International Journal of Heat and Technology
Vol. 42, No. 3, June, 2024, pp. 812-822
Journal homepage: http://iieta.org/journals/ijht

Effect of Hybrid Fuels of Aqueous Ammonia, Dimethyl Ether, Biodiesel and Diesel Fuel on Thermal Performance of Diesel Engine

Wisam Al-Obaidi*, Mohamed F. Al-Dawody, Khaled Al-Farhany

Department of Mechanical Engineering, University of Al-Qadisiyah, Al-Qadisiyah 58001, Iraq

Corresponding Author Email: wisam.jasim@qu.edu.iq

https://doi.org/10.18280/ijht.420311

Received: 10 February 2024
Revised: 29 March 2024
Accepted: 12 April 2024
Available online: 27 June 2024

Keywords:
DME, green biodiesel, hybrid blends, NH_4OH, NO_x-PM relation, thermal characteristics

ABSTRACT

The present study aims to evaluate numerically the thermal parameters of dual fuel diesel engine working on two different hybrid fuels using the simulation code Diesel-RK. The combustion chamber is divided into several independent zone and the governing equation are solved for each zone. Initially the standard diesel fuel is tested in the engine to report the basic data for comparison. Then, the engine is turned to work on dual fuel mode operating on two hybrid fuels contains different blends of aqueous ammonia (NH_4OH), Dimethyl ester (DME), and algae biodiesel derived from spirulina algae. The hybrid 1 consists of (20% diesel+50% NH_4OH+30% DME) and the hybrid 2 involves (40% diesel+40% NH_4OH+20% biodiesel). All blends are calculated on energy replacement. The obtained results showed decrease in the rate of heat release and compared to the fuel of diesel. An apparent increase in the brake specific fuel consumption is noticed due to the difference in the density, viscosity, and heating values for both hybrid fuels relative to diesel. The Bosch smoke number (BSN) is strikingly reduced by 51.2% and 53.2%, when hybrid 1 and hybrid 2 is used respectively. Promising reductions in NO_x emissions achieved as follows: 48.12% for hybrid 1 and 37% for hybrid 2. The results highlighted that using hybrid 2 (40% DF+40% NH_4OH+20% biodiesel) is preferable more than hybrid 1 (20% DF+50% NH_4OH+30% DME) since the presence of biodiesel's properties showed better response than DME. The considered results showed noticeable altitude to fight the trade-off relation NO_x-BSN. The validation of the results is checked through studies conducted by different researchers.

1. INTRODUCTION

Compression engines play a key role in the transportation part, power generation and agriculture section owing to the high value of the brake power, low fuel consumption, long lasting and high torque. Thus, compression engines CI represented as a key contributor to the global warming and pollution of air. As a primary energy source for humans, fossil fuels have gradually replaced other sources. Since, there is a limited supply of fossil fuels, the researcher is actively investigating alternative energy options. Large capital expenditures, complex procedures, and increasing pollution output are also required for the extraction and processing of fossil fuels. Furthermore, a number of hazardous pollutants are released when fossil fuel-derived products are burned. That being said, alternative fuels are currently being researched to replace diesel produced from petroleum because environmental protection organizations worldwide have imposed strict emission limitations and because of worries about the depletion of petroleum stocks [1, 2].

The transportation industry is primarily responsible for most of the air pollution, which is very detrimental to the environment and public health. It is necessary to find appropriate substitutes and give the aesthetic environment quick attention in order to preserve it. Additionally, the demand for energy is rising each year [3].

The hybrid fuel engine is a concept in which the most favorable blends of fuel are assumed in different operative circumstances to control or reduce the produced emissions of the CI engines. The feasibility of this approach has shown to improve the performance of engines work with diesel or gasoline fuel [4, 5]. The potential use of renewable fuels in the hybrid fuel engines is high due to variation of their properties.

2. LITERATURE REVIEW

Different fuel mixtures have been investigated by many researchers in a way to achieve high thermal efficiency and reducing the emissions [6-9]. Blending DME with diesel and bio-diesel was conducted to investigate their influence on the combustion process and emission production using single and pilot injection techniques [10].

