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RESEARCH ARTICLE

Effects of Direct Water Injection on the Nitrogen Oxide Emission Characteristics of Marine Diesel Engines

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Abstract

This study examines the issue of diesel emissions from vehicles and vessels and their impact on environmental degradation with a focus on nitrogen oxide (NOx) emissions and their contribution to air pollution-related deaths worldwide. The novelty of this work is the use of computational fluid dynamics simulations to investigate the effectiveness of water addition for reducing NOx emissions. This study considers two methods of water addition, i.e., injection of water and air into a combustion chamber and mixing of water with fuel before injection. Adding water to air systems at 10% and 20% ratios reduces NOx emissions by 5% and 10%, respectively, whereas mixing water with fuel at the same ratio reduces NOx emissions by 25%. Increasing the water percentage can further reduce emissions by up to 35%. This study indicates that water addition is a cost-effective method for reducing emissions, and numerical analysis is crucial for demonstrating its effectiveness.

Keywords: Computational fluid dynamics, Nitrogen oxide emissions, Water addition method, Combustion chamber

1. Introduction

Diesel engines are extensively utilized across various sectors worldwide (including marine transport, construction, mining, and agriculture) owing to their superior operational efficiency [1,2]. Moreover, compared to gasoline engines, diesel engines consume less fuel and are increasingly employed in heavy-duty and commercial vehicles [3]. Nevertheless, diesel engines are one of the primary sources of greenhouse gases and other harmful emissions, such as carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM), as evidenced by the information presented in the third International Maritime Organization (IMO) greenhouse gas study (2014) [4]. In the maritime sector, numerous marine organizations, including the IMO, European Environment Agency (EEA), United States Environmental Protection Agency (USEPA), and Lloyd's Register (LR), have conducted preliminary research on marine diesel engine emissions and produced valuable baseline data. They have suggested specific emission factors for pollutants (such as NOx, CO, CO_2, SO_2, and PM) for a given load range [5,6]. According to statistics, global shipping generated 796 Mts of CO_2 in 2012, with predictions of a 50−250% increase by 2050 owing to growth in maritime transport. Additionally, NOx and SOx emissions contribute to approximately 13% and 12% of total emissions each year, respectively [7,8]. The IMO aims to reduce carbon emissions (greenhouse gases (GHGs)) by 50% by 2050 compared to the 2008 values [9].

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Abbreviation	Description
CO_2	Carbon dioxide
NOx	Nitrogen oxides
SOx	Sulphur oxides
PM	Particulate Matter
IMO	International Maritime Organization
EEA	European Environment Agency
USEPA	United States Environmental Protection Agency
LR	Lloyd's Register
GHG	Greenhouse gas
MGO	Marine gas oil
EGR	Exhaust gas recirculation system
SCR	Selective Catalytic Reduction
DWI	Direct water injection
FEM	Finite-element model
WIA	Water addition into air
W/F	Water addition into fuel

For NOx emissions, the IMO set limits in the form of different levels (Tiers) that are based on the ship construction date and engine speed [10]. Tier I and II standards apply globally, whereas Tier III standards are applicable only in NOx emission control areas [7]. The Tier I NOx emission percentage for engines manufactured before 2011 is 17 g NOx/kWh for low-speed engines, 17−9.8 g NOx/kWh for medium-speed engines, and <9.8 g NOx/kWh for high-speed engines (above 3000 RPM). The IMO adopted two additional NOx levels, Tier II and III standards, which became useful in 2011 and 2016, respectively, and required 15% and 80% decreases in NOx emissions, respectively, compared to those for Tier I, as shown in Fig. 1 [11−13].

The implemented regulations led to ships adopting new strategies to decrease emissions, which include using marine gas oil (MGO) with a low sulfur content or implementing scrubbers [14]. However, these methods have resulted in higher fuel costs. The IMO offers various mechanisms to decrease NOx emissions, as presented in Table 1.

2. NOx formation

NOx refers to nitrogen monoxide (NO) and nitrogen dioxide (NO_2), which significantly affect air pollution and human health [2,17]. NOx is formed via four distinct chemical kinetic processes: thermal NOx formation, prompt NOx formation, fuel NOx formation, and intermediate N_2O formation [18,19].

- **Thermal NOx**: The oxidation of atmospheric nitrogen that is present in the combustion air produces thermal NOx. Thermal NOx has a significant effect only at high temperatures above 1300 °C, and it is negligible at low temperatures below 760 °C, according to the Zeldovich equations [20]. Equation (1) shows the chemical equation for thermal NOx generation.

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O \tag{1}$$

$$N + OH \rightarrow NO + H$$

- **Fuel NOx**: When nitrogen molecules combine with oxygen during combustion in liquid and solid fuels, fuel NOx is produced. However, most gaseous fuels are nitrogen-free.

