AL-QADISIYAH JOURNAL FOR ENGINEERING SCIENCES 17 (2024) 436–444

Contents lists available at http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

A numerical study of the effects of various diesel fuel types on the performance of single-cylinder diesel engines

Wisam Jasim Kadhim Al-Obaidi [1*], *and* ***Wasim Jamshed*** [2]

[1] *Department of Mechanical Engineering, Collage of Engineering, University of Al-Qadisiyah, Al-Diwaniyah, Iraq*

[2] *Department of Mathematics, Capital University of Science and Technology (CUST), Islamabad, Pakistan.*

A R T I C L E I N F O

Article history:

Received 27 May 2024

Received in revised form 27 August 2024

Accepted 20 December 2024

Keywords:

Diesel grades

Pollutant emissions

Combustion in diesel engines

Diesel-RK

A B S T R A C T

The present study examines numerically the combustion, performance, and emissions parameters of diesel engines powered by different grades of diesel. The Diesel-RK software version 4.3.0.189 is used to simulate the combustion process with a multi-zone model. The Iraqi diesel, EN 590, Heavy diesel, and light diesel are considered. Their energy content, sulfur, cetane number, and other additives are different, hence it's logical to observe different results. The condition of full load point is selected since the air-to-fuel ratio is minimum, hence a better comparison among the fuels is captured. The diesel EN 590 reported a lower ignition delay (9.1 deg.) due to the lower cetane number, while it is 10.8, deg. 17.4 deg., and 14.1 deg. for Iraqi diesel, heavy diesel, and light diesel respectively. Compared to other fuels considered the light diesel offered lower fuel consumption and higher thermal efficiency. The results showed less CO_2 emissions in the case of light diesel (778.3 kg/kWh), compared to heavy diesel which had an obvious rise in CO_2 emissions (817.08 kg/kWh). The difference in the density chemical structure, the results showed that Bosh smoke number (BSN) values of Iraqi, and EN 590 diesel were almost the same at 1.39, and 1.385 respectively, while the BSN of light diesel was slightly higher at 1.44 compared to 1.8 for heavy diesel. The higher NOx levels of about 2400 and 2225 ppm, respectively, were produced by Iraqi and EN 590 diesel. But out of all the fuels, heavy diesel had the lowest NOx rating, at 1000 ppm. The accuracy of the software used is validated with the results of other studies.

1. Introduction

The demand for zero emissions and highly efficient performance in diesel-engines are the focus of many research works worldwide these days. Diesel or compression engines, recognized for both endurance and good efficiency, are commonly employed in transportation (trains), industrial applications (heavy-duty machines), and power generation (generators and turbines)[1]. Nevertheless, diesel engines represent a major contributor to global warming and air pollution owing to the exhaust releases such as nitrogen oxides (NOx), hydrocarbons (HC), and carbon monoxide (CO)[2, 3]. The components of diesel fuel are (naphthene, olefins, alkanes, and aromatics) which can be represented by the carbon formula C_9–C_{27} [4]. In addition, the quality and the type of diesel depend on the density, sulfur, viscosity, distillation curve, and cetane index [4] [5]. Diesel fuel in European countries are usually known as EN 590 fuel which fits their tough standards and specifications of fuel depending on the viscosity, density, distillation properties, sulfur content, and cetane number.

* *Corresponding author.*

E-mail address: wisam.jasim@qu.edu.iq (Wisam Al-Obaidi)

https://doi.org/10.30772/qjes.2024.153932.1401

Nomenclature:

NOx	nitrogen oxides	*BSN*	Bosh smoke number
HC	hydrocarbons	EFM	The speed of transformation of an elementary fuel mass
CO	carbon monoxide	V_0	the EFM initial speed at the nozzle-injector
CO2	carbon dioxide	*V*	the EFM instantaneous speed
BTE	Brake Thermal Efficiency	*l*	the distance between the nozzle-injector and the EFM
LD	light diesel	l_m	the length of penetration of (EFM) measured to the end front of a spray
HD	heavy diesel	*PM*	Particulate Matter
UHC	unburned hydrocarbon	SE	air pollutant emission
BSFC	Brake-Specific Fuel Consumption	*Greek symbols*	
LPG		ϕ	the proportion of equivalence
EN590	Diesel fuel in European countries	Ø	a function that expresses the completion of the combustion of fuel vapor in zones

The reason behind applying these high specifications of fuel is to make sure to obtain a high-quality fuel that is compatible with advanced diesel engines, as well as improve the efficiency of combustion and minimize exhaust emissions [6] [7]. Konjević et al [8] evaluated the properties of blending diesel fuel with alcohol based on the EN590 standards. It was found that mixing a percentage (5% or 10% volume) of alcohol with diesel fuel enhances the density, distillation, and viscosity. Therefore, the blends reached the requirements of EN590 as no negative influence on the performance and emission of the engine was observed. The light diesel fuel can be characterized by low viscosity and density compared to heavy diesel. The features of using light diesel in compression engines are to improve the performance of the engine and decrease the emissions by ensuring that complete fuel combustion and good atomization are achieved. Kar et al [9]examined the use of light diesel (obtained from heavy oil) in the distribution of HC in a low-cost catalyst. The findings showed a strong impact on the HC distribution due to the light diesel and low-cost catalyst. The consistency of characteristics properties such as density, viscosity, and HC distribution of light diesel was shown to be good compared to other diesel fuels. Thus, using a low-cost catalyst was successful in obtaining light diesel from heavy oil. Mahfouz et al.[10] blended light diesel with waste cooking oil at various equivalence ratios using an oil burner. The results showed that using (20% on a mass basis) of both light diesel/cooking oil led to obtaining a high performance and low emissions compared to light diesel only. Gad et al.[11] studied the influences of blending light diesel with fuel additives at four ratios on the combustion characteristics and spray of a boiler of output power 500kW. The outcomes of the study showed that adding the additives to the light diesel decreases the emissions of CO as shown also in[12], and the local cone angle by 87.5% and 2.7% respectively. However, the additives to light diesel revealed an increase in the temperature of the exhaust and the efficiency of the combustor by (14.45%) and (80%) respectively. Expenditure and high demand for diesel fuel in developing countries lead to unpredictable rises in fuel prices. Heavy diesel fuel is cheaper than light diesel fuel, therefore, people around the world are taking into consideration switching from light to heavy diesel to reduce the pollution and expenditures of fuel[13]. A number of experiments and research have been conducted to use alternative fuels or to enhance the combustion characteristics of diesel such as using biodiesel fuel [14-16], or using a duel fuel system by adding LPG[17] [18] [19] [20]or Hydrogen[21] to fuel. Strict standards are being set globally to protect the environment by reducing the limits or controlling emissions (0.5 % sulfur[22], NOx, and other pollutants[23]). The majority of heavy diesel fuel is being used in ships and submarine engines which highly contribute to air pollution due to emissions.

