Engineering and Technology Journal e-ISSN: 2456-3358

Volume 10 Issue 10 October-2025, Page No.-7274-7278

DOI: 10.47191/etj/v10i10.07, I.F. – 8.482

Comparative Strategies for Nox Reduction in Diesel Engines

Musaab O. El-Faroug[1]*, Atif Ismail Adam Bashr[2]

[1]Elimam Elmahdi University, Faculty of Engineering, Mechanical Engineering Department, Kosti, Sudan

[2]Kosti Technical College, Mechanical Engineering Department, Kosti, Sudan

ABSTRACT: This study investigates the reduction of nitrogen oxide (NOx) emissions in diesel engines using computational simulations performed with Diesel-RK. Three in-cylinder control strategies were evaluated: exhaust gas recirculation (EGR), direct water injection, and variations in combustion chamber depth. Simulations were conducted on a six-cylinder, four-stroke diesel engine at engine speeds ranging from 1000 to 3000 rpm. The results show that increasing EGR lowers NOx emissions by reducing peak combustion temperatures through oxygen dilution and enhanced mixture heat capacity. Water injection was found to be the most effective strategy, reducing NOx to nearly negligible levels across all speeds by combining evaporative cooling, heat absorption, and oxygen displacement. Changes in combustion chamber depth had a moderate influence, with shallower chambers improving swirl and mixing, thereby lowering local temperature peaks and suppressing NOx formation. Overall, the findings highlight water injection as the most effective standalone strategy, while combining it with optimized chamber geometry and moderate EGR offers a promising integrated approach for NOx control in diesel engines.

KEYWORDS: Diesel engine, RK-diesel, NOx emission, Optimization

I. INTRODUCTION

Global population growth, economic expansion, and urbanization have driven increased reliance on internal combustion (IC) engines, which are widely used in automobiles, portable machinery, and locomotives due to their high power-to-weight ratio and compact size [1]. Currently, over 600 million vehicles operate worldwide. However, IC engines emit pollutants such as NOx, CO, CO_2, hydrocarbons, and particulate matter, posing significant environmental and health risks.

NOx formation is strongly influenced by combustion temperature, residence time of high-temperature gases, oxygen availability, and turbulence [2]. Longer exposure of burnt gases to high temperatures and pressures promotes NOx production, particularly in low-speed engines. Turbulence accelerates fuel-air mixing, increasing reaction rates. Techniques to reduce peak combustion temperatures can lower NOx but may affect other emissions and engine performance, often resulting in a fuel penalty. No single strategy effectively optimizes both emissions and performance.

To mitigate these effects, governments have implemented stringent emission standards, including Euro standards in Europe, EPA standards in the USA, and Japanese regulations, with Euro 6 introduced in 2014 and Euro 7 planned by 2025. Policies also promote eco-friendly vehicles and early retirement of older diesel engines, alongside advanced after-treatment technologies, to reduce NOx emissions and their environmental impact [3].

Exhaust Gas Recirculation (EGR) is an effective and economical strategy to reduce NOx by lowering peak combustion temperatures through recirculating part of the exhaust into the intake, which reduces oxygen concentration [4]. Banglin et al. [5] reported that EGR nearly halved NOx emissions and reduced PM and PN, with minimal impact on fuel consumption and slight efficiency gains. However, higher HC and CO emissions occurred due to combustion deterioration, highlighting the trade-offs between emission control and engine performance. Deng et al. [5] reported that EGR rate significantly affects diesel engine thermal efficiency. Experiments with a two-stage turbocharged engine showed distinct trends between 0–18% and 18–51% EGR, with total input energy and intake enthalpy as the main factors influencing efficiency. Hu et al. [6] used CFD to study EGR in methanol-fueled marine engines, finding that while NOx was reduced by up to 65%, high EGR extended ignition delay, combustion duration, and lowered cylinder pressure. Rajesh Kumar and Saravanan [7] observed maximum NOx reductions of 27–35% with 30% EGR, but higher soot, HC, and slight CO increases occurred due to reduced oxygen availability, highlighting the trade-offs between emissions and combustion performance.