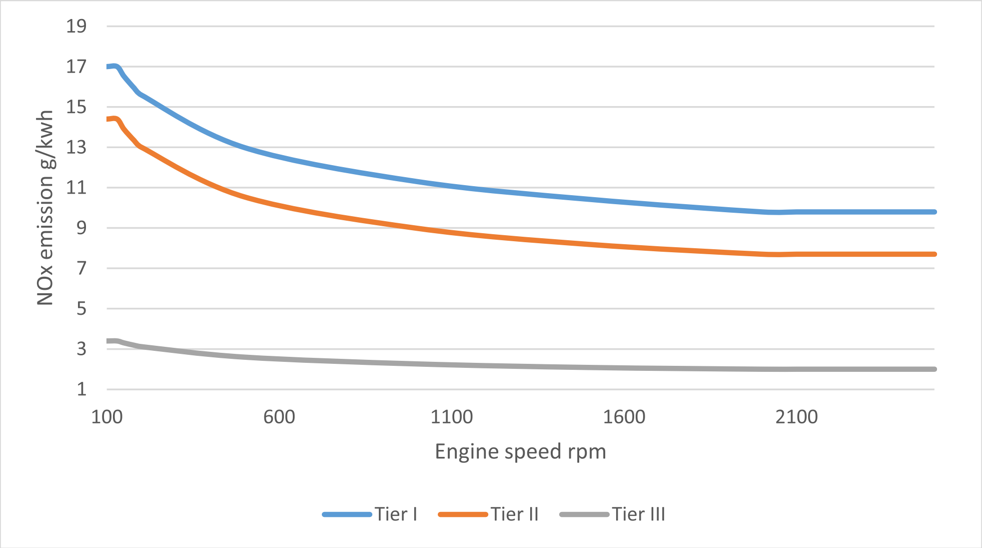


Fig. 1. The established nitrogen oxide emission limits as a function of engine speed.

Table 1. NOx reduction technologies and methods for ships [15,16].

	Pre-combustion	During Combustion	After treatment
NOx emissions	Water addition to the air system Water addition to the fuel system (emulation) Use alternative fuels Engine modification	Exhaust gas recirculation system- (EGR) Water addition to the cylinder	Selective Catalytic Reduction system (SCR)

- **Prompt NOx**: This is produced by direct reaction between nitrogen in the air and fuel under fuel-rich conditions, and it is present in all combustion processes.

3. Water injection technique

Diesel engines release more NOx because of excess air, which enhances NO formation and decreases HC and CO production [21]. One of the most promising approaches to reduce diesel engine NOx emissions is to supply water to the engine; there are three methods to supply water to the cylinders [22].

The first approach is direct water injection (DWI), which has been described by Arto Sarvi; research in this field is slow owing to challenges with modifying the cylinder head to accommodate an additional water injection system. Although DWI significantly reduces NOx and HC emissions, it causes a slight increase in soot and PM emissions [1,23]. Kökkülünk et al. (2013) used a new electronically controlled vapor injection method to control NOx emissions in a direct injection (DI) diesel engine [24]. Their results demonstrate that at 1200 rpm, NO and CO_2 emissions decrease by 22.4% and 4.3%, respectively, while the smoke density increases from 44% to 46% at 2200 rpm. Exhaust gas recirculation (EGR) with water injection techniques reduce emissions by 82%, which allows vessels to meet IMO Tire III requirements [25]. In 2019, Mingrui achieved a 34.6% NO decrease with a 15% water injection for a given fuel mass [26]. In 2020, Vezir and Ylmaz investigated DWI and achieved a 61% reduction in NOx emissions as well as significant improvements in engine performance [27].

The second method, which is emulsification, involves mixing fuel with a specific percentage of water prior to injection. In 2006, a test with a water-in-diesel emulsion revealed a 71% reduction in PM outflow [28]. Hountalas conducted a comparison test between EGR, DWI, and fuel–water emulsion for reducing NOx and found that the fuel–water emulsion decreased soot emission levels at the same NOx reduction level. The diesel–water emulsion has some limitations such as high engine costs and possible changes in the fuel emulsion physical properties [29]. In 2019, a review of studies on NOx emission from water injection, emulsification, and injection timing retardation was published, and it indicated that the emulsification method can reduce NOx by 10–60% compared to conventional diesel [21]. Water injection, compared to EGR and selective catalytic reduction (SCR), has the advantage of reducing NOx emissions during the entire engine operation while not increasing PM emissions [20].

Fumigation is another method of feeding water into cylinders; this approach is widely used in large marine diesel engines [17]. Compared to water emulsion and DWI, the limitation of this technique is that it uses a lot of water. Furthermore, at the end of the compression process, water cannot be ejected [30]. In 2020, a comparative study of emulsion and fumigation methods for reducing NOx and smoke emissions was performed by Gowrishankar et al. using a small-bore diesel engine [31]. However, despite the numerous studies on the effects of adding water during the combustion process on pollution rates, this field lacks analytical studies involving simulations that aim to obtain the best results and compare them to experimental studies to save time and costs.

The objective of this study was to investigate the efficacy of NOx emission reduction techniques using computational fluid dynamics (CFD) simulations performed in ANSYS FLUENT. Specifically, we analyzed the impact of water injection into air prior to the compression process and blending water with fuel. Thus, we assessed the effectiveness of this method for decreasing NOx emissions and evaluated its potential as a sustainable solution for reducing the environmental impact of diesel engines.

4. ANSYS FLUENT CFD simulation

ANSYS FLUENT is fluid simulation software that allows to solve problems and develop mathematical models using computational fluid dynamics principles [13,32]. In this work, the combustion of diesel engine with the air inside a combustion chamber was studied using the non-premixed model developed in ANSYS FLUENT. Specifically, we calculated the amount of emitted NOx without water addition and then study the effect of water addition to the chamber (at a ratio of 10%, 20%, or 30%) on the production of thermal and prompt NOx. As previously stated, ANSYS FLUENT allows to add water by DWI or by mixing water with fuel. Finally, the simulation results were validated using other experimental results.