Researchers have been seeking alternative engines and fuels to reduce emissions. For instance, Van Hoecke et al.[24] employed hydrogen as a fuel in marine ships. For another example, Mentese and Selcuk [25] conducted a study in Turky to examine the emissions obtained from various pollutants (cars, ships, industries) for 4 years. The results showed that the emissions of NOx and sulfur enlarged with the growth of the number of cars, trucks, and ships. Thus, the quality of the air is decreased due to the growth of the pollution produced by diesel engines. Iraq is one of the countries that uses heavy diesel fuel in small ships, agriculture pumps, heavy trucks, and electric generators[26]. Despite the increased effects of using heavy diesel on the environment (contains high sulfur of 3 % and 2.5 % in heavy and light diesel respectively), people still prefer this kind of fuel due to affordability[27]. Abollé et al.[28] performed an experimental study to examine the effects of mixing (mass basis) diesel fuel with vegetable oils on the viscosity of the diesel fuel. It was found that the viscosity was greatly affected due to the mixing of vegetable oils. Tareq and Saleh[29] conducted a study to examine the performance and emissions of diesel engines by blending light and heavy diesel with the following percentage (80% LD and 20% HD). In order to reduce the density and viscosity of the blends, a preheating process was applied to the blends before injecting the fuel into the engine. The outcomes of the study found that the (BTE) Brake Thermal Efficiency for heavy and blends fuel is lower than for light diesel. While the (BSFC) Brake Specific Fuel Consumption increased compared to the light diesel fuel. In addition, it was noticed an increase in the (UHC) unburned hydrocarbon, NOx emissions, and CO concentrations for the heavy diesel fuel compared to the light diesel. The preheating process affected in reducing the viscosity and density of the blends and enhances the combustion spray of the fuel and engine performance. This study aims to examine how the characteristics of performance, combustion, and exhaust emissions of naturally aspirated single-cylinder diesel engines are impacted by using various grades of diesel (EN590, light, heavy, and Iraqi diesel). The investigation is conducted with the use of simulation software Diesel-RK.

2. Method

The properties of the heavy, light, EN 590, and Iraqi diesel are presented in Table 1. The carbon and hydrogen contents, viscosity, heating value, and molecular weight in diesel fuels are almost similar in all fuel types. The Iraqi diesel contains 0.4 % oxygen; however, other diesel contains no oxygen in their texture. EN 590 fuel has a tiny amount of Sulphur and the highest cetane number compared to zero amount and almost the same cetane number among the other fuels.

Table 1: Properties of Diesel fuels used in this study [3, 6, 30]

Property	Iraqi diesel	Diesel EN590	Heavy diesel	Light Diesel
Carbon %	87.0	86.2	87.0	86.5
Hydrogen %	12.6	13.7	13.0	13.4
Oxygen%	00.4	00.0	00.0	00.0
Sulpher %	00.0	0.03	00.0	00.0
Density (kg/m3)	830	810	981	838.3
Viscosity (Pa.s)	0.003	0.003	0.003	0.003
Cetane number	48.0	53.3	46.0	48.0
Heating value (MJ)	42.5	43.1	40.6	42.86
Molecular weight	190.0	182.0	190.0	190.0

2.1 Numerical analysis

A diesel-RK solver version 4.3.0.189 was hired to solve the governing equations and a model of multizone combustion was employed and formulated in this work [31, 32].

2.1.1 Conservation equations

As shown in Eq. 1, the total mass flow across an open system is conserved.

$$\frac{dm}{dt} = \sum_i m_i \quad (1)$$

where mi denotes the mass flow rate of each species

The analytical equation for species conservation is shown in Eq. (2):

$$Y_i = \sum_i \frac{m_i}{m} \quad (2)$$

Where Yi represents the mass fraction of each species. Open thermodynamic systems can be expressed by the subsequent standard energy formula:

$$\frac{d(mu)}{dt} = -p\frac{dv}{dt} + \frac{dQ_{ht}}{dt} + \sum_i m_i h_i \quad (3)$$

Equation (3) indicates the energy change rate on the left side, while the entropy flux, heat transfer rate, and displacement work rate are shown on the right side.

2.1.2 Model of Spray Assessment

The speed of transformation of an elementary fuel mass, (EFM), between injectors during a small time_step and then directed to the spray-tip. The EFM can be represented by Equation (4) and shown in Fig. 1.

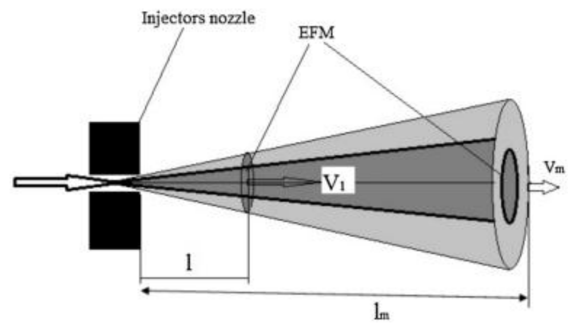

Figure 1. Schematic representation of the fuel-spray [33].

$$\left[\frac{V}{V_o}\right]^{3/2} = 1 - \frac{1}{l_m}\, 1 \quad (4)$$

Where: V– the EFM instantaneous speed, V_o- the EFM initial speed at the nozzle-injector, l- the current_distance between the nozzle-injector and the EFM, l_m– the length of penetration of (EFM) measured to the end of a spray. The Eq. 4 is partially solved as:

$$3l_m\left[1 - \left[1 - \frac{l}{l_m}\right]^{0.333}\right] - V_o\tau_k = 0 \quad (5)$$

Where:(τ_k) travel time for the (EFM) to amount to the length (l)from the nozzle-injector when the (EFM) is stopped at a spray-tip, then $l = l_m$ and $\tau_k = \tau_m$. Where (τ_m) is the travel time for the (EFM) to amount to the spray's front before ending. Eq. 5 can be rewriter as:

$$l_m = V_o\,\frac{\tau_m}{3} \quad (6)$$

By employing Eqs. 4 to 6 the present speed and the (EFM) length can be achieved as:

$$V = V_o\left[1 - \frac{\tau_k}{\tau_m}\right]^2 \quad (7)$$

$$l = l_m\left[1 - \left[1 - \frac{\tau_k}{\tau_m}\right]^3\right] \quad (8)$$

Several dimensionless parameters are introduced to calculate the geometry of the spray which account for the design parameters of the injector and physical properties of the fuel, namely Weber number; square ohenzorge number. In modeling the fuel spray behavior, it is assumed that its evolution occurs in two phases, namely initial (a) and main (b). The boundary between these two phases is denoted by lg, and the period of time for the jet to reach this boundary by tg. Further details can be found in Mahkamov K. et al[34].