Muhammad et al. [8] reviewed 204 studies (1958–2024) on water injection in diesel engines, identifying Direct Water Injection (DWI), Emulsion Injection, and Intake Manifold Water Injection (IMWI) as main methods. Emulsion and IMWI were favored for requiring minimal engine modification. Water injection improved brake thermal efficiency by 10–15%, reduced BSFC by 5–10%, and cut

emissions (up to 60% NOx, ~25% PM, 10–20% CO/CO_2), with emulsion injection offering the best balance between performance and emission reduction. Ahmad et al. [9] reported that water-diesel emulsions (5–20% water, 2% surfactant) enhanced fuel efficiency and reduced NOx and PM, though CO and CO_2 increased under specific loads. The E20 blend showed in-cylinder pressures comparable to diesel with higher heat release, confirming emulsions as a viable strategy for improving efficiency and lowering emissions. Sun et al. [10] showed that Direct Water Injection (DWI) during the compression stroke can reduce NOx emissions by up to 55.6% by lowering flame temperatures through water evaporation. However, this approach may slightly increase particulate matter (PM) and, at higher water levels, CO and unburned hydrocarbons (HC). Zhangming et al. [11] studied water port injection in diesel/methane dual- and tri-fuel engines. Methane reduced combustion intensity and delayed ignition, while water further delayed combustion. Combined injection notably decreased NOx and PM, though CO and HC increased. The results indicate that water and methane injection together can effectively mitigate both NOx and particulate emissions.
In this study, computational simulations were performed using Diesel-RK to analyze a diesel engine operating on conventional diesel fuel. The model investigated the effects of exhaust gas recirculation (EGR), water injection, and combustion chamber geometry on NOx emissions, aiming to identify effective strategies for their reduction.

II. METHODOLOGY

DIESEL-RK is a comprehensive thermodynamic simulation platform designed for full-cycle analysis of internal combustion engines. The software integrates advanced computational models that allow for detailed examination of combustion dynamics, emission formation processes, and strategies for performance optimization. Initially developed at Bauman Moscow State Technical University between 1981 and 1982, DIESEL-RK has undergone extensive development through multiple versions. What started as a tool focused on combustion optimization has evolved into a robust simulation environment widely used in internal combustion engine research and development. Its core mathematical frameworks—including the RK-model for spray dynamics and the Zeldovich and detailed kinetic mechanisms for NOx prediction—have been thoroughly validated across diverse engine configurations. Ongoing enhancements, driven by both industrial and academic demands, have added capabilities such as multiparametric optimization algorithms, fuel spray visualization tools, and user-friendly interface wizards, making the platform suitable for both practical engineering applications and scientific investigations [12].
Accurate fuel physical properties are essential as input data for calculating spray dynamics, droplet size, and, consequently, evaporation and heat release rates. The properties of diesel fuel used in this study are summarized in Table 1.

Table 1: Properties of Diesel fuel [13].

Property	Diesel
C Mass Fractions (%)	0.87
H Mass Fractions (%)	0.126
O Mass Fractions (%)	0.004
Sulfur Fraction (%)	0
Low Heating Value (MJ/kg)	39
Apparent Activation Energy (kJ/mol)	23
Cetane Number	48
Density at 323K (kg/m3)	830
Dynamic Viscosity coefficient (Pa.s)	0.003
Molecular Mass	190

In this study, the formation and reduction of nitrogen oxide (NOx) emissions from diesel combustion were investigated using computational simulation. Three different control strategies were evaluated to identify the most effective approach for minimizing NOx emissions: (i) exhaust gas recirculation (EGR), (ii) direct water injection, and (iii) modification of the combustion chamber depth. The numerical simulations were carried out on a six-cylinder, four-stroke diesel engine, whose detailed technical specifications are listed in Table 2. To ensure a comprehensive assessment, engine performance and emission behavior were analyzed under five distinct operating speeds: 1000, 1500, 2000, 2500, and 3000 rpm. This approach allowed for the evaluation of the effectiveness of each method under varying operating conditions, thereby providing a comparative basis for optimizing NOx reduction strategies in diesel engines.

Table 2: Details of the simulation diesel engine.