5. Methodology

5.1. Model description

A cylindrical chamber was used to study combustion using commercial CFD fluid flow software to assess the effect of water addition on NOx emission. The dimensions of the chamber are shown in Table 2. The cylinder geometry, air flow, and fuel addition were evaluated, as shown in Fig. 2.

5.2. Mesh generation

The finite-element model (FEM) is a numerical solution technique that evaluates the behavior of complex systems by splitting them into a small number of components that relate to each other at nodes. A mesh is a collection of these elements. Mesh generation is the most significant procedure in CFD analysis because it generates a grid of elements from which all preferred equations of fluid flow can be solved with high accuracy. An increase in the number of elements has a significant impact on computational time. Owing to the complexity of this process, practice and trial and error are required. In this study, we developed meshing tools (such as inflation) by following the ANSYS meshing tutorial, as shown in Fig. 3. Table 3 shows the main parameters for mesh sizing.

The mesh metric's skewness, aspect ratio, and smoothness are essential tools used to assess the precision of a mesh metric. The overall skewness varies from 0 to 1, with 0 being the best and 1 being the worst. If the maximum skewness is less than 0.5, the solution will quickly generate a divergence error and fail to converge. The aspect ratio is computed by dividing the longest edge's length by the shortest edge's length [33]. Table 4 shows the statistics for the mesh metrics of skewness, aspect ratio, and inflation.

Table 2. Main dimension of combustion.

Chamber dimensions	
Length (chamber)	1500 mm
Diameter (chamber)	450 mm
Dimeter (nozzle)	10 mm
Length (nozzle)	10 mm

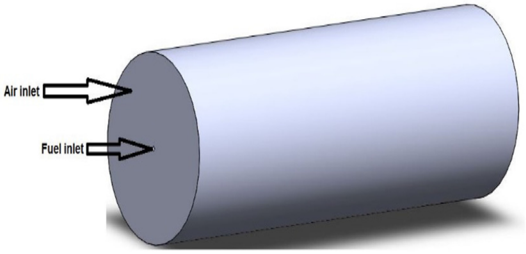


Fig. 2. 3D combustion chamber.

5.3. Solution Setup

In this study, ANSYS FLUENT was chosen because it includes a good set of tools for simulating combustion phenomena. The program goes through a series of significant steps that are required to generate a high-quality solution. In addition to defining the type of ignition, fuel, and boundary conditions, the model comprises mathematical formulas to solve problems.

5.3.1. Governing equations

Fluid flow equations govern CFD calculations and mathematical processes. These equations represent a collection of fluid properties such as mass conservation (continuity equation), mass fraction, momentum equation, and energy [34].

- Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla . \rho U = 0 \tag{2}$$

- Momentum equation

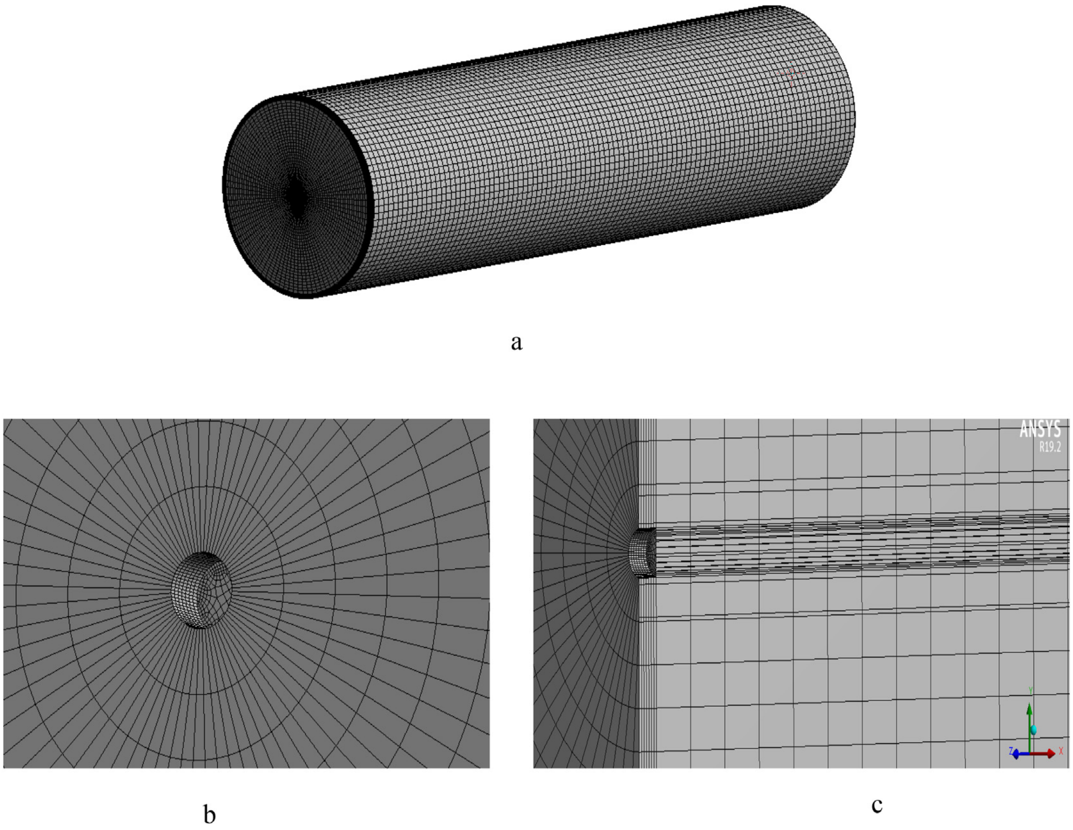
$$\frac{\delta \rho U}{\delta \mathrm{t}} + (\nabla . \rho U U) = -\nabla p + \nabla . \tau + \rho g \tag{3}$$