Blends of diesel, biodiesel-diesel (B_{80}/D_{20}) and DME-biodiesel (DME_{80}/B_{20}) were tested on diesel engine equipped to a passenger car. The characteristics of combustion showed that a high pressure in the mixture ($DME_{80}B_{20}$) in comparison to pure diesel and the mixture ($B_{80}D_{20}$). However, mixture of DME and biodiesel revealed a minor peak when the pilot injection strategy is used. In terms of the emissions, the

$DME_{80}B_{20}$ produced NO_x emissions higher than $B_{20}D_{80}$ and diesel. Whereas zero soot emissions were noticed in the single injection and pilot injection strategies. Mixing diesel, algal biodiesel, and diethyl-ether to examine the emissions production and performance of a small CI engine was studied [11]. The obtained results revealed that adding diethyl-ether enhance heat release rate, ultimate pressure within cylinder and the brake thermal efficiency. It can be attributed to the following parameters of the additive: high oxygen value, volatility, and great cetane-number. The accuracy of the variables (brake-thermal-efficiency, NO_x, brake-specific-fuel-consumption, CO, and HC) was examined by using correlation coefficient (0.9746 - 0.9999), mean absolute error of low range from (0.001 to 2.591), and low mean squared error (11.023).

A work was conducted to analyze the oil extracted from lemon peel to produce biodiesel fuel [12]. Various blends (diesel and lemon peel oil) of fuels based on volume were used of 10%, 20% and 30% at normal conditions of CI engine. The results revealed that 20% blend showed good performance and lowering the exhaust emissions. Furthermore, diethyl-ether of 5% and 10% with 20% blend of lemon peel oil were added. The brake-thermal-efficiency for (20% blend of lemon peel oil and 10% diethyl-ether) was increased by 3.7% at ultimate load compared to the 20% lemon peel oil. Correspondingly, the harmful emissions (HC, NO_x, CO) and soot at full load were significantly reduced by 24.4%, 16.9%, 11.8% and 12.5% compared to 20% lemon peel oil. Diesel fuel, 20% lemon peel oil and (10% diethyl-ether / 20% lemon peel oil) were tested at similar conditions using DIESEL-RK software. Both the experimental and the theoretical data showed that (10% diethyl-ether/20% lemon peel oil) improves the performance of the engine and condense the toxic emissions. Further study was conducted on a single cylinder CI engine to evaluate combustion, performance, and characteristics of emissions [13]. The fuel used were blends of diesel, diethyl-ether and WCSO biodiesel. Findings of blending (diesel/WCSO biodiesel) showed that B_{20} achieved close engine characteristics to pure diesel. Next, B_{20} was mixed with diethyl-ether at volume ratios of (5%, 10%, and 15%). An enhancement of (2.8%) in the cetane-index when an addition of 10% diethyl-ether with B20, as well as a noticeable reduction of (29%) in the viscosity.