2.1.3 Model of Heat Release

The following two assumptions are made to calculate the heat release rate in the cycle [35]:

1. The speed of the fuel evaporation in each zone is equal to the sum of the speeds of evaporation of the separate fuel droplets.
2. The ratio of evaporation constant to initial droplet diameter is constant during the whole process of the fuel injection.

The process of combustion can be split into four stages, in which each stage has particular chemical and physical characteristics restricting the burning rate-speed. Stages are described below [36]:

1. The period of the ignition delay stage is obtained by:

$$\tau = \sqrt{\frac{T}{P}} * e^{\left(\frac{E_a}{8{,}312T} - \frac{70}{CN+25}\right)} * 3.8 * 10^{-6} * (n * 1 - 1.6 * 10^{-4}) \quad (9)$$

2. Stage of Premixed-combustion, where the combustion-process of the blend of air and the fuel-vapor occurred by the combustion:

$$\frac{dx}{dt} = \varphi_1 \left(\frac{d\sigma_u}{d\tau}\right) + \varphi_o * \left[(\sigma_{ud} - x_o)(0.1\sigma_{ud} + x_o)A_o \left(\frac{m_f}{V_i}\right)\right] \quad (10)$$

3. Stage of diffusive-combustion where the blended fuel is injected and directly combusted:

$$\frac{dx}{d\tau} = \varphi_2 \left((\sigma_u - x)(\emptyset - x) * A_2 \left(\frac{m_f}{V_c}\right) \right) + \varphi_1 (\frac{d\sigma_u}{d\tau}) \quad (11)$$

4. Late burning stage (the fuel burning after the completed injection):

$$\frac{dx}{d\tau} = (1 - x)(\varepsilon_b \emptyset - x) * \varphi_3 K_T A_3 \quad (12)$$

$\varphi_3 = \varphi_2 = \varphi_1 = \varphi_o$ Representing a function that expresses the completion of the combustion of fuel vapor in zones:

$$\phi = 1 - (A_1/\varepsilon_b \emptyset - x) \frac{dx}{dt} \left\{ r_v + \sum_{i=1}^{m_w} \left[r_{wi} * 300 * e^{\left(\frac{-16000}{2500 + r_{wi}}\right)} \right] \right\} \quad (13)$$

Where : (ε_b) represents the efficiency of using air, (r_v) describes the proportion of relative-evaporation in the environment-zones and front, (ϕ) describes the proportion of equivalence, (r_{wi}) describes the proportion of the related-evaporation during different zones inside wall-surface flow.

2.1.4 Model of NO_x formation

Normally, the emissions of NOx consist of a mixture of both NO and NO_2. The current work hired the mechanism of (Zel'Dovich) within the solver of the Diesel-RK program to evaluate the emissions of Nox [37]:

$$O_2 \leftrightarrow 2O \quad (14)$$

$$O + N_2 \leftrightarrow NO + N \quad (15)$$

$$O_2 + N \leftrightarrow NO + O \quad (16)$$

The concentration of atomic-oxygen influences the reaction-rate as shown in Eq. 16. The concentration volume of NO is calculated using the equation:

$$\frac{d[NO]}{d\theta} = \frac{e^{-38020/T_z} [N_2]_e [O]_e \left(1 - \left(\frac{[NO]}{[NO]_e}\right)^2\right) * 2.33 * 10^7 P}{RT_z \left[1 + \left(2365/T_z\right) e^{3365/T_z} [NO] / [O_2]_e \right]} \left[\frac{1}{rps}\right] \quad (17)$$

2.1.5 Modelling of Soot concentration

The definition of soot is a tiny black (carbon particle) in the vapor carrier existence, that is produced due to the incomplete combustion-process of hydrocarbon. Modeling of soot can be found in detail in the literature [38]. The concentration of soot in the exhaust relative to the normal operating conditions is described as:

$$[C] = \int_{\theta_B}^{480} \frac{d[C]}{d\tau} \frac{d\theta}{6n} \left[\frac{0.1}{P}\right]^{\gamma} \quad (18)$$

Hartidge smoke level was determined using the equation (19):

$$\text{Hartidge} = 100 * \left[1 - e^{(-24226[C])} * 0.9545\right] \quad (19)$$

Equation (20) was employed to calculate the Particulate Matter [PM] as a function of [BSN]:

$$[PM] = 565 * \left[\ln \frac{10}{10 - Bosch}\right]^{1.206} \quad (20)$$

The combination of pollutants [PM] and [Nox] that describes the air pollutant emission [SE] [39]:

$$SE = C_{PM} \left[\frac{PM}{0.15}\right] + C_{NO} \left[\frac{NO_x}{7}\right] \quad (21)$$

2.1.6 Software Validation

The accuracy of the solver (Diesel-RK) is validated by comparing the obtained results with the work performed by A.J. Reiter[40]. Table.2 shows the operating conditions and engine features used in the validation part. The curve of pressure evolution during per crank angle is seen in Fig. 2. The used engine with turbocharged is turned to the mode of dual-fuel working on (60%) diesel and (40%) ammonia based on energy. The current work reveals the same tendency with an inconsiderable deviation of about (5%) compared to the literature [40]. The value of ultimate pressure is (7.8393 Mpa) happens at (6 deg.) ATDC meanwhile the current study showed a pressure of (7.466 Mpa) at (5 deg.) ATDC.

The CO_2 volumetric concentration and how it is influenced by the replacement of NH_3 in diesel is illustrated in Fig. 3; in which both curves reveal similar behavior with insignificant variance. In terms of using mono-fuel of 100% diesel, the concentration of CO_2 is shown (2.083%) deviation compared to the results by A.J. Reiter [40]. While using a mixture fuel of (60% diesel) and (40% NH_3) in the mode of dual-fuel the deviation in the results is shown (6%). Thus, from the comparison above it can be considered that the solver is a reliable and functional tool for solving the process of combustion in compression engines.

