioning from conventional micro-scale orifices to nano-scale geometries to enhance atomization and reduce emissions in aero engine applications. The system begins with the geometric modeling of a real-time fuel injector nozzle, referenced from a twin-cylinder diesel engine, and redesigned using CATIA V5 to incorporate nano-scale orifice structures. This modification aims to improve spray breakup, fuel-air mixing, and combustion efficiency while minimizing NOx emissions.

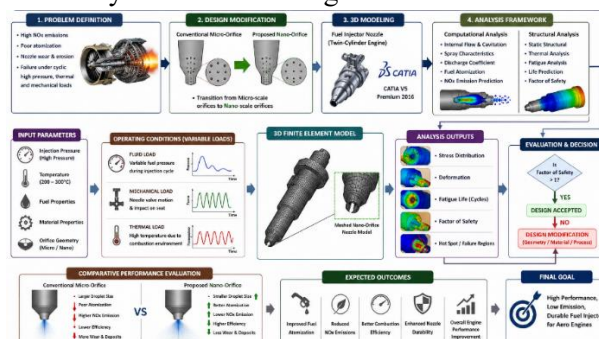


Fig 2. Proposed system architecture of advanced fuel injection nozzle

The developed 3D model is then subjected to computational and structural analysis, where the

nozzle operates under high-pressure fuel injection conditions, cyclic mechanical loads from needle valve motion, and elevated thermal environments (200–300°C). A detailed fatigue analysis framework is applied to evaluate the durability of the modified nozzle under these coupled loading conditions. The system computes critical parameters such as stress distribution, deformation, life cycles, and factor of safety, enabling identification of failure-prone regions. Special attention is given to the influence of nano-orifice geometry on flow behavior, cavitation tendencies, and structural integrity.

Furthermore, the proposed system integrates a comparative performance evaluation between conventional micro-hole nozzles and the newly designed nano-hole configuration. Key performance indicators include fuel atomization quality, spray penetration, emission characteristics, and mechanical reliability. The overall objective of this system is to develop a high-performance, low-emission, and structurally robust fuel injection nozzle, suitable for next-generation aero engines, by combining advanced design techniques with fatigue-aware engineering analysis.

4. RESULTS ANALYSIS

Fig 3 shows the meshed model of rigid flange coupling in the ANSYS analysis for the static structural process. To analyze, the FEM triangular type of mesh is used for the rigid flange coupling in the ANSYS environment. The number of elements used in this meshing is 71441 and the number of nodes is 122228. In this process regular type of meshing is done to analyze the process.

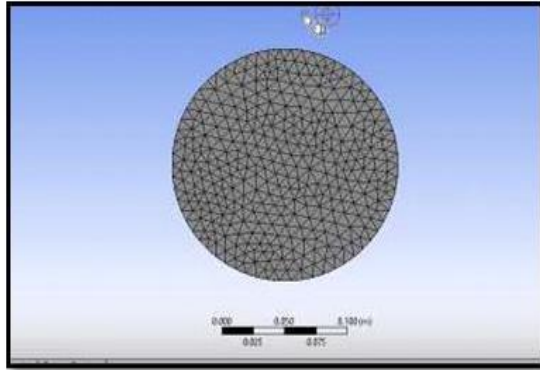


Fig 3. Element mesh of the fuel injector nozzle. Fig 4 presents the finite element analysis result of the fuel injector nozzle, showing the contour distribution of stress or deformation along its geometry under operating conditions. The color gradient indicates that the central tapered region of the nozzle experiences the highest stress (red zone), primarily due to high-pressure fuel flow, thermal effects, and cyclic mechanical loading, while the inlet and outlet ends (blue regions) are subjected to relatively lower stress levels. This distribution highlights critical regions prone to fatigue and potential failure, thereby providing valuable insight into the structural behavior and durability of the modified nano-orifice nozzle design in aero engine applications.