Improving the properties of the fuel by adding 10 % DEE led to reduction in ignition delay and duration of combustion, while produced high value of peak in cylinder pressure. At full load, Noticeable decrease of BSFC by 3.2% and increase of BTE by 1.3% were found when adding 10% DEE compared to B_{20}. Therefore, the observations of diesel/biodiesel and DEE blends largely reduced the smoke by (3.6%) and CO by (49.9%) emissions compared to diesel, while the emissions of (HC) were enlarged. The stability of combustion in CI engines is essential. Thus, a study was conducted to analyze quantitatively the combustion-characteristics that affect the stability of the combustion for engines powered with biodiesel-methanol blends [14]. The obtained results, at (2400) r/min and full load, revealed that a 10% volume basis of methanol boosts the ultimate pressure. In addition, the increase of methanol ratio was observed to increase the characteristics of combustion (distribution range of low Ea, the number of PIP) and the difference of pressure. Mixing dimethyl-ether, methyl-deaconate and biodiesel using (air-side) and (fuel-side) techniques was studied using counter flow flame-modeling [15]. Flame temperature profiles and heat release rate were analyzed when DME and MD mixed together in order to show the kinetic variances in combustion modes between pre- and post-mixing of biodiesel and dimethyl-ether. The findings showed that both additions of dimethyl-ether (air and fuel sides) can slightly increase the ultimate temperature and expand the reactions areas of flames. In the flame zone, DME and MD represent mainly oxidized and two different oxidation regions respectively. Premixing DME with fuel dehydrogenate MD by improving OH and H formation. The physicochemical properties of blending DME and biodiesel were observed to be better than using each fuel separately. A study was carried out to investigate in-depth the characteristics of combustion when Biodiesel and DME were blended using skeletal mechanism [16]. The approach involves four sub mechanisms related to ester sets, fuels, emissions, and small molecules. Methyl group (palmitate, stearate, linoleate, n-decane and 5-decenoate) were employed to reflect the behavior of combustion of various forms of biodiesel. The results showed that the characteristics of emissions and combustion of mixing DME with biodiesel fuel can be achieved by the mechanism. In addition, the increase of DME ratio led to an increase in the ignition delay and peak pressure within the cylinder, however, soot production was decreased. To improve the usage of methanol in the compression engines, an experimental study was conducted using three ratios of (diethyl-ether and n-octanol) to enhance the ignition and co-solvents in diesel engines [17]. The first part of the work was conducted under various temperature range (10°C, 20°C, and 30°C) of and involved blends of methanol (pure and hydrous) with biodiesel extracted out of waste cooking oil. The findings of mixing biodiesel with pure methanol observed to be stable at all sets of temperatures. As a co-solvent, n-octanol was added to the mixture of biodiesel and hydrous-methanol to enhance the solubility. The ratios of blends were as follow: (15%- 25%- and 35%) of methanol, n-octanol and diethyl ether rate of (10%) and (2.5%) respectively. The results showed that the lowest value of the ultimate in cylinder pressure, pressure rise-rate and heat release-rate were observed in the blends of (biodiesel/ methanol/ diethyl ether and n-octanol) compared with biodiesel only. Moreover, an increase in the brake-specific-fuel consumption, smoke and CO levels were observed, whereas the thermal efficiency and NO_x levels and exhaust emissions were reduced. A study was conducted used a hybrid fuel prepared by mixing (Pongamia oil/ hydrated-ethanol 95% purity and butanol) on CI engine [18]. The findings showed that (Pongamia oil) properties such as viscosity and density were decreased significantly when blended with ethanol. The magnitude of brake-thermal efficiency showed to be similarly for hybrid fuel and pure diesel. Decrease in the NO_x, CO_2 and SO_2 emissions produced by hybrid fuels were observed. A numerical investigation was applied on homogeneous compression ignition engine using various ratios of mixtures of DME, methanol and pure diesel [19]. The investigation comprised two stages: the first, performance and combustion characteristics were discussed when two or three fuel blended, secondly, comparison and examination of engine speed and EGR effect of (20%) mass ratio were carried out for two blends of minimum and maximum ratio of diesel fuel. The indications of the results showed that mixing 50% diesel, 20% DME and 30% methanol at rpm of 1400 produces high pressure, the best mechanical efficiency of 35% and the heat accumulated of 330.569 J. However, 80% diesel and 20% methanol at rpm of 2000 the EGR 20 low combustive performance and efficiency. the blend of 60% diesel, 30%