Table 2. Features of the engine employed for the validation process [40]

Technical details	Information
Engine type	In-line, 4-stroke
Engine model	4045TT068
Compression ratio	17:1
Bore and stroke	106 x 127 (mm)
Injection system	Standyne DB4 rotary pump
Aspiration	Turbocharged
Fuel	NH_4OH+Diesel
Engine speed	1000 rpm
Peak power @2100 rpm	66 kW
Peak torque @1300 rpm	387 N.m

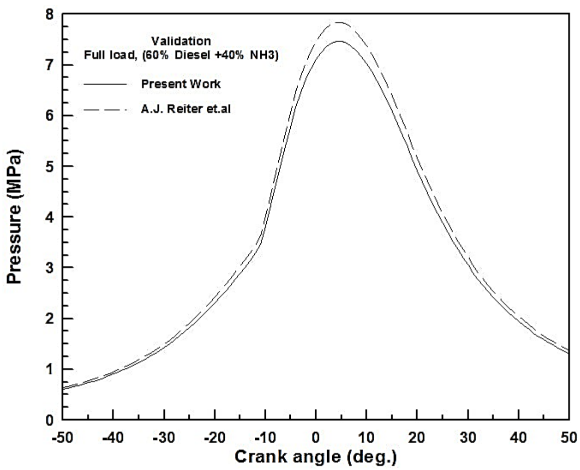

Figure 2. Validation and comparison of cylinder pressure profiles

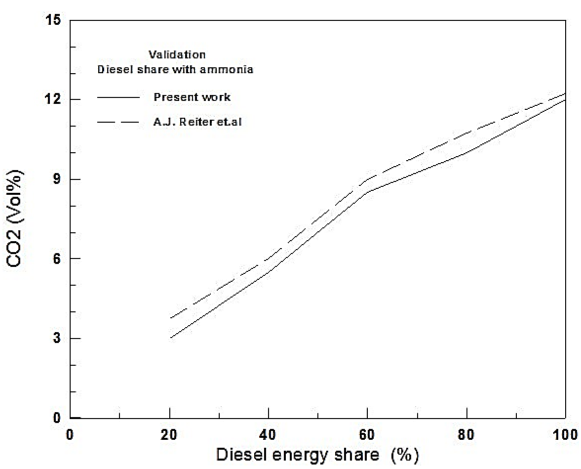

Figure 3. Validation and comparison of (CO_2) concentration per (% diesel energy).

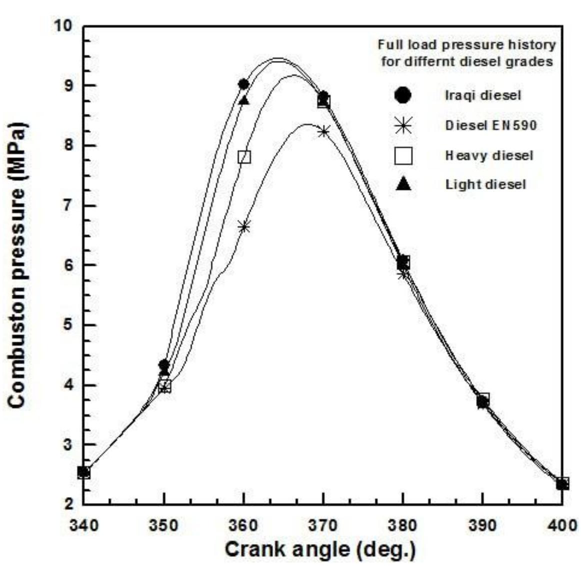

Figure 4. Illustrates the trends of combustion pressure per crank angle for different diesel fuels.

The software generates an additional set of validations to confirm the results of other researchers. It uses the same configurations and states in its databases are compared to those obtained in **[41] [42] [43]** under the same operating circumstances for the current study. The technical specifications for the engines used for validation are listed in Table 3. The engines run on regular diesel fuel. The pressure progression and the spray form in relation to the crank angle are shown in Figures 5 and 6. With a real little change, the comparison shows an attractive convergence. A little discrepancy has been noted. Diesel-RK is a reliable tool for simulating the combustion process in internal combustion engines, as evidenced by its minimum variation percentage.

Table 3. Specifications of three engines setup used for validation [41] [42] [43]

Test facility	Set-up1 Kirloskar	Set-up 2 Kirloskar TV1	Set-up 3 Legion Brothers
Engine type	Single-cylinder 4-stroke, CI	single-cylinder 4-stroke, CI engine	single-cylinder 4- stroke, CI engine
Bore x Stroke	87.5 mm x 110 mm	87.5 mm x 110 mm	80mm x 110 mm
Cooling system	Air-cooled	Air-cooled	Water cooled
Comp. ratio	17.5:1	17.5:1	17.5:1
Rated output	7 BHP @1500 rpm	5.2 kW@ 1500 rpm	3.7 kW @1500 rpm
Injection pressure	200 bar	160 bar	200 bar
Injection timing	23º BTDC	20º BTDC	23º BTDC

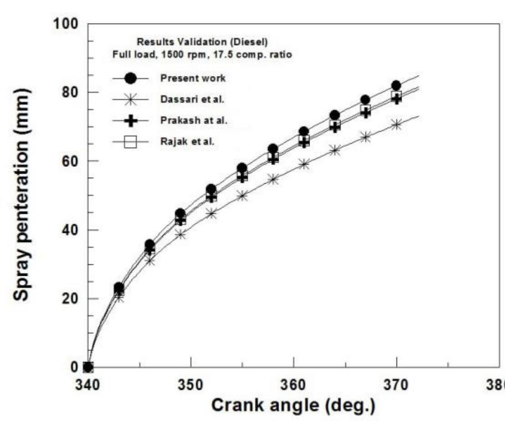

Figure 5. Validation of spray diffusion versus crank angle.

3. Result and Discussion

The grade of diesel fuel can significantly impact the combustion, performance, and emissions of diesel engines. The investigation of combustion, performance, and emissions are explained below:

3.1 Combustion Study

The history of combustion pressure through a 60º crank angle from 340º to

400^0 at full load for all tested fuels is shown in Fig. 4. This period has been chosen since significant changes occurred in this duration. It is apparent that Iraqi diesel has an earlier start of combustion followed by light diesel, and then heavy diesel and diesel EN590 respectively. The difference in the Cetane number affects the ignition delay higher Cetane number leads to shorter ignition delay [44]. The peak value is recorded for Iraqi diesel 9.462 MPa at 364º while diesel EN590 reported a lower peak value (8.365 MPa at 368º) than other grades. The difference in the energy content is responsible for this trend.