Type	6L15/18
No. of Cylinder	6 in - line
Cooling System	liquid
Cylinder Bore (mm)	150
Piston Stroke (mm)	180
Cylinder Head Design	Four valves

III. RESULTS AND DISCUSION

Figure 1 depicts the effect of exhaust gas recirculation (EGR) on NOx emissions during diesel engine operation. The findings indicate that higher EGR levels consistently reduce NOx emissions compared with baseline operation without EGR. This reduction is mainly associated with the lowering of peak in-cylinder temperature, a dominant factor in NOx formation, as highlighted in earlier research [14]. Introducing recirculated exhaust gases into the intake charge produces two key outcomes: first, a dilution of the oxygen concentration, which slows the combustion reactions by limiting oxidizer availability; and second, an increase in the effective heat capacity of the charge, which dampens the temperature rise for a given heat release. Together, these effects suppress the thermal NOx pathways, typically described by the extended Zeldovich mechanism, by lowering the maximum combustion temperature [15]. Consequently, higher EGR rates reduce NOx emissions by weakening combustion intensity and decreasing peak in-cylinder temperatures [16].

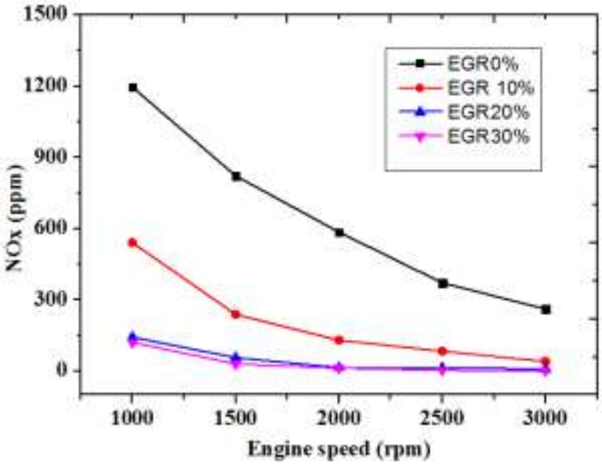

Figure1: Variation of NOx emission with different EGR ratio

Figure 2 illustrates the variation of NOx emissions with engine speed for a diesel engine fueled with conventional diesel and diesel–water blends containing 10%, 20%, and 30% water. For the pure diesel case, NOx emissions are relatively high at lower engine speeds and progressively decline as speed increases, a trend that can be attributed to reduced high-temperature residence time at higher speeds, which limits NOx generation [2]. In contrast, the addition of water results in a sharp reduction in NOx emissions, which remain close to zero across the entire speed range. This pronounced decrease is primarily governed by three mechanisms: (i) evaporative cooling from water vaporization, which significantly lowers in-cylinder flame temperatures [17], (ii) the increased specific heat capacity of the charge, which dampens the temperature rise during combustion [18], and (iii) partial dilution of oxygen concentration, which slows the oxidation reactions and suppresses thermal NOx formation through the extended Zeldovich mechanism [19]. Collectively, these effects demonstrate the strong potential of water–diesel blends in mitigating NOx emissions compared with conventional diesel operation.