Here, ∇ is the partial derivative of a quantity system, $\frac{\partial \rho}{\partial t}$ represents unsteady flow, p is the static pressure, τ is the stress, and ρg is the gravitational body force.

- Energy equation

$$\begin{aligned} \frac{d(p.Et)}{dt} + \nabla . \left[p\overrightarrow{V} \left(Et + \frac{\mathrm{p}}{p} \right) \right] \\ = \nabla . \left[K.\nabla T + \sum_j h_j J_j + \left(\bar{\boldsymbol{\tau}} . \overrightarrow{\boldsymbol{V}} \right) \right] + \dot{S}e \end{aligned} \tag{4}$$

The energy equation can be used to solve for the temperature field T and heat fluxes, K is the effective conductivity, ∇T is the temperature gradient, (τ .V →) is the viscous work, and Jj is the diffusion flux of the species. The first three terms on



a

b

c

Fig. 3. Fine mesh at body and fuel and air nozzle inlet (a) 3D model (b) 3D fuel nozzle (c) 2D nozzle.

the right-hand side of this equation represent energy transfer owing to conduction, species diffusion, and viscous dissipation, respectively. Se is the source of energy (heat of the chemical reaction).

5.3.2. Turbulent model

The flow inside the combustor is turbulent; thus, the viscous model was developed. According to previous research, one of the most common turbulent models is the k-ε model; this model is practical for many flows, relatively simple to implement, and easy to converge. The model consists of two equations, i.e., for turbulent kinetic energy (k) and for the rate of turbulent dissipation (ε).

Table 3. Mesh sizing setting parameters.

Item	Final setting
Physics preference	CFD
Solver preference	fluid
Element size	30 mm
pinch tolerance	0.27 mm
Maximum size	30 mm
Number of Nodes	84,348
Number of Elements	81,286

$$\frac{\partial}{\partial t}(pk)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_K+P_b-\rho\epsilon-Y_M+S_K \tag{5}$$

$$\frac{\partial}{\partial t}(p\epsilon)+\frac{\partial}{\partial x_i}(\rho\epsilon u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right]+C_{1\epsilon}\frac{\epsilon}{k}(P_K+C_{3\epsilon}P_b)-\rho C_{2\epsilon}\frac{\epsilon^2}{k}+S_\epsilon \tag{6}$$

Here, μ_t is the eddy viscosity ($\rho C_\mu \frac{k^2}{\epsilon}$), P_b is the effect of buoyancy ($\beta g_i \frac{\mu_t}{pr_t}\frac{\partial T}{\partial x_i}$), $\beta=-\frac{1}{\rho}\left(\frac{\partial p}{\partial T}\right)_p$ is the component of the gravitational vector, Pr is the turbulent Prandtl number, which is 0.85 for a realizable k-ε

Table 4. Statistic on mesh metric for skewness.

Mesh Metric	skewness
Min skewness	3.3561e-003
Max skewness	0.51228
Mesh Metric	**Aspect Ratio**
Min	2.3279
Max	371.63
Smoothing	High
Inflation	**Smooth transition**
Transition ratio	0.272
Maximum layer	5

Table 5. Boundary condition for fuel and air.

Air inlet		Fuel inlet	
Mass flow rate kg/s 0.095438	Mass fraction O_2 0.23	type n-heptane (C_2h_7)	Mass flow rate kg/s 0.004338
T °C 677	The air/fuel ratio 0.22	Mass fraction 1	Initial pressure (atm) 1

model, and ($P_k = - \rho u_i \acute{u}_j \frac{\partial \acute{u}_j}{\partial x_i}$). In addition, model constants are calculated by numerous iterations.

$C_\mu = 0.09$, $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.9$, $\sigma_k = 1$, $\sigma_\epsilon = 1$.

5.3.3. Boundary conditions

All inlet and outlet boundaries, as well as the wall and interior body, are defined during this process, as shown in Table 5. Because the combustion process in diesel engines occurs at nearly constant pressure, two parameters are essential to specify the initial conditions for both air intake and fuel. The mass flow rate of air and fuel can be estimated using the total air-to-fuel ratio and inlet area values for each. The air temperature is determined by the compression process, and the fuel is assumed to be injected at ambient temperature.