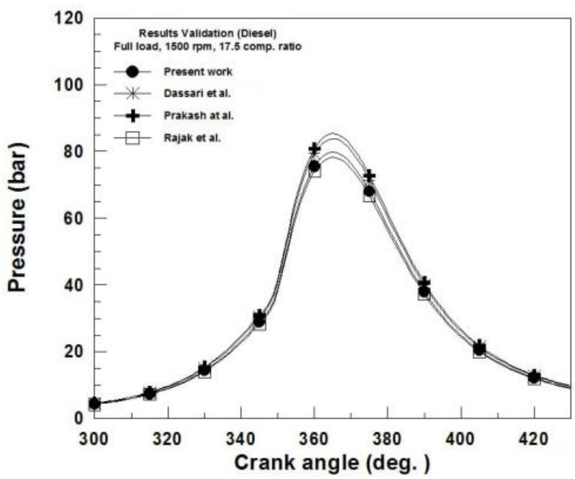

Figure 6. Validation of cylinder pressure versus crank angle

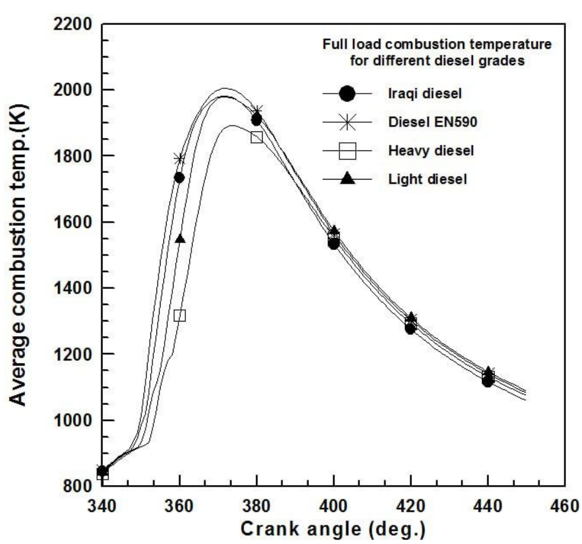

Figure 7. Average combustion temperature against crank angle.

Figure 7 Illustrates the profile of average combustion temperature at full load for various diesel fuels. It can be seen that all grades have similar trends and they are different in the peak value and initiation of combustion. The peak average combustion temperatures for Iraqi diesel, light diesel, EN590, and heavy one are: 1982 K, 1979 K, 2005 K, and 1892.5 K respectively. Relative to all grades tested, heavy diesel recorded the lowest peak combustion temperature compared to other diesel fuels.

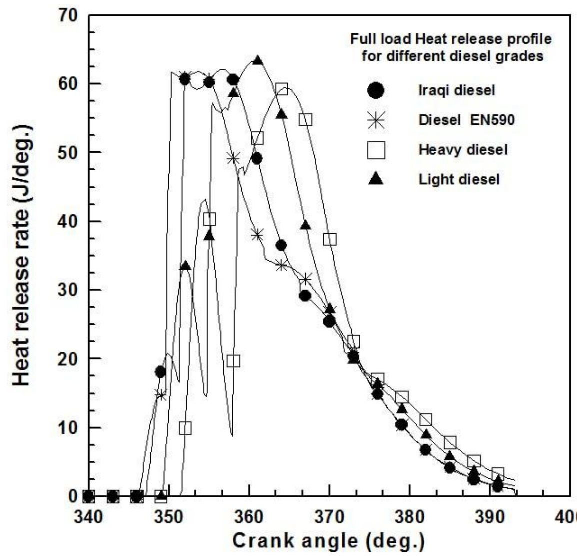

Figure 8. Illustrates the heat release rate values vs crank angle

The distribution of heat release per crank angle is presented in Fig. 8. It is observed that from 345 to 360-degree crank angle, significant fluctuations happened for all fuels under study. For better capturing the trends of curves the calculations are done per 0.2 crank angle. The peak rates of 61.85 J/deg at 353.8º, 61.07 J/deg. at 352.2, 57.15 J/deg. at 355.4º and 43.32 J/deg. at 354.4 for EN590, Iraqi diesel, Light and heavy diesel respectively. The difference in the lower heating values among tested grades is the main reason for this behavior [16]. Another important combustion parameter (ignition delay) is explained in Fig. 9. Simply it can be defined as the time difference between the start of combustion and the start of injection[45]. The grades of diesel are essentially differentiated by their cetane number, which is a measure of the ignition quality of fuel. It is observed from Fig. 9. that heavy diesel fuel offers a maximum ignition delay compared to other fuels; this may be due to the low cetane number for diesel compared to other fuel blends. The ignition delay for Iraqi diesel is 10.8 deg. while other grades offer 9.1 deg., 17.4 deg., and 14.1 deg. for diesel EN590, heavy diesel, and light diesel respectively.

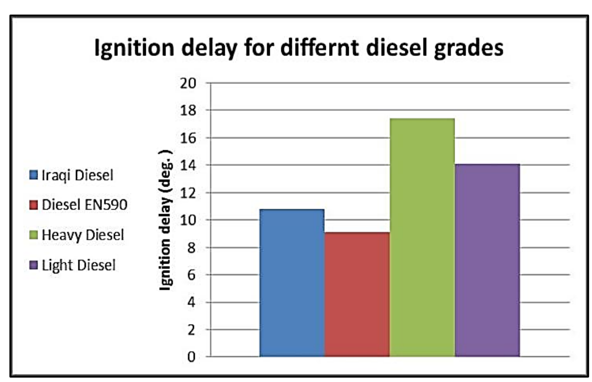

Figure 9. Illustrates the ignition delay for various diesel fuels.

3.2 Performance study

BSFC values were compared for Iraqi diesel, EN 590, heavy diesel, and light diesel in Fig. 10. The BSFC for heavy diesel is higher when compared to other blends due to the minimum energy content in the fuel. Correspondingly the BSFC for Iraqi diesel, diesel EN590, heavy and light diesel are 0.25131kg/kWh, 0.24961 kg/kWh, 0.25358 kg/kWh, and 0.24285 kg/kWh. The obtained values of BTE for different diesel grades are presented in Fig. 11. The results showed that heavy diesel has a lower BTE value compared to other fuels. The light diesel offers a higher value of BTE. Modern light diesel fuels have lower sulfur content, which reduces the formation of sulfur dioxide during combustion. Lower sulfur levels can lead to reduced emissions and potentially higher thermal efficiency. While Iraqi diesel and diesel EN590 recorded 33.706% and 34.586%, other grades heavy and light recorded 33.461%, and 34.968 respectively.

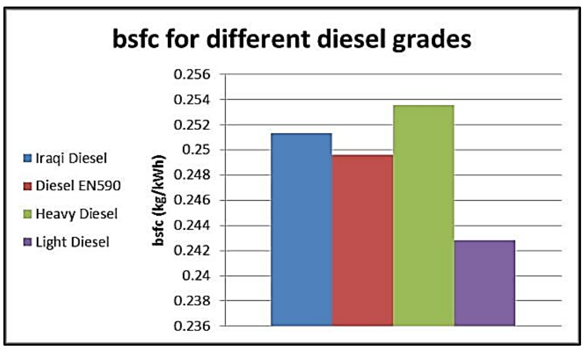

Figure 10. BSFC values for various diesel fuels.

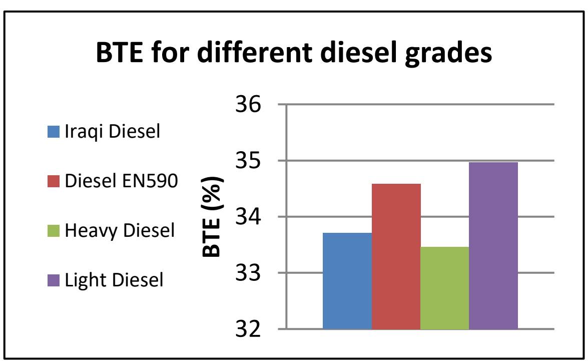

Figure 11. Values of BTE for different diesel grades.

