RESEARCH ON THE EFFECT OF FUEL INJECTORS ON THE COMBUSTION PROCESS AND NO_x EMISSIONS IN DIESEL ENGINES

Tang Ba Dai[1,*], Nguyen Trung Dung[1], Dao Quang Ke[2]

DOI: https://doi.org/10.57001/huih5804.2026.014

ABSTRACT

This study presents a numerical simulation of the combustion process in a turbocharged diesel engine using Diesel-RK software to evaluate the effects of two injector configurations: a single-hole nozzle and a four-hole nozzle. Simulations were conducted across an engine-speed range of 700 - 2600rpm under conventional operating conditions. The results show that the four-hole injector significantly improves combustion and emission characteristics: the maximum cylinder pressure increases by about 3%, the peak rate of heat release (ROHR) increases by 10%, and the occurrence of p_{max} shifts 2.5°CA closer to top dead center, indicating more favorable combustion phasing. NO_x emissions decrease by an average of 17% (and up to 43%), soot decreases by 37.5%, brake specific fuel consumption (BSFC) is reduced by 5%, and thermal efficiency increases from 38.2% to 40.1%. The findings confirm the strong applicability of the multi-hole injector model for improving the design and optimization of modern diesel engines using numerical simulation tools.

Keywords: *Diesel engine; NO_x; Thermal efficiency; Diesel-RK; Fuel injector.*

[1]Viet-Hung Industrial University, Vietnam
[2]Hoa Binh University, Vietnam
*Email: tbdaicnh@gmail.com
Received: 02/11/2025
Revised: 15/12/2025
Accepted: 28/01/2026

1. INTRODUCTION

In the context of increasingly stringent emission regulations and the growing demand for enhanced energy efficiency, the optimization of fuel-injection systems has become a critical aspect of modern diesel engine design. Injector geometric parameters particularly the number and diameter of nozzle holes-directly influence air-fuel mixing quality, combustion rate, and the formation of NO_x and soot emissions [1, 2]. Among current numerical tools, Diesel-RK is widely recognized for its multi-zone combustion model and its capability to represent detailed injector configurations with high fidelity.

Recent studies have further emphasized the importance of mixture formation, flame propagation, and combustion kinetics in controlling emissions and improving engine efficiency [3]. However, most existing research has predominantly focused on injection timing and injection-control strategies, while the specific influence of nozzle-hole number has not been comprehensively assessed [4, 5].

Against this background, numerical simulation and engine-operating optimization have become increasingly important, offering valuable insights into performance and emission characteristics under various conditions. Therefore, the present study employs Diesel-RK to simulate the combustion process in a turbocharged diesel engine using two injector configurations-single-hole and four-hole nozzles. The aim is to evaluate the effects of injection characteristics on NO_x emissions, soot formation, brake specific fuel consumption (BSFC), and thermal efficiency. The findings provide a scientific basis for selecting injector designs that meet both performance targets and emission-reduction requirements.

2. RESEARCH OBJECT AND METHODOLOGY

2.1. Research Object

The research object is a modeled four cylinder, water cooled turbocharged diesel engine operating within the speed range of 700 - 2600rpm. The model is fully developed using Diesel-RK software. The injectors compared include a single-hole nozzle with a concentrated spray and a four-hole nozzle with a dispersed spray pattern. Simulated output parameters include: pressure-crank angle (p-θ) diagram, rate of heat release (ROHR), NO_x emissions, BSFC, exhaust gas temperature, and thermal efficiency.

2.2. Research Methodology

Diesel-RK software was employed to simulate the combustion process of the diesel engine on a crank-angle resolved basis. The input parameters included:

Geometric parameters: cylinder bore of 102mm, piston stroke of 118mm, compression ratio of 17:1, and combustion chamber volume of 34.7cm^3.