5.3.4. Species transport: non-premixed model

Non-premixed combustion is an ANSYS FLUENT framework in which the fuel and oxidizer flows are introduced separately, and then, the fuel and oxidizer mix on the molecular scale, resulting in combustion. Many practical ignition devices, such as furnaces, steam boilers, diesel engines, liquid rocket motors, and gas turbine engines, use non-premixed combustion [26,35]. The non-premixed model is built on the basis of the simplified assumption that the fluid's thermochemical state is demonstrated as a scalar quantity known as the mixture fraction f, which can be expressed in terms of the atomic mass fraction, $f = \left(\frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}}\right)$,
where Zi denotes the elemental mass fraction, OX denotes the oxidizer stream inlet value, and fuel denotes the fuel stream inlet value. The equation is the same for all elements. Therefore, the mixture fraction is the elemental mass fraction derived from the fuel stream.

6. Results

CFD simulations generate a large amount of data; however, in this study, we focused on the most important data:

1. The maximum temperature created by combustion.
2. The mass fraction of NOx pollution for 10%, and 20% water addition to air (WIA) and fuel (W/F).
3. The amount of produced thermal and prompt NOx for 10%, and 20% water injection. In addition, we visualized the temperature distribution, which has an important role in evaluating the high-temperature concentration zones. The first step was to perform the simulation without water addition (dry case).

6.1. Water addition to air (WIA) and fuel (W/F)

In the initial scenario, n-heptane was employed as a fuel and injected at a temperature of approximately 23 °C, while water and air were mixed in various ratios of 0%, 10%, and 20% during the intake process at a temperature of 677 °C, thus introducing water to air (WIA). In the second case, we examined the effect of injecting water to fuel (W/F) using the same numerical conditions as in the previous calculation case. Tables 6 and 7 show the amounts of air and fuel used during the operation. First, the total mass flow rate of air was 0.095438 kg/s. The mass fraction of O_2 remained constant at approximately 0.23, while the N_2 mass fraction decreased owing to water addition. Second, in the case of W/F (both of O_2 and N_2), the mass fraction remained constant, while the fuel injection rate increased from 0.004338 to 0.00438 kg/s, and the H_2O flow fraction decreased to 0.0008676.

Table 6. WIA condition mass fraction and rate in Ansys.

Water mass %	Air + water Rate Kg/s	H_2O flow fraction	n-heptane Rate Kg/s	N_2 mass fraction	O_2 mass fraction
0	0.095438	0	0.0043354	0.765	0.23
10	0.095438	0.009538	0.0043354	0.75546	0.23
20	0.095438	0.019076	0.0043354	0.745924	0.23

Table 7. W/F condition mass fraction and rate in Ansys.

Water mass %	n-heptane + water Rate Kg/s	H_2O flow fraction	Air Rate Kg/s	N_2 mass fraction	O_2 mass fraction
0	0.004338	0	0.095438	0.765	0.23
10	0.00435	0.0004338	0.095438	0.75546	0.23
20	0.00438	0.0008676	0.095438	0.745924	0.23

Table 8. NOx rate and mass fraction for WIA case.

Water ratio	Temperature °C	Mass fraction NOx	No-thermal rate kgmol/m^3	No-prompt rate kgmol/m^3	NO-ppm
0%	1902	0.00441	0.000103	0.00011	4270
10%	1878	0.0042	0.000084	0.000091	4196
20%	1864	0.00397	0.0000671	0.0000855	4034

6.2. CFD simulation results

The obtained simulation profiles show the effect of water addition to air and fuel in the combustion chamber. The reduction of the thermal and prompt rates leads to reduce NOx emission in addition to the maximum temperature decrease. The formula $\left(\frac{\text{Nomole Fraction}\times10^6}{1-\text{H}_2\text{omole Fraction}}\right)$ was used to calculate the amount of produced NOx in ppm NOx.

Tables 8 and 9 show the simulation results, which include the amount of NOx in ppm and the production rate of prompt and thermal NOx. In the WIA case, increased water addition reduced the total temperature from 1902 to 1864 °C and reduced the NOx mass fraction from 0.00441 to 0.00397. Both thermal and prompt NO decreased by 34.85% and 22.27%, respectively. In the W/F case, there was a significant decrease in temperature from 1902 to 1782 °C. Furthermore, the total reductions of thermal and prompt NO were 58.9% and 72%, respectively. Compared to the WIA method, injecting water into fuel yields better results. The amount of NO decreased to 3103 ppm using this method compared to 4034 ppm for the WIA method.

All profiles presented below were obtained by CFD in ANSYS FLUENT using a 3D cylinder to achieve results that could be compared with experimental results.

6.3. Temperature profile

In terms of the temperature effects, according to the case study, the maximum temperature of combustion was 2170 °C. Numerical analysis revealed that adding 10% and 20% water to air reduced the temperature from 1902 °C to 1878 °C and 1864 °C, respectively, while adding water to fuel reduced the temperature from 1875 °C to 1782 °C upon 20% water addition, as shown in Fig. 4. The temperature was consistent throughout the chamber, and water addition to the combustion process did not have a noticeable effect on the ignition efficiency. The temperature of the wall was consistent throughout in the range of 570–670 °C.