DME and 10% methanol produced the ultimate exergy performance-coefficient of 2.063 owing to the lowest irreversibility and high work. A further study examined the influence of various ratios of diethyl-ether, biodiesel, and diesel fuel on the characteristics of a diesel engine [20]. The mixtures of (diesel 80% /biodiesel 20%) and (2.5%-5% -7.5%- and 10%) of diethyl-ether with (biodiesel-diesel) were prepared and examined on a single-cylinder/diesel, 4 stroke, direct-injection GDI engine. In addition, the GDI-engine was running at five various loads and constant speed. The results of adding 10% diethyl ether showed an apparent decrease in the BTE 17.39% compared to diesel fuel, however, an increase in the BSFC of 29.15% was observed. Moreover, the mixtures of diethyl/ether, biodiesel and pure-diesel showed mitigation in the smoke, HC, and NO_x emissions of 4.12%, 12.89% and 8.84% respectively compared to pure diesel. High ratios of diethyl-ether with diesel increased the CO emissions. However, CO and CO_2 dropped down at high loads of the engine. Consequently, diethyl-ether can be employed as a favorable addition of 10% to the biodiesel/ diesel with no modifications to the engine. An experimental comparison was conducted to show the influence of the addition of diethyl-ether and methyl-tertiary-butyl-ether to diesel and biodiesel mixtures on CI engines [21]. Fractions based volume of ethers of (5% and 10%) mixed with 50% diesel and the rest is biodiesel. The findings of (50% diesel/45% biodiesel / 5% diethyl-ether) mixture revealed an increase of (5.3%) in the thermal-efficiency compared to other mixtures. In contrast, mixtures of (50% diesel/45% biodiesel / 5% diethyl-ether) and (50% diesel/45% biodiesel / 5% methyl-tertiary-butyl-ether) showed a good reduction in the emission of CO of 14.8% and 8.1% respectively compared to pure diesel. Furthermore, NO_x emission of the blends (50% diesel/40% biodiesel / 10% diethyl-ether) and (50% diesel/40% biodiesel / 10% methyl-tertiary-butyl-ether) was reduced by (32%) and (8.8%) respectively at full load. In terms of HC emission, all ether group showed significant decrease compared to diesel and biodiesel, whereas blend of (50% diesel/45% biodiesel / 5% diethyl-ether) produced lower smoke than pure diesel.

A new technique that added nano-particles, the titanium oxide (TiO_2), to blend of (diesel- biodiesel (Jojoba) - alcohol) in order to enhance the combustion and performance of the CI engines [22]. The fractions used in the study were as follow: TiO_2 of 25 and 50 mg/L, 40% diesel, 50% biodiesel, and 10% n-butanol. The results showed that heat release-rate and ultimate pressure are grown by (1.5%) and (2%) respectively when the nanoparticles of TiO_2 was added to blend of fuel. Exhaust emissions CO and HC showed an apparent reduction of (30%) and (50%) respectively. On the other hand, emissions of NO_x showed an increase of 30%. In conclusion, to obtain high thermal-efficiency and ultra-reduction of HC and CO emissions the following blends fuel (TiO_2, 50% jatropha biodiesel, 40 5 diesel and 10% n-butanol) is recommended. A study used a hybrid multi-criteria decision making (MCDM) approaches to overcome the difficulties of obtaining the optimum parameters of good performance and characteristics combustion of CI engines [23]. Test conditions were a 10.8 kW resistive load and constant-speed. The obtained outcomes showed that the best hybrid models are ANP-MOORA and SWARA-MOORA, as well as the optimal fuels were biodiesel extracted from animal fat and vegetable, diesel, and the blend fuels. Base on the results, both hybrid models showed that biodiesel of 20% is the best fuel. A numerical model was developed using artificial-neural-network to investigate the predicted outcomes of exhaust emissions and brake specific-energy consumption. The study proposed to work on a CI (single cylinder) compression engine fueled with (diesel- biodiesel (palm) - ethanol) mixtures [24]. The results were obtained at conditions of load range from (20-100%) and constant speed of 1500 rpm. The obtained results showed that the predicted performance and emissions had a range of correlation coefficient between (0.99329 and 0.99875) and the magnitude of the mean square error of (0.000179082 to 0.000465809). A comparison was made between the predicted data and the experimental work to find the best operating conditions for the CI engine. For instance, multi-performance-characteristics index values were found to be the highest (0.705/ numerical model) and (0.718 /experimental) for the blend (85% diesel/ 10% biodiesel /5% ethanol) at 20% engine load. An experimental work conducted to evaluate the combustion of the blends (biodiesel/bioethanol/diesel) on single-cylinder CI engine [25]. The brake thermal-efficiency and brake specific-fuel-consumption, CO, NO_x, and smoke emissions were evaluated. An approach of kernel based-extreme-learning machine is proposed to collect the theoretical data of engine performance and emissions. The experimental results of the blend (biodiesel/bioethanol/diesel) showed a reduction in the brake-specific fuel-consumption, CO, and smoke, however, an increase in the brake-thermal-efficiency was noticed. The mean absolute-percentage errors are brake-thermal-efficiency (1.482%), the brake-specific fuel-consumption (1.363%), CO (4.597%), NO_x (2.224%) and smoke (2.090%). Finally, the findings of K-ELM technique are in good agreement with experimental data. Thus, its reliable to evaluate the performance and the emissions of the exhaust for a single-diesel engine fueled with (biodiesel/bioethanol/diesel) blends. Fractions of biogas with diesel and waste plastic oil were studied on diesel engine to examine the improvement in the performance and emissions [26]. The studied fractions of biogas based on the volume were (10%, 20%, 30%, and 40%), and these fractions were added to (20%) waste plastic oil and diesel blends. The response-surface method was proposed and employed to evaluate the desirable engine performance such as high exergy efficiency, HC emissions. The values of the engine parameters were: energy efficiency (18.6%), exergy efficiency (50.05%), BSFC (0.46 kg/kWh), and CO (0.16 ppm), HC (41.28 ppm), and NO_x (107.81 ppm) emissions. The results found at engine load of (57.12%), compression ratios of 18, and (20% biogas / 20% WPO- 60% diesel) blend. Optimization of engine behavior was studied using algorithms of meta-heuristic-optimization method combined with experimental data [27]. In addition, the artificial neural networks were hired to estimate the emissions and performance of diesel engine fueled with hybrid blends of biodiesel. In order to examine the validity of the ANN method, 4 statistical benchmarks R2 and MSE were employed. The obtained results showed that ANN and RSM were outstanding modeling approaches with decent accuracy. ANN technique predicted performance better than RSM of [R2=0.978 for BTE] and [R_2=0.960 for BTE], respectively. However, the 5ml additive of (PJB_{20}) biodiesel blend improved the BTE by (52.8%) and decreased BSFC (34.9%) at full load. The smoke and CO_2 emissions were reduced by 7.1% and 19.14% respectively compared to pure diesel. The focus on obtaining hybrid blends fuel out of oil generated -(karanja) biodiesel-diesel is currently the aim of any researchers [28]. The (karanja) biodiesel and (pyrolysis) oil were blended to boost the low value of calorific in the biodiesel. On a single-cylinder