Injection parameters: single-hole and four-hole injectors, nozzle hole diameter of 0.28mm, injection pressure of 80 - 100MPa, and main injection timing at 10°CA before TDC.

Operating conditions: engine speed ranging from 700 to 2600rpm, intake pressure of 0.18 - 0.24MPa, intake air temperature of 320 - 340^{0}K, EGR rate of 10%, and coolant temperature of 360^{0}K. Spray characteristics were determined based on the geometric configuration of each injector type:

The single-hole injector features a narrow spray cone (≈12°), producing a concentrated spray along the chamber axis with a penetration length of approximately 32mm. The four-hole injector provides a total spray cone angle of 140 - 150°, with uniformly distributed jets, an average penetration length of about 28mm, and a maximum jet velocity of ~250m/s.

A multi-zone combustion model was applied to describe fuel-air mixing and combustion reactions. Model parameters followed. Kuleshov A. [6], with m_1 = 2.0, m_2 = 1.5, n = 3.0, and an energy partition ratio of 0.35: 0.65. Preliminary calibration was performed using data from comparable turbocharged diesel engines to ensure that the simulated pressure crank angle (p-θ) characteristics matched realistic engine behavior. The simulation results were validated against the dataset of. Kuleshov A. [6], with deviations below 5% in peak pressure and the timing of p_{max}, confirming that the model provides sufficient accuracy for comparative analysis of the injector configurations.

2.3. Research Limitations

This study was conducted entirely using the Diesel-RK simulation platform, without experimental data for model calibration. The results therefore provide qualitative comparisons between the two injector types. Fuel evaporation is assumed to occur instantaneously within the low-temperature regime, and the interaction between EGR flow and fuel spray is simplified using an average mixing coefficient. Consequently, discrepancies may arise when applying the findings to engines with different injection strategies or operating conditions. To enhance model reliability, future work should incorporate experimental calibration and evaluate the model's accuracy with respect to key injection parameters.

3. RESULTS AND DISCUSSION

3.1. Pressure-Crank Angle (p-θ) Characteristics

The simulation results show that the four-hole injector produces a maximum combustion pressure (p_{max}) that is approximately 2 - 4bar higher than that of the single-hole injector. At the same time, the location of p_{max} shifts about 2.5°CA closer to top dead center, indicating a more efficient combustion process and, consequently, an increase in work-generation efficiency

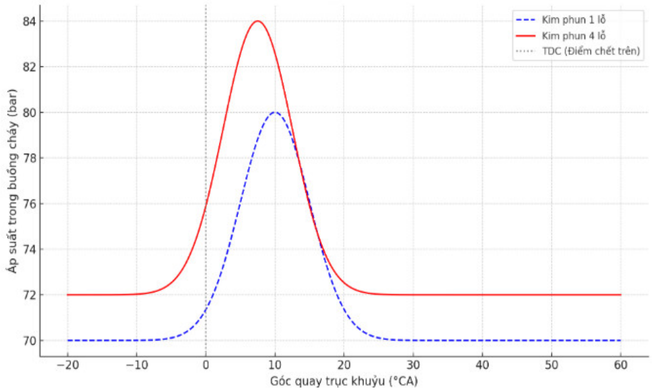

Figure 1. Pressure and crankshaft rotation angle

The four-hole injector achieves an earlier p_{max} (7.5°CA compared with 10°CA after TDC), resulting in an improved expansion process and higher indicated work. At the same time, its p_{max} value is higher due to more effective fuel-air mixing and faster combustion.

3.2. Rate of Heat Release (ROHR)

The four-hole injector produces a maximum rate of heat release approximately 10% higher than that of the single-hole injector (120 vs. 132 J/°CA), indicating improved fuel air mixing and a faster combustion rate. Its ROHR peak appears about 2.5°CA earlier and closer to TDC, reflecting a more concentrated and efficient combustion process. This improvement is attributed to the more uniform fuel dispersion, which increases the evaporation surface area and reduces ignition delay. At higher engine speeds (2200 - 2600rpm), the heat release profile of the four-hole injector remains stable, demonstrating better combustion control and higher thermodynamic stability, thereby contributing to improved efficiency and reduced heat losses.