3.3 Emission study

It is imperative to acknowledge that the BSN is not the exclusive criterion for assessing the quality of diesel fuel. Nitrogen oxides (NOx), Particulate matter (PM), and other emissions including, hydrocarbons (HC), carbon dioxide (CO_2), and carbon monoxide (CO) are also significant for air quality and environmental effects. The CO_2, Bosch smoke number (BSN), and NOx are selected to specify how using different diesel grades can influence the emissions of diesel engines. The amount of CO_2 emitted by burning different types of diesel fuel is shown in Fig. 12. The heavy diesel emits more CO_2 compared to other grades followed by Iraqi diesel then Diesel EN590, and light diesel showed less CO_2. Higher density, heavier fuels might contain more carbon, which could lead to increased CO_2 emissions. The CO_2 values for the tested fuels are 809.78 kg/kWh, 797.46 kg/kWh, 817.08 kg/kWh, and 778.3 kg/kWh corresponding to Iraqi diesel, diesel EN590, heavy diesel, and light diesel.

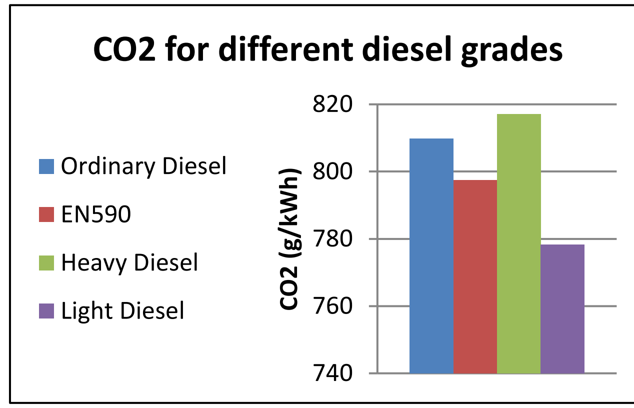

Figure 12. CO2 values for different diesel grades

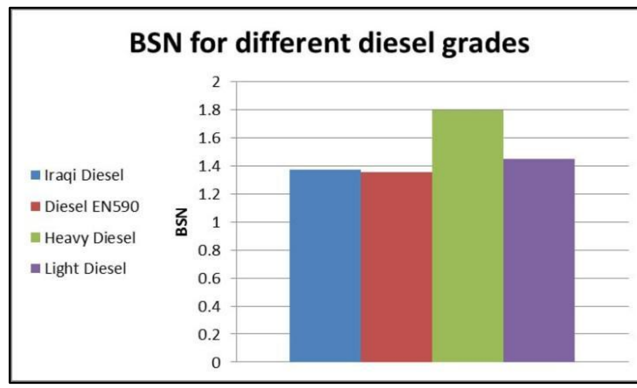

Figure 13. BSN values for different diesel grades.

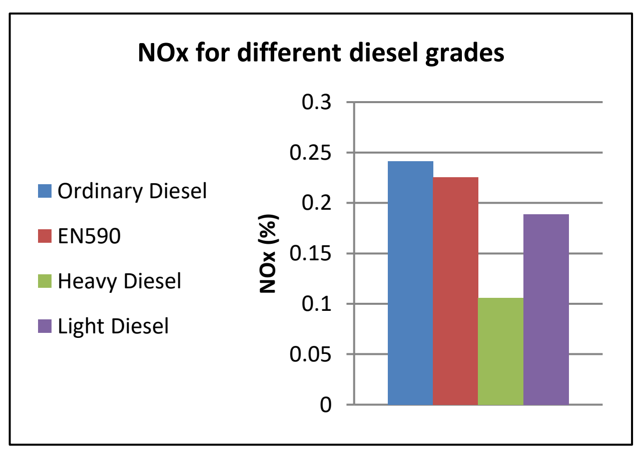

Figure 14. NOx values for diesel fuels.

Figure 13 displays the BSN values for the tested diesel fuels. The findings revealed that heavy diesel produces smoke higher than Iraqi, EN 590, and light diesel due to the higher density and lower volatility may not vaporize as easily, leading to incomplete combustion and higher smoke emissions. Another important point is the lower ratio of Hydrogen to carbon (H/C) compared to other grades [46]. The results showed BSN values of Iraqi, and

EN 590 were almost the same at 1.39, and 1.385 respectively, while the BSN of light diesel was slightly higher at 1.44 compared to 1.8 for heavy diesel. Fig. 14 shows a comparison of the NOx values for different diesel fuels, as it is crucial for periodic inspection of the vehicles[47]. Based on the results obtained Iraqi and EN 590 diesel produced higher NOx values of almost 2400 and 2225 ppm respectively. However, heavy diesel produced the lowest NOx value of 1000 ppm among all the fuels. The combustion temperature and oxygen content have a direct relationship with NOx formation [48]. Since heavy diesel has a lower combustion temperature as seen in Fig 7., hence it is logical to observe lower NOx emissions than all other tested fuels

4. Conclusion

In this investigation, the impact of employing different grades of diesel fuels (light, heavy, EN590, and Iraqi) and their influence on combustion, performance, and emissions was studied. The conclusions obtained from this investigation are as follows:

1) The profiles of combustion pressure showed that all grades followed the same trend with variance in the top and low peak values where the Iraqi diesel obtained the peak value of 9.462 MPa at 364° and diesel EN590 obtained the lowest peak value of 8.365 MPa at 368° compared to other grades.
2) Trends of average combustion temperature for all grades showed good similarity despite the difference in the peak values and the initiation of combustion. The Iraqi diesel was seen to have the ultimate peak value of combustion temperature of 1982 K while the lowest peak value was noticed at the heavy diesel of 1892.5 K.
3) At 0.2 crank angle, the peak value of heat release dropped from the top to the low values for the EN590, Iraqi diesel, Light, and heavy diesel respectively.
4) Heavy diesel performs a maximum ignition delay (17.4 deg) compared to other diesel fuels as follows: (light diesel/ 14.1 deg.), (Iraqi diesel/10.8 deg), and (diesel EN590/ 9.1 deg).
5) Compared to other grades, heavy diesel recorded the maximum BSFC and the lowest BTE values of 0.25358 kg/kWh and 33.461% respectively. However, light diesel obtained the lowest BSFC and the maximum BTE values of 0.24285 kg/kWh and 34.968 respectively.
6) An apparent increase in the emissions of CO_2 (817.08 kg/kWh) and BSN of (1.8) values for the heavy diesel compared to other grades followed by Iraqi diesel then Diesel EN590, and light diesel showed less CO_2 (778.3 kg/kWh) and BSN of 1.44.
7) In terms of NOx values, Iraqi and EN 590 diesel produced higher NOx values of almost 2400 and 2225 ppm respectively. However, heavy diesel produced the lowest NOx value of 1000 ppm among all the fuels.
8) Studying the benefit factor for various grades of diesel is suggested in the upcoming future works.
9) An optimization study is suggested to investigate which grade of diesel is the best one to impact the thermal characteristics of the engine.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors would like to acknowledge Dr Mohamed F. Al-Dawody for his valuable guidance and support in achieving this work.