CI engine, the examined blends are [10% of tire/pyrolysis (TP), 20% karanja/biodiesel (KB) and 70% of diesel], in addition [20% of tire/pyrolysis (TP), 10% karanja/biodiesel (KB) and 70% diesel]. The results of the two blends showed high combustion characteristics and performance compared to pure diesel. An experimental investigation was implemented to highlights the advantage of using hydrogen on CI engines fueled with [ethanol-jatropha biodiesel] blend [29]. Various engine loads of (25%, 50%, 75% and 100%), five durations of hydrogen injection of (1200/ 2500/ 3700/ 4500 and 6000 µs) and 1500 r.p.m speed were used. The observations showed that the blend [10% ethanol- 90% (jatropha) biodiesel] enhance slightly the parameters of performance, exergy, and combustion. Improvements were seen in brake-thermal efficiency, exergetic efficiency, exergy destruction-rate and entropy generation of (2.09-2.92%), (1.85-2.67%), (1.72-7.05%) and (4.26-9.47%) respectively when a slight amount of hydrogen injected at 2500 µs. Thus, injecting large amount of hydrogen into the hybrid mixture remarkably decreases the UHC and CO emissions, however, slightly increases the NO_x emissions.

The scope of previous studies indicated several points like; numerical investigation in most of studies are absent. Furthermore, no hybrid fuel consists of different blends used in diesel engine is seen as the literature articles showed the single use of (biodiesel, water ammonia solution and DME) along with diesel engine rather that combined form of hybrid fuel with different blends. These gaps can be bridged in the present work that aims to investigate numerically using Diesel-RK code the impact of using two different hybrid fuels content different blends of algae biodiesel, water ammonia solution and DME on the thermal parameters of constant speed dual fuel diesel engine.