6.4. NOx mass fraction

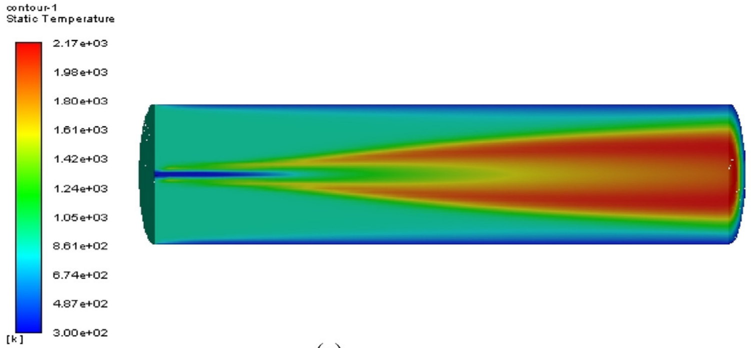
Emitted NOx comprises NO, NO_2, and nitrous oxide (N_2O), which collectively contribute to the depletion of the ozone layer and production of acid rain. ANSYS FLUENT offers three ways to generate NOx emissions: thermal, fuel, and prompt NOx. Fig. 5 shows that W/F achieves the best results compare to WIA. Injecting 20% water into air reduced the NOx mass fraction from 0.0042 to 0.00397 with a ratio of 8.3%, while injecting 20% water into fuel reduced the NOx mass fraction from 0.00364 to 0.00331 with a ratio of 23.556%.

7. Validate results

There have been a few small studies that have utilized the CFD modeling technique to assess the effect of water addition to fuel; however, the ability of these techniques to meet the requirements at a low cost and in a short period of time is critical, and it is essential to use experimental approaches

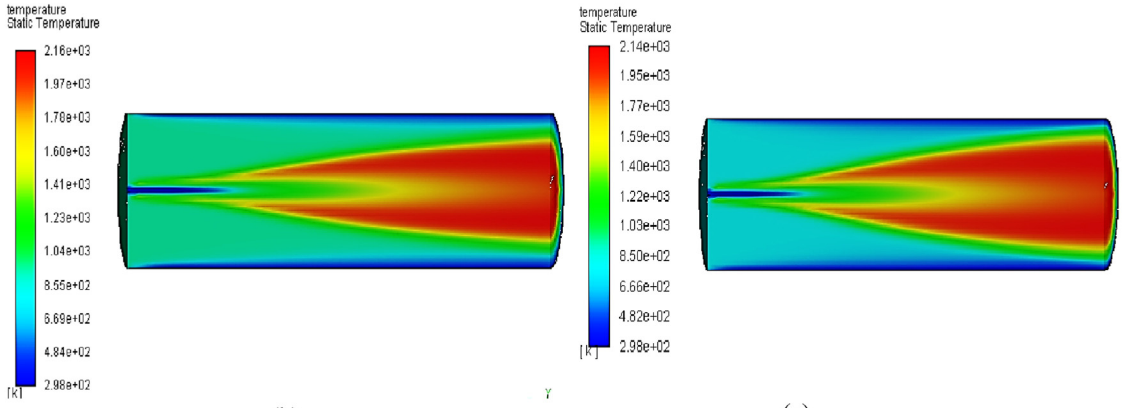
Table 9. NOx rate and mass fraction for WIF case.

Water ratio	Temperature °C	Mass fraction NOx	NO-thermal rate kgmol/m^3	NO-prompt rate kgmol/m^3	NO-ppm
0%	1902	0.00441	0.000103	0.00011	4270
10%	1875	0.00364	0.00004836	0.00006746	3341.7
20%	1782	0.00331	0.00004228	0.0000297	3103



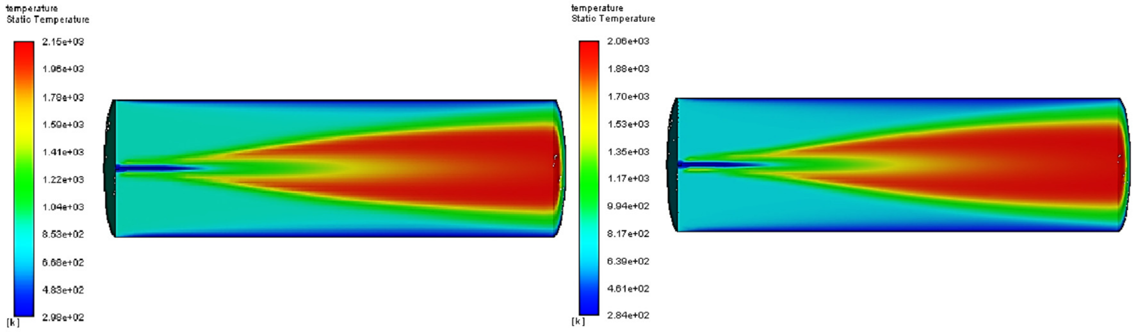
(a)

- WIA profile:



(b) (c)

- WF profile:

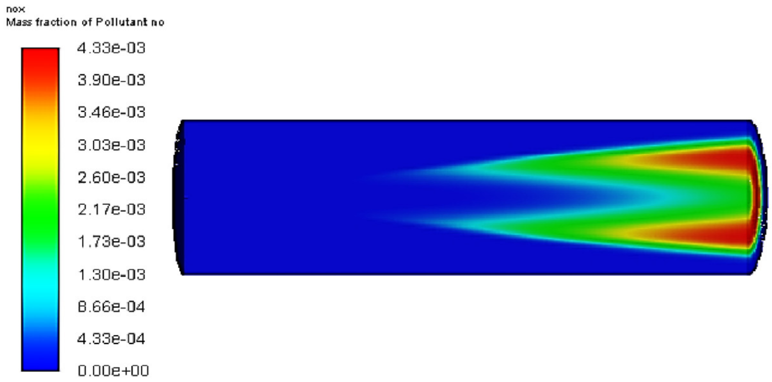


(d) (e)

Fig. 4. Result for Temperature profile: (a) with 0% water addition, (b) with 10% WIA, (c) with 20% WIA, (d) with 10% W/F, and (e) with 20% W/F.