REFERENCES

[1] Musthafa, M.M., et al., *A comparative study on performance, combustion and emission characteristics of diesel engine fuelled by biodiesel blends with and without an additive.* Fuel, 2018. **225**: p. 343-348. DOI: http://10.1016/j.fuel.2018.03.147.
[2] Zhang, Z., et al., *Investigation on combustion, performance and emission characteristics of a diesel engine fueled with diesel/alcohol/n-butanol blended fuels.* 2022. **320**: p. 123975. DOI: http://dx.doi.org/10.1016/j.fuel.2022.123975.
[3] Zhang, Y., et al., *A Comprehensive Review of the Properties, Performance, Combustion, and Emissions of the Diesel Engine Fueled with Different Generations of Biodiesel.* 2022. **10**(6): p. 1178. DOI: http://dx.doi.org/10.3390/pr10061178.
[4] Demirbas, A. and H.S. Bamufleh, *Optimization of crude oil refining products to valuable fuel blends.* Petroleum Science and Technology, 2017. **35**(4): p. 406-412. DOI: 10.1080/10916466.2016.1261162.
[5] Bolf, N., G. Galinec, and T. Baksa, *Development of a soft sensor for diesel fuel quality estimation.* Chemical Engineering and Technology, 2010. **33**(3): p. 405-413. DOI: 10.1002/ceat.200900435.
[6] Murphy, F., et al., *The evaluation of viscosity and density of blends of Cyn-diesel pyrolysis fuel with conventional diesel fuel in relation to compliance with fuel specifications EN 590:2009.* Fuel, 2012. **91**(1): p. 112-118. DOI: https://doi.org/10.1016/j.fuel.2011.06.032.
[7] Ulberth-Buchgraber, M., J. Charoud-Got, and A. Held, *Certified reference materials for effective automotive diesel fuel testing.* Fuel, 2021. **286**: p. 119367. DOI: https://doi.org/10.1016/j.fuel.2020.119367.
[8] Konjević, L., et al., *A comprehensive study on application properties of diesel blends with propanol, butanol, isobutanol, pentanol, hexanol, octanol and dodecanol.* Energy, 2023. **262**: p. 125430. DOI: https://doi.org/10.1016/j.energy.2022.125430.
[9] Kar, Y., D.Ş. Göksu, and Y. Yalman, *Characterization of light diesel fraction obtained from upgraded heavy oil.* Egyptian Journal of Petroleum, 2018. **27**(4): p. 1301-1304. DOI: https://doi.org/10.1016/j.ejpe.2018.08.001.
[10] Mahfouz, A., et al., *Comparative study of combustion characteristics and exhaust emissions of waste cooking-diesel oil blends.* Ain Shams Engineering Journal, 2018. **9**(4): p. 3123-3134. DOI: https://doi.org/10.1016/j.asej.2018.03.004.
[11] Gad, M.S., A. Mahfouz, and A. Emara, *Spray and combustion characteristics for light diesel/waste cooking oils blended with fuel additives inside an industrial boiler.* Fuel, 2021. **286**: p. 119247. DOI: https://doi.org/10.1016/j.fuel.2020.119247.
[12] Millo, F., et al., *A fundamental study of injection and combustion characteristics of neat Hydrotreated Vegetable Oil (HVO) as a fuel for light-duty diesel engines.* Fuel, 2025. **379**: p. 132951. DOI: https://doi.org/10.1016/j.fuel.2024.132951.
[13] Hao, Y., et al., *Numerical simulation on structural optimization design of combustion chamber of high strength diesel engine.* Energy Sources, Part

A: Recovery, Utilization and Environmental Effects, 2022. **44**(4): p. 9682-9702. DOI: 10.1080/15567036.2022.2136796.

[14] Akbarian, E. and B. Najafi, *A novel fuel containing glycerol triacetate additive, biodiesel and diesel blends to improve dual-fuelled diesel engines performance and exhaust emissions.* Fuel, 2019. **236**: p. 666-676. DOI: 10.1016/j.fuel.2018.08.142.

[15] Dhahad, H.A., et al., *Influence of fuel injection timing strategies on performance, combustion, emissions and particulate matter characteristics fueled with rapeseed methyl ester in modern diesel engine.* Fuel, 2021. **306**. DOI: 10.1016/j.fuel.2021.121589.

[16] F. Al-Dawody, M. and s.K. Bhatti, *Effect of variable compression ratio on the combustion, performance and emission parameters of a diesel engine fuelled with diesel and soybean biodiesel blending.* World Applied Sciences Journal, 2014. **30**: p. 1852-1858. DOI: 10.5829/idosi.wasj.2014.30.12.338.

[17] Musthafa, M.M., *A comparative study on coated and uncoated diesel engine performance and emissions running on dual fuel (LPG – biodiesel) with and without additive.* Industrial Crops and Products, 2019. **128**: p. 194-198. DOI: 10.1016/j.indcrop.2018.11.012.

[18] Talib Hashem, G., M.F. Al-Dawody, and I.E. Sarris, *The characteristics of gasoline engines with the use of LPG: An experimental and numerical study.* 2023. **18**: p. 100316. DOI: 10.1016/j.ijft.2023.100316.

[19] Al-Dawody, M.F., et al., *Thermal characteristics of gasoline engine powered by petrol and LPG under variable speed, compression ratio.* Australian Journal of Mechanical Engineering, 2024. DOI: 10.1080/14484846.2024.2366612.

[20] Al-Tayyar, M.A., et al. *Premixed Flame Characteristics for LPG/Air Mixture With CO2 Dilution*. in *AIP Conference Proceedings*. 2023. DOI: 10.1063/5.0182428

[21] Chaichan, M.T., *Performance and emission characteristics of CIE using hydrogen, biodiesel, and massive EGR.* International Journal of Hydrogen Energy, 2018. **43**(10): p. 5415-5435. DOI: 10.1016/j.ijhydene.2017.09.072

[22] Yue, Y., Y.J.S.E.T. Ying, and Assessments, *Real option analysis for emission reduction investment under the sulfur emission control.* 2021. **45**: p. 101055

[23] Yue, Y. and Y. Ying, *Real option analysis for emission reduction investment under the sulfur emission control.* Sustainable Energy Technologies and Assessments, 2021. **45**. DOI: http://dx.doi.org/10.1016/j.seta.2021.101055.