3. MATERIALS AND METHODS

Starting with plain diesel with no additives as the initial baseline for comparison. This work aims to examine the usage of two hybrid fuels on single cylinder, four stroke, direct injection dual diesel engine. The hybrid 1 consist of (20% diesel+50% NH_4OH+30% DME) while the hybrid 2 involves (40% diesel+40% 20% NH_4OH+20% biodiesel). Table 1 shows the mode of operation and identification of blends examined. The aqueous ammonia can be inducted through intake manifold while the use of DME can be injected directly to the combustion chamber. The used biodiesel is derived from green algae and produced though transesterification process. Further information is mentioned in the work of Murad and Al-Dawody [30]. The ordinary diesel is missed with 20% biodiesel and injected through main injection system of the engine. The technical date for the engine as well as the physicochemical properties of the hybrid fuels are listed in Table 2 and Table 3 respectively.

Table 1. The energy replacement of tested fuels

Blends	Diesel (DF) %	NH_4OH %	DME %	Biodiesel %	Identify	Operation Mode
1	100	0	0	0	DF	Mono-fuel
2	20	50	30	0	Hybrid 1	Dual fuel
3	40	40	0	20	Hybrid 2	Dual fuel

Table 2. Engine information [31]

Technical Details	Specifications	Units
Engine type	Kirloskar TV1 diesel	-
Cylinder and stroke	4-stroke, single-cylinder	-
Bore × Stroke	80×110	mm
Compression ratio	15.5	-
Speed	1500	rpm
Rated output	3700	W
Cooling system	Liquid (water) cooling	-
Injection pressure	16000	kPa
Injection timing	20^o BTDC	Degree
Injection duration	30^o	Degree

Table 3. Properties of hybrid fuels blends [32-37]

Properties	Units	Diesel	NH_4OH	DME	Biodiesel	Hybrid 1	Hybrid 2
C	%	87	0	52.1	75.1	33.03	52.2
H	%	12.6	14.2	13	13.2	13.52	13.22
O	%	0.4	45.7	34.7	11.7	33.34	18.44
Molecular weight	-	190	35.046	46	249.84	69.323	128.02
Density	g/cc	0.830	0.8903	0.61833	0.869	0.7966	0.8541
Heating value	(kJ/kg)	45830	9839	28430	38920	22595	30067.2
Viscosity	Pa.s	0.00226	0.00047	0.00011	0.00432	0.00048	0.00160
CN	-	53.4	-	60	49.85	28.68	29.16
Heat of vap.	(kJ/kg)	250	230	467	325	190.1	150
Auto ign. temp	K	530	927	508	672	722	717

4. NUMERICAL ANALYSIS

The current wok involves the use of the DIESEL-RK program version (4.3.0.189) is intended for the calculation and optimization of two-stroke and four-stroke internal combustion engines. The program allows you to carry out thermal calculations, analysis, and research of the following types of internal combustion engines: diesel, gasoline spark both (carburetor and gasoline injection) and gas spark (conventional as well as pre chamber). DIESEL-RK belongs to the class of thermodynamic programs, where engine cylinders are considered in it as open thermodynamic systems. The diesel combustion model allows us to study a multi-fuel engine operating as a diesel engine. fuel and biofuels, including their mixtures with (diesel fuel) in different proportions. The chemical and physical behaviors of fuels can be specified by the user and saved in the program database. For each engine operating mode, you can set your own fuel [38].

In this study the combustion model of multizone was employed, and Diesel-RK software was used to solve the governing equations. Additional details about the formulation of the model used in this work were adopted from Al-Dawody and Bhatti [39], Al-Dawody and Edam [40].