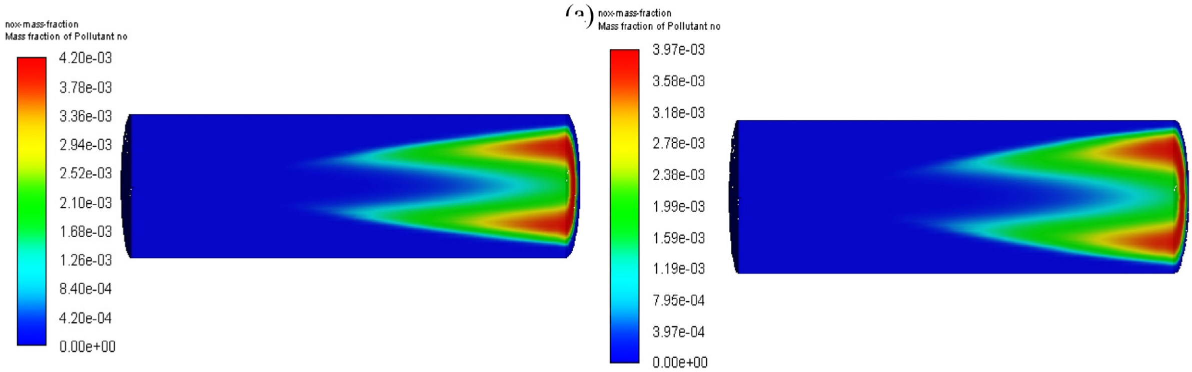
to enhance these results. Niko Samec (2000) showed an excellent example of adding water to air and fuel using n-heptane as the fuel. Table 10 shows the specifications of the diesel engine that he used [36].

Figs. 6 and 7 show a comparison of experimental results with the CFD simulation for direct water addition to air [36]. There is a small difference between the numerical and experimental results. The simulation shows that adding 20% water to air and fuel reduces NOx emissions by approximately 10% and 22%, respectively, whereas the ratios are approximately 8.9% and 21% for the experimental results.



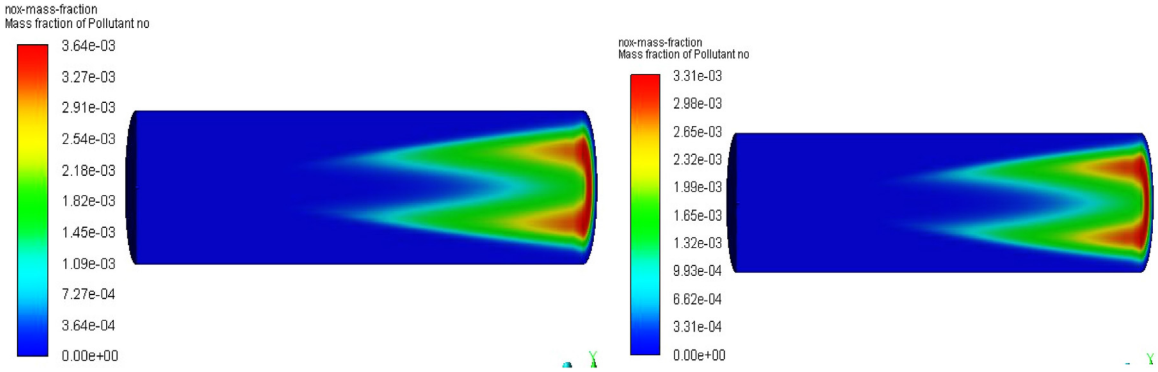
- WIA profile:

(a)



(b) (c)

- W/F profile:



(d) (e)

Fig. 5. Result for mass fraction profile: (a) with 0%WIA, (b) with 10%WIA, (c) with 20%WIA, (d) with 10%W/F, and (e) with 20% W/F.

Table 10. Test-engine specifications.

Model	TAM F4L 515FRC	Compression ratio	18:1
Capacity	7118 cm3	Valve	8
Max. Power	150 kW	Injection pump	Bosch PES 4
Max. Torque	315 Nm	Turbocharger	Holset H1E

8. Discussion and furthre studies

According to this case study, there is approximately 44,741.09 ppm of NOx emitted for each n-heptane kg/s. Figure 8 shows our comparison of the two methods (i.e., adding water to fuel and air) in terms of the decrease in NOx emission. The W/F

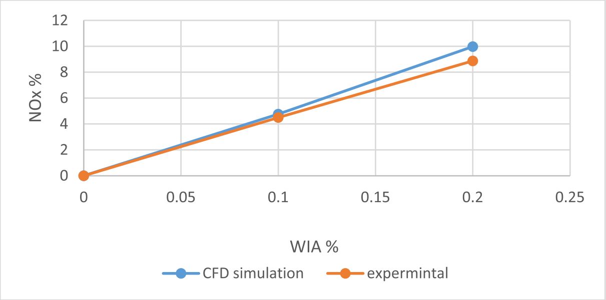


Fig. 6. NOx% reduction with WIA.