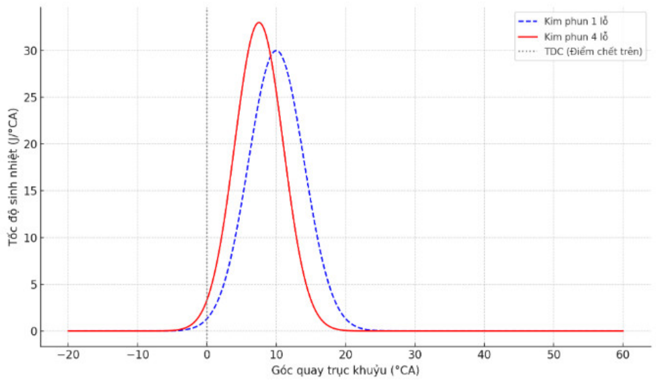

Figure 2. Crankshaft rotation angle heat generation follow rate (ROHR) graph

3.3. NO_x Emissions

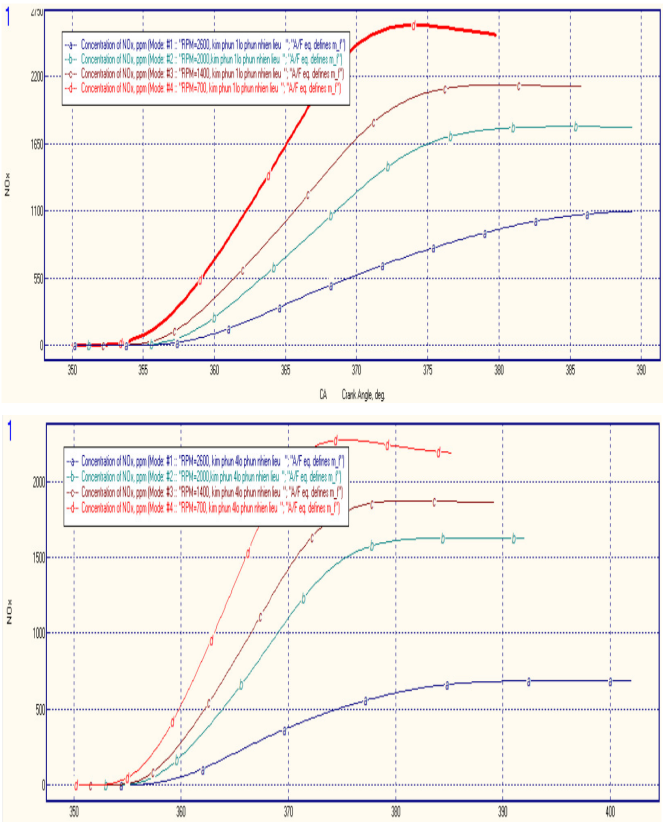

Figure 3. NO_x distribution according to crankshaft angle (°CA) of 1- and 4-hole fuel injectors

The simulation results show that NO_x emissions from the four-hole injector decrease by an average of 17% and up to 43% compared with the single-hole configuration, while soot emissions are reduced by approximately 37.5%. These differences arise from the combustion mechanism and the fuel-air distribution characteristics inside the combustion chamber.

NO_x formation predominantly occurs in high-temperature regions (T > 2000⁰K) where the excess-air ratio is λ > 1. With the four-hole injector, the smaller and more uniformly distributed fuel jets create a more homogeneous mixture, reducing localized over-temperature zones and thereby weakening NO_x formation reactions.

Conversely, soot is mainly formed in fuel-rich regions (λ < 1) at temperatures between 1600 and 2000⁰K. Increasing the number of nozzle holes reduces droplet size, enhances evaporation rates, and improves mixing with air. As a result, fuel-rich zones shrink and oxidation becomes more complete, leading to a significant reduction in soot formation within the combustion chamber.