4.1 Spray assessment model

An elemenatry-fuel-mass (EFM) has a speed, transfers between the injector towards the spary-tip at a short time step illustrated in Figure 1, which can be found from Eq. (1).

$$\left[\frac{\mathrm{U}}{\mathrm{U_0}}\right]^{\frac{3}{2}} = 1 - \frac{\mathrm{l}}{\mathrm{l_m}} \tag{1}$$

where: U: (EFM) current-speed, U∘: (EFM) initial-speed at the nozzle-injector, l: the current distance between the (EFM) and the nozzle-injector $\mathrm{l_m}$: the penetration length of EFM till the end in front of a spray. The differential Eq. (1) is solved partially as:

$$3l_m\left[1 - \left[1 - \frac{l}{l_m}\right]^{0.333}\right] - V_o\tau_k = 0 \tag{2}$$

where: τ_k - travel period for the EFM to amount to the length l from the nozzle injector.

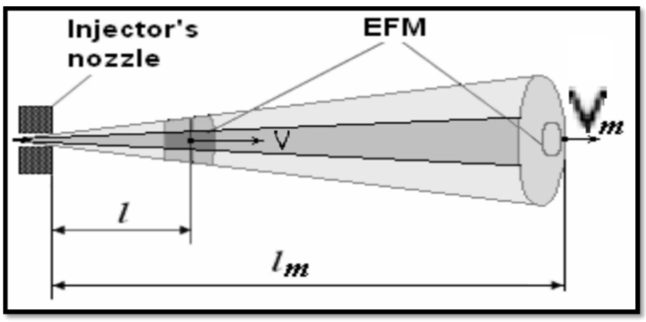

Figure 1. Illustration of the fuel-spray [41]

When (EFM) is stopped in a spray-tip ($l = l_m$) and $\tau_k = \tau_m$.

Where: τ_m- represents period of traveling for the (EFM) to amount the (spray's front) before stopping.

Eq. (2) then rewritten as:

$$\mathrm{l_m} = \mathrm{V_o}\,\frac{\tau_\mathrm{m}}{3}(3) \tag{3}$$

From Eqs. (1) to (3) the (EFM) current-speed and length were obtained as follow:

$$V = V_o\left[1 - \frac{\tau_k}{\tau_m}\right]^2 \tag{4}$$

$$l = l_m\left[1 - \left[1 - \frac{\tau_k}{\tau_m}\right]^3\right] \tag{5}$$

4.2 Heat release model

Four phases during the combustion process are observed, each phase has specific physical and chemical characteristics restricting the burning rate-speed. Those phases are described below [42]:

1. Ignition delay period phase can be obtained from:

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

2. The process of combustion for the mixtures of (air/fuel vapor) is called premixed combustion-phase:

$$\frac{dx}{dt} = \varphi_1\left(\frac{d\sigma_u}{d\tau}\right) + \varphi_o * \left[(\sigma_{ud} - x_o)(0.1\sigma_{ud} + x_o)A_o\left(\frac{m_f}{V_i}\right)\right] \tag{7}$$

3. The process when the fuel is directly injected and combusted is called diffusive combustion-phase.

$$\frac{dx}{d\tau} = \varphi_2\left((\sigma_u - x)(\emptyset - x) * A_2\left(\frac{m_f}{V_c}\right)\right) + \varphi_1\left(\frac{d\sigma_u}{d\tau}\right) \tag{8}$$

4. The process of burning fuel when the injection is completed is called late burning-phase:

$$\frac{dx}{d\tau} = (1 - x)(\varepsilon_b\emptyset - x) * \varphi_3 K_T A_3 \tag{9}$$

$\varphi_3 = \varphi_2 = \varphi_1 = \varphi_o$ represents a function that describes the combustion is completed in the zones of fuel-vapor:

$$\phi = 1 - (A_1/\varepsilon_b\emptyset - x)\frac{dx}{dt}\left\{r_v + \sum_{i=1}^{m_w}\left[r_{wi} * 300 * e^{\left(\frac{-16000}{2500 + r_{wi}}\right)}\right]\right\} \tag{10}$$

where: ε_b represents the efficiency of air-use, r_v relative-evaporation rate in the front and zones of the environment, ϕ the equivalence-ratio, r_{wi} the relative-evaporation-rate through different zones inside wall surface-flow.