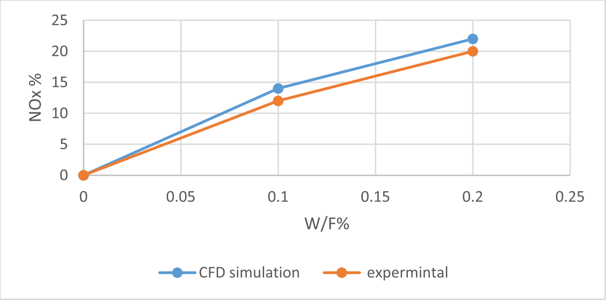


Fig. 7. NOx% reduction with W/F.

method decreased NOx emission by 27%, while the WIA method reduced it by approximately 5.5% compared to the W/F approach.

NOx is a significant air contaminant that is responsible for several environmental issues including photochemical haze, acid rain, depletion of the ozone layer, and an increase in ultraviolet radiation. Moreover, NOx can cause health problems, such as irritation of the eyes and throat, pneumonitis, pulmonary edema, and respiratory and cardiovascular diseases, when present in high concentrations. The reduction in emitted NOx depends on various interconnected factors, including the approach used to add water, the velocity and location of injection, and the fuel properties. The initial effect of adding water is linked to the fact that introducing steam to the combustion zone increases the concentration of active hydroxyl radicals (i.e., OH), which efficiently oxidize precursors to carbon black. In this study, we used diesel fuel as a reference fuel and compared the NOx emissions from the engine's exhaust using emulsified and WIA fuels. A numerical investigation of water injection showed that the addition of 20% water leads to a reduction of 23.556% in NOx emissions in combustion systems than when using a mixture of water and fuel. Figure 6 provides a comparison and shows that NOx concentration decreases as the water ratio in the fuel increases. Burning of emulsified fuels results in reduced NOx emissions compared to burning pure diesel. This occurs because the combustion of the W/F emulsion leads to a decrease in fuel consumption and subsequently reduces the temperature of the reactant mixture.

Further studies are required to expand the use of water injection in the combustion process to create heat and electricity, with the objective of creating new low-NOx technologies and devices based on reliable scientific data. In addition, it is crucial to investigate the environmental impact of alternative fuels, such as methanol and natural gas, which produce high NOx emissions. Numerical simulations are essential for realizing these goals; however, such simulations have limitations including the lack of information on chemical kinetics for non-standard fuels. Therefore, conducting thorough experimental studies on the chemical kinetics of combustion with steam injection is necessary to achieve reduced NOx emissions and complete combustion.

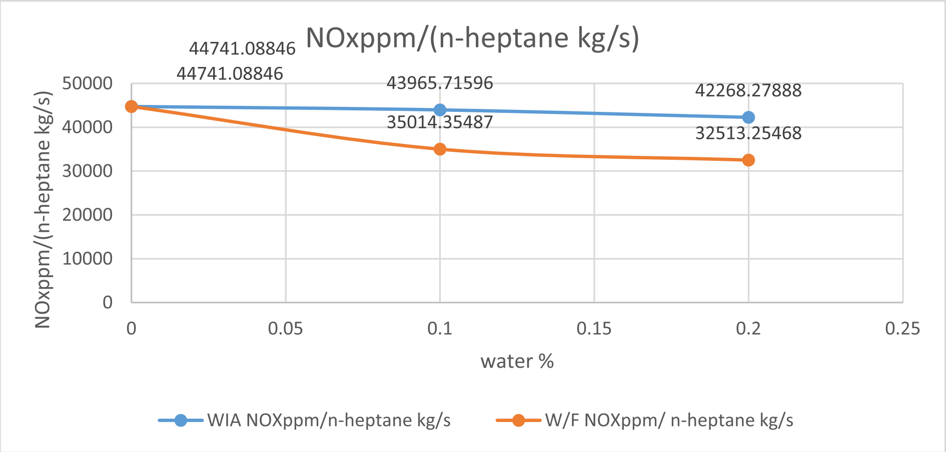


Fig. 8. NOx ppm reduction for WIA and W/F methods.

9. Conclusion

The numerical analysis presented in this paper increases the potential for using water addition to diesel engines with n-heptane as a fuel, and the obtained results demonstrate numerous options for lowering NOx emissions. The performed simulations reveal that water addition reduces total and static temperatures, both of which significantly contribute to NOx emissions. Based on this study, the following conclusions were made.

- The numerical analysis revealed that adding 20% water to air before compression reduces the temperature from 1902 °C to 1864 °C, while adding 20% water to the fuel reduces the temperature from 1875 °C to 1782 °C.
- The addition of water to the combustion chamber reduces the thermal NOx production rate by 34.85%, while the addition of water to the fuel reduces the thermal NOx production rate by 53%. These systems have a significant impact on the concentration of $^{\bullet}OH$, which decreases with an increase in the amount of added water, thereby decreasing NOx formation.
- An increase in the amount of added water lowers NOx production. According to the simulation results, the addition of 20% water reduced the total mass fraction of NOx by 10% for the WIA system and by 25% for the W/F system.
- Finally, because many studies focus on improving the effectiveness of water injection systems and studying the characteristics of the combustion chamber and soot emission, CFD simulations play an important role in improving this research with minimal time and cost commitment.

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Conflict of interest

The authors declare that they have no competing interests.

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