The temperature-equivalence ratio (λ-T) distribution further highlights two key trends when using the four-hole injector: (1) fuel-rich regions become narrower, and (2) the optimal combustion region (λ ≈ 1, T ≈ 1800⁰K) expands. These effects explain the soot reduction due to improved mixture homogeneity.

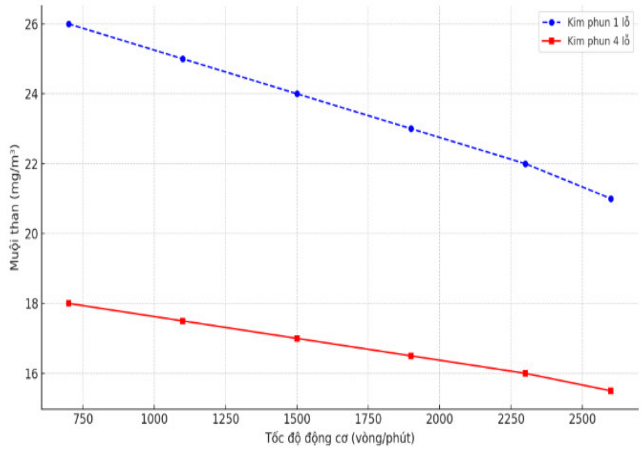

Figure 4. Graph of carbon black content according to crankshaft angle

The single-hole injector generates higher soot levels, decreasing from 26 to 21mg/m³ as engine increases, whereas the four-hole injector shows a more significant reduction, down to 15.5mg/m³. Soot is formed in locally fuel-rich regions at elevated temperatures. Increasing the number of nozzle holes produces finer, more uniformly distributed spray droplets that evaporate more rapidly, creating a more homogeneous mixture. This reduces both fuel-rich zones and localized peak temperatures, thereby lowering NO_x and soot emissions simultaneously while maintaining strong combustion performance.

3.4. Exhaust Gas Temperature, BSFC, and Thermal Efficiency

Exhaust gas temperature decreases from 410°C (One-hole injector) to 395°C (Four-hole injector), indicating reduced heat losses to the surroundings. BSFC decreases from 238g/kWh to 226g/kWh, equivalent to a 5% improvement in fuel-consumption efficiency.