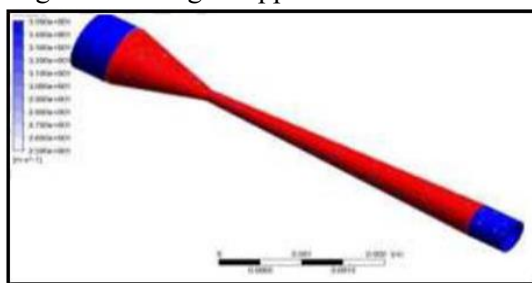


Fig 4. structural analysis result of the fuel injector nozzle

Fig 5 illustrates the finite element analysis contour of the fuel injector nozzle, showing the variation of stress or deformation across its geometry under operating conditions. The color gradient indicates that the highest concentration (red region) occurs near the inlet and transition zone, where geometric changes and pressure effects are significant, while the elongated outlet

section (blue region) experiences comparatively lower values. This distribution highlights how load transfer and structural response vary along the nozzle, helping to identify critical regions that may be susceptible to fatigue or failure in high-pressure, thermo-mechanical environments relevant to aero engine applications

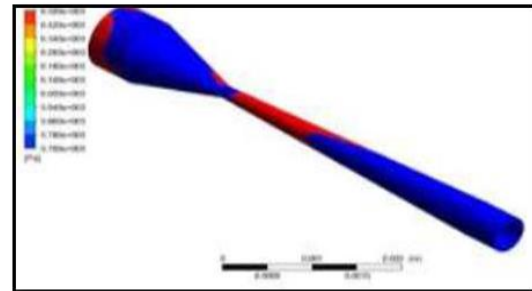


Fig 5. Pressure Distribution Contours of Fuel Injector Nozzle.

Fig 6 depicts the velocity distribution within the fuel injector nozzle, particularly emphasizing the flow behavior at the outlet region. The contour shows that most of the nozzle body experiences relatively low velocity (blue region), while significantly higher velocities (green to red zones) are concentrated near the nozzle exit holes. This indicates strong acceleration of fuel as it passes through the small orifices, which is essential for effective atomization and spray formation. The localized high-velocity jets highlight the influence of nozzle geometry, especially the nano/micro-scale holes, on enhancing fuel breakup and mixing. Such velocity characteristics are crucial for improving combustion efficiency, reducing emissions, and ensuring optimal performance of the aero engine fuel injection system.

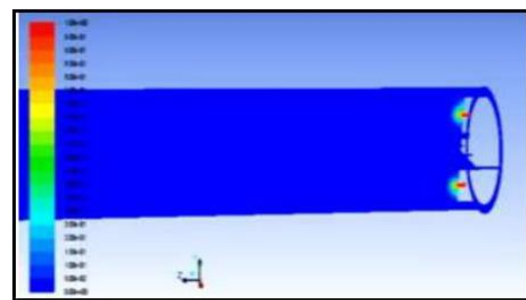


Fig 6. Velocity Contour Distribution at Fuel Injector Nozzle Exit

Fig 7 illustrates the temperature distribution inside the fuel injector nozzle obtained from thermal or CFD analysis under high-temperature operating conditions. The contour indicates that higher temperature regions (red to orange zones) are dominant along the main flow path, while relatively lower temperatures (green to blue regions) are observed near the nozzle exit and around the orifice zones due to rapid fuel expansion and cooling effects. The variation in temperature highlights the influence of fuel flow, heat transfer, and nozzle geometry on thermal behavior. Such analysis is crucial for evaluating thermal stresses, material durability, and the overall reliability of the nozzle, especially in high-temperature aero engine environments where thermal fatigue and material degradation are significant concerns

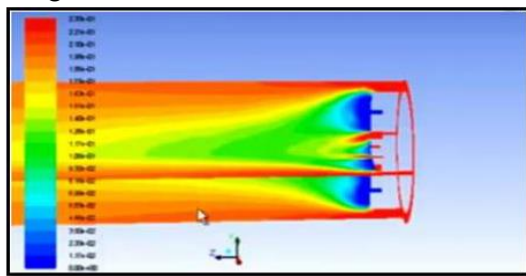


Fig 7. Temperature Distribution within Fuel Injector Nozzle under Combustion Conditions