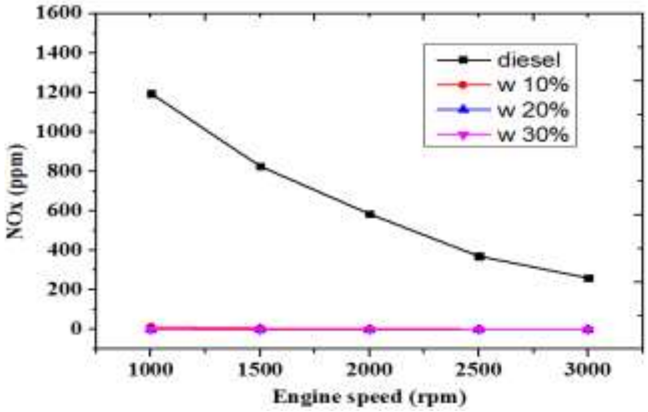

Figure2: Variation of NOx emission with different water ratio

Figure 3 presents the variation of NOx emissions with engine speed for a diesel engine operating with different combustion chamber depths (d11, d13, d17, d20, and d23). In all cases, NOx emissions are highest at lower engine speeds and progressively decline with increasing speed, approaching approximately 200 ppm at 3500 rpm. Among the chamber configurations, the shallowest design d11consistently yields the lowest NOx emissions, whereas deeper chambers such as d20 and d23 tend to produce higher emissions, particularly in the low-speed range. This trend can be explained by the influence of chamber geometry on in-cylinder air–fuel mixing, turbulence intensity, and combustion temperature distribution. Shallow chambers promote enhanced swirl and mixing, resulting in more homogeneous combustion and reduced peak flame temperatures, thereby suppressing NOx formation. In contrast, deeper chambers localize combustion in restricted zones, leading to elevated peak temperatures that favor thermal NOx generation through the extended Zeldovich mechanism [20]. The overall reduction in NOx with increasing engine speed is consistent with the shorter high-temperature residence time of combustion products, which constrains NOx formation despite higher operating loads [21]. These observations emphasize that careful optimization of combustion chamber depth is a viable design approach to improve mixing quality, control temperature distribution, and mitigate emissions in diesel engines.

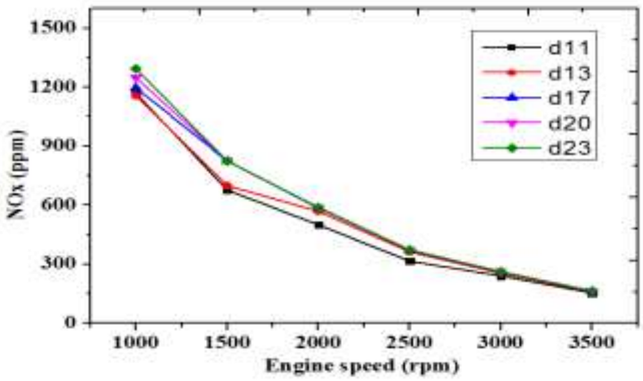

Figure3: Variation of NOx emission with different combustion chamber depth

Figure 4 compares three NOx reduction strategies water injection, EGR, and variations in combustion chamber depth and highlights the superior effectiveness of water addition. Among the tested methods, water injection achieves the greatest reduction, driving NOx emissions to nearly negligible levels across all engine speeds. This strong performance results from its combined effects: evaporative cooling that lowers in-cylinder flame temperatures, increased mixture heat capacity that limits temperature rise, and partial oxygen dilution that slows reaction rates, all of which suppress the thermal NOx pathway [22]. EGR also reduces emissions by diluting oxygen and increasing thermal capacity of the intake charge [23], while chamber geometry adjustments provide only moderate benefits by influencing swirl, mixing, and local temperature distribution [24]. Overall, water injection is clearly the most effective standalone technique, and its integration with optimized chamber design and moderate EGR could yield an even more robust NOx control strategy for diesel engines.

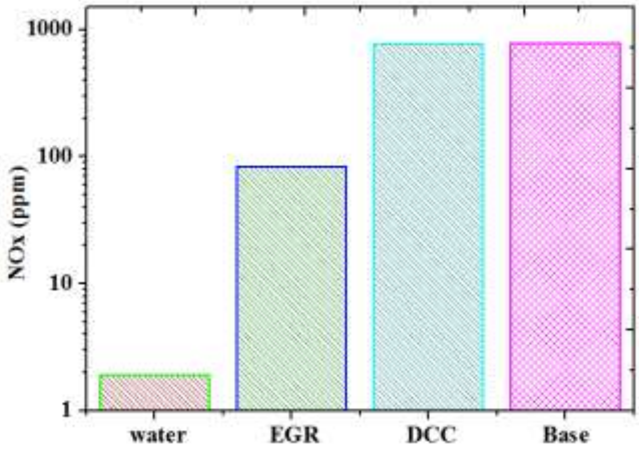

Figure3: Comparison of predicted NOx with different strategies

IV. CONCLUSION

- NOx emissions are mainly controlled by in-cylinder temperature, oxygen concentration, and mixture heat capacity.
- Water injection was the most effective method, nearly eliminating NOx across engine speeds through cooling, heat absorption, and oxygen dilution.
- EGR reduced NOx by lowering oxygen availability and increasing mixture heat capacity, though less effectively than water injection.
- Combustion chamber depth had a moderate effect, with shallower chambers lowering NOx due to better swirl and mixing.
- Higher engine speeds consistently reduced NOx because of shorter high-temperature residence times.
- The best results can be achieved by combining water injection with optimized chamber geometry and moderate EGR.

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