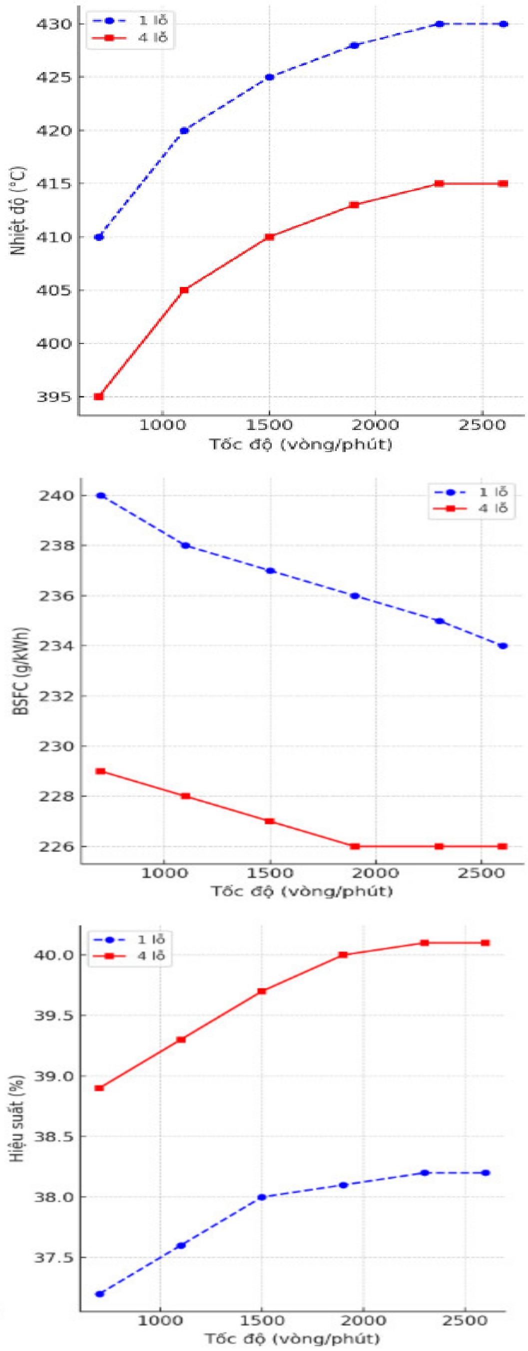

Figure 5. Exhaust gas temperature, BSFC, and thermal efficiency

Thermal efficiency increases from 38.2% to 40.1%, attributed to the combustion process occurring closer to TDC and reduced heat losses.

Table 1. Comparison of performance characteristics between single-hole and four-hole injectors

Parameter	One -hole injector	Four-hole injector	Change (%)
Maximum pressure p_{max} (bar)	81	83.5	+3%
Maximum ROHR (J/°CA)	120	132	+10%
Location of p_{max} (°CA after TDC)	10.5°	8.0°	Shifted 2.5° closer to TDC
NOx emissions (g/kWh)	6.4	5.3	-17%
Soot (mg/m^3)	28	17.5	-37.5%
BSFC (g/kWh)	238	226	-5%
Thermal efficiency (%)	38.2	40.1	+5%

Combustion efficiency is significantly improved: p_{max} increases by 3%, the ROHR rises by 10%, and the location of p_{max} moves 2.5°CA closer to TDC, indicating a stronger and more uniform combustion process. Emissions are also better controlled, with NO_x reduced by an average of 17% and soot reduced by 37.5%, thanks to the more uniform fuel distribution that limits locally fuel-rich regions. At the same time, BSFC decreases from 238 to 226g/kWh (-5%), and thermal efficiency increases from 38.2% to 40.1%, demonstrating a more effective and successful conversion of fuel energy into useful work.

3.5. Extended Discussion and Practical Application Orientation

The simulation results show that the four-hole injector significantly enhances combustion efficiency while simultaneously reducing NO_x and soot emissions. These findings are consistent with recent studies, which confirm that multi-hole injectors improve fuel-air mixing, expand the optimal combustion region, and mitigate the NO_x soot trade off.

The four-hole injector generates finer fuel jets that provide a larger surface area for interaction with air, resulting in a more homogeneous mixture. This leads to a more uniform temperature distribution within the combustion chamber, a reduction in localized high-temperature zones (T > 2000^{0}K), and a decrease in fuel-rich regions (λ < 1). These outcomes suggest that the Diesel-RK simulation tool can effectively support the optimization of injector design such as the number of holes, spray angle, and injection pressure to enhance thermal efficiency and reduce exhaust emissions.

4. CONCLUSION

This study conducted a simulation of the combustion process in a turbocharged diesel engine using Diesel-RK software to compare two injector configurations: a single-hole nozzle and a four-hole nozzle. The results show that the four-hole injector offers superior thermodynamic, emission, and energy-efficiency performance. Specifically, peak cylinder pressure increases by 3%, the rate of heat release (ROHR) increases by 10%, and the location of p_{max} shifts closer to TDC, thereby optimizing the work-generation process. At the same time, NO_x emissions decrease by up to 43%, soot emissions decrease by 37.5%, BSFC decreases by 5%, and thermal efficiency increases from 38.2% to 40.1%. These findings confirm the strong potential of the four-hole injector model for application in the design and optimization of modern diesel engines.

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