5. CONCLUSION

The research emphasizes the critical role of fuel injector design in enhancing the performance and emission characteristics of advanced engine systems. Through detailed computational analysis, it is observed that key flow parameters such as pressure, velocity, heat transfer rate, and mass flow rate are significantly influenced by variations in inlet velocity and nozzle geometry. In particular, reducing the nozzle diameter leads to improved fuel atomization and more efficient combustion, thereby contributing to enhanced overall engine efficiency and reduced emission levels. The investigation highlights that precise control of fuel injection characteristics including

spray formation and discharge behavior—is essential for minimizing issues such as flow choking and uneven combustion, especially in alternative fuel applications. By utilizing advanced simulation tools like ANSYS, the internal flow dynamics within the injector nozzle can be accurately predicted, enabling optimization of design parameters without excessive reliance on physical prototyping. The application of finite element and computational fluid dynamics techniques not only improves design reliability but also reduces development time and cost. Overall, the study demonstrates that optimized nozzle configurations, supported by simulation-driven design approaches, can significantly enhance injector durability, combustion efficiency, and environmental performance, making them highly suitable for next-generation aero engine applications.

REFERENCES

- [1]. Robart, D.; Breuer, S.; Reckers, W.; Kneer, R. Assessment of Pulsed Gasoline Fuel Sprays by Means of Qualitative and Quantitative Laser-based Diagnostic Methods. *Part. Part. Syst. Charact* **2020**, *18*, 179–189.
- [2]. Mohan, B.; Du, J.; Sim, J.; Roberts, W.L. Hydraulic characterization of high-pressure gasoline multi-hole injector. *Flow Meas. Instrum.* **2018**, *64*, 133–141.
- [3]. Salvador, F.J.; De La Morena, J.; Carreres, M.; Jaramillo-Císcar, D. Numerical analysis of flow characteristics in diesel injectors nozzles with convergent-divergent orifices. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2017**, *231*, 1935–1944.
- [4]. Karra, P.K.; Kong, S.C. Experimental Study on Effects of Nozzle Holes Geometry on Achieving Low Diesel Engine Emissions. *J. Eng. Gas Turbines Power* **2020**, *132*, 022802.

- [5]. Nerkar, A. Optimization and Validation for Injector Nozzle Hole Diameter of a Single Cylinder Diesel Engine using GT-Power Simulation Tool. *SAE Int. J. Fuels Lubr.* **2019**, 5, 1372–1381.
- [6]. P. Hooper, “Experimental experience of cold starting a spark ignition UAV engine using low volatility fuel,” *Aircr. Eng. Aerosp. Technol.*, vol. 89, no. 1, pp. 106–111, Jan. 2017.
- [7]. H. Bayındır, M. Z. Işık, and H. Aydın, “Evaluation of combustion, performance and emission indicators of canola oil-kerosene blends in a power generator diesel engine,” *Appl. Therm. Eng.*, vol. 114, no. 5, pp. 234–244, Mar. 2017.
- [8]. Pankaj Dubey and R. Gupta, “Effects of dual bio-fuel (Jatropha biodiesel and turpentine oil) on a single cylinder naturally aspirated diesel engine without EGR,” *Appl. Therm. Eng.*, vol. 115, no. 25, pp. 1137–1147, Mar. 2017.
- [9]. M. Shamekhi and A. H. Shamekhi, “A new approach in improvement of mean value models for spark ignition engines using neural networks,” *Expert Syst. Appl.*, vol. 42, no. 12, pp. 5192–5218, Jul. 2018.
- [10]. K. Nikzadfar and A. H. Shamekhi, “An extended mean value model (EMVM) for control-oriented modeling of diesel engines transient performance and emissions,” *Fuel*, vol. 154, no. 15, pp. 275–292, Aug. 2018.
- [11]. B. Lu, Q. Yu, X. Fu, Y. Shi, and M. Cai, “Parameter matching of hybrid coaxial rotors and multi-rotor UAV’s power system,” in *Proc. IEEE Int. Conf. Aircraft Utility Syst. (AUS)*, Oct. 2016, pp. 1099–1104