4.3 NO_x formation modeling

The ordinary mixing of (NO_2/ NO) lead to produce of (NO_x emissions). In the current study, employing the software of (Diesel-RK), the method of Zel'Dovich is utilized [43]:

$$O_2 \leftrightarrow 2O \tag{11}$$

$$O + N_2 \leftrightarrow NO + N \tag{12}$$

$$O_2 + N \leftrightarrow NO + O \tag{13}$$

The concentration of atomic-oxygen influences the reaction-rate as shown in Eq. (13). The volume-concentration of (NO) is calculated using the equation below:

$$\frac{d[NO]}{d\theta} = \frac{e^{-38020/T_z}[N_2]_e[O]_e\left(1-\left(\frac{[NO]}{[NO]_e}\right)^2\right)*2.33*10^7 P}{RT_z\left[1+\left(2365/T_z\right)e^{3365/T_z}\,[NO]/[O_2]_e\right]}\left[\frac{1}{rps}\right] \tag{14}$$

4.4 Soot concentration modeling

The incomplete (HC) combustion will result tiny black carbon-particles called soot [44]. The concentration of soot in the engine' exhaust at the standard conditions is found to be:

$$[C] = \int_{\theta_B}^{480} \frac{d[C]}{d\tau}\frac{d\theta}{6n}\left[\frac{0.1}{P}\right]^{\gamma} \tag{15}$$

The level of Hartidge smoke is calculated as follow:

$$\text{Hartidge} = 100 * \left[1 - e^{(-24226[C])} * 0.9545\right] \quad (16$$

Eq. (17) is used to define the Particulate-Matter (PM) as a function of BSN:

$$[PM] = 565 * \left[\ln\frac{10}{10 - Bosch}\right]^{1.206} \tag{17}$$

The air pollutant emission equation (SE) is another important equation combines (PM) and (NOx) pollutants [45]:

$$SE = C_{PM}\left[\frac{PM}{0.15}\right] + C_{NO}\left[\frac{NO_x}{7}\right] \tag{18}$$

4.5 Software validation

The reliability of the (Diesel-RK) solver is checked via the comparison with the results of study conducted by Reiter and Kong [46]. Similar engine details as well as operating conditions are used as shown in Table 4. The pressure development curve through per crank angle is shown in Figure 2. The turbocharged engine is turned to dual fuel mode working on 60% diesel and 40% ammonia) on energy basis. The present study shows same trend with slight deviation around 5% compared to the work of Reiter and Kong [46]. The peak pressure is 7.8393 Mpa occurs at 6 deg. ATDC while the present work reported pressure of 7.466 MPa at 5 deg. ATDC.

Figure 3 illustrates how the volumetric concentration of CO_2 impacted by NH3 replacement in diesel. Both curves have similar attitude with minor difference. For mono fuel diesel (100% operation). The CO_2 concentration is deviated by 2.083% from the results obtained by Reiter and Kong [46] while for (60% diesel+40% NH3) on dual fuel mode the obtained results is differed by 6%. Its worthy to say that the simulation software is trusted enough and can be considered an efficient tool to simulate the combustion process in diesel engine.

Table 4. Engine's information used for validation [46]

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

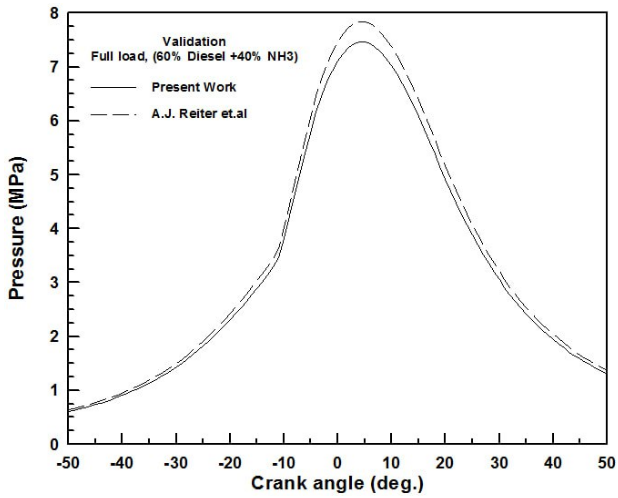

Figure 2. Validation of cylinder pressure profile