[24] Van Hoecke, L., et al., *Challenges in the use of hydrogen for maritime applications.* Energy and Environmental Science, 2021. **14**(2): p. 815-843. DOI: 10.1039/d0ee01545h

[25] Mentese, S. and B. Selcuk, *Assessment of ambient air quality, meteorological parameters, and emission source characteristics of Çanakkale, Turkey.* International Journal of Environmental Science and Technology, 2022. **19**(2): p. 1025-1040. DOI: 10.1007/s13762-021-03494-w.

[26] Ahmed, W.K., et al., *Environmental impact of using generators in the university of technology in Baghdad, Iraq.* 2020. **6**(6): p. 272-281. DOI: http://dx.doi.org/10.18186/thermal.822496.

[27] Chaichan, M.T., H.A. Kazem, and T.A. Abed, *Traffic and outdoor air pollution levels near highways in Baghdad, Iraq.* Environment, Development and Sustainability, 2018. **20**(2): p. 589-603. DOI: 10.1007/s10668-016-9900-x.

[28] Abollé, A., L. Kouakou, and H. Planche, *The viscosity of diesel oil and mixtures with straight vegetable oils: Palm, cabbage palm, cotton, groundnut, copra and sunflower.* Biomass and Bioenergy, 2009. **33**(9): p. 1116-1121. DOI: https://doi.org/10.1016/j.biombioe.2008.01.012

[29] Tariq, A.I. and A.M. Saleh, *An experimental investigation into the combustion properties, performance, emissions, and cost reduction of using heavy and light fuel oils.* Case Studies in Thermal Engineering, 2023. **44**: p. 102832. DOI: https://doi.org/10.1016/j.csite.2023.102832.

[30] Guido, C., et al., *Chemical/Physical Features of Particles Emitted from a Modern Automotive Dual-Fuel Methane–Diesel Engine.* Energy & Fuels, 2018. **32**(10): p. 10154-10162. DOI: https://doi.org/10.1021/acs.energyfuels.8b01011.

[31] Al-Dawody, M.F. and S.K. Bhatti, *Optimization strategies to reduce the biodiesel NOx effect in diesel engine with experimental verification.* Energy Conversion and Management, 2013. **68**: p. 96-104. DOI: https://doi.org/10.1016/j.enconman.2012.12.025

[32] Al-Dawody, M.F. and M.S. Edam, *Experimental and numerical investigation of adding castor methyl ester and alumina nanoparticles on performance and emissions of a diesel engine.* Fuel, 2022. **307**: p. 121784. DOI: https://doi.org/10.1016/j.fuel.2021.121784.

[33] Al-Dawody, M.F. and S. Bhatti, *Optimization strategies to reduce the biodiesel NOx effect in diesel engine with experimental verification.* Energy conversion and management, 2013. **68**: p. 96-104. DOI: http://dx.doi.org/10.1016/j.enconman.2012.12.025.

[34] Kuleshov, A. and K. Mahkamov, *Multi-zone diesel fuel spray combustion model for the simulation of a diesel engine running on biofuel.* 2008. **222**(3): p. 309-321. DOI: 10.1243/09576509jpe530.

[35] Hiroyasu, H., T. Kadota, and M. Arai, *Supplementary Comments: Fuel Spray Characterization in Diesel Engines.* Combustion Modeling in Reciprocating Engines, 1980: p. 369-408. DOI: 10.1007/978-1-4899-5298-1_12.

[36] Al-Amir, Q.R., M.F. Al-Dawody, and A.m. Abd, *Design of Cooling System for an Automotive using Exhaust Gasses of Turbocharged Diesel Engine.* Journal of The Institution of Engineers (India): Series C, 2022. **103**(3): p. 325-337. DOI: 10.1007/s40032-021-00787-4.

[37] Al-Dawody, M.F., et al., *Mechanical engineering advantages of a dual fuel diesel engine powered by diesel and aqueous ammonia blends.* Fuel, 2023. **346**: p. 128398. DOI: https://doi.org/10.1016/j.fuel.2023.128398

[38] Kuleshov, A., *Model for predicting air-fuel mixing, combustion and emissions in DI diesel engines over whole operating range*. 2005, SAE Technical Paper DOI: http://dx.doi.org/10.4271/2005-01-2119.

[39] Kuleshov, A., *Use of multi-zone DI diesel spray combustion model for simulation and optimization of performance and emissions of engines with multiple injection*. 2006, SAE Technical Paper DOI: http://dx.doi.org/10.4271/2006-01-1385.

[40] Reiter, A.J. and S.-C. Kong, *Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel.* Fuel, 2011. **90**(1): p. 87-97. DOI: https://doi.org/10.1016/j.fuel.2010.07.055.

[41] Dasari, S.R., et al., *In-situ alkaline transesterification of castor seeds: Optimization and engine performance, combustion and emission characteristics of blends.* Energy Conversion and Management, 2017. **142**: p. 200-214. DOI: https://doi.org/10.1016/j.enconman.2017.03.044.

[42] Prakash, T., et al., *Effect of ternary blends of bio-ethanol, diesel and castor oil on performance, emission and combustion in a CI engine.* Renewable Energy, 2018. **122**: p. 301-309. DOI: https://doi.org/10.1016/j.renene.2018.01.070.

[43] Rajak, U., et al., *Numerical investigation of performance, combustion and emission characteristics of various biofuels.* Energy Conversion and Management, 2018. **156**: p. 235-252. DOI: https://doi.org/10.1016/j.enconman.2017.11.017.

[44] Al-Obaidi, W., M.F. Al-Dawody, and K. Al-Farhany, *Effect of hybrid fuels of aqueous ammonia, dimethyl ether, biodiesel and diesel fuel on thermal performance of diesel engine.* International Journal of Heat and Technology, 2024. **42**(3): p. 812-822. DOI: https://doi.org/10.18280/ijht.420311.

[45] Heywood, J., *Internal Combustion Engine Fundamentals 2E*. 2018: McGraw Hill LLC.

[46] Mohsen, M.J., et al., *Experimental and numerical study of using of LPG on characteristics of dual fuel diesel engine under variable compression ratio.* Arabian Journal of Chemistry, 2023. **16**(8): p. 104899. DOI: https://doi.org/10.1016/j.arabjc.2023.104899.

[47] Franzetti, J., et al., *Measuring NOx during periodic technical inspection of diesel vehicles.* Environmental Sciences Europe, 2024. **36**(1). DOI: 10.1186/s12302-024-01002-8.

[48] Murad, M.E. and M.F. Al-Dawody, *Effect of microalgae biodiesel blending on diesel engine characteristics.* 2022. **51**(7): p. 6616-6640. DOI: https://doi.org/10.1002/htj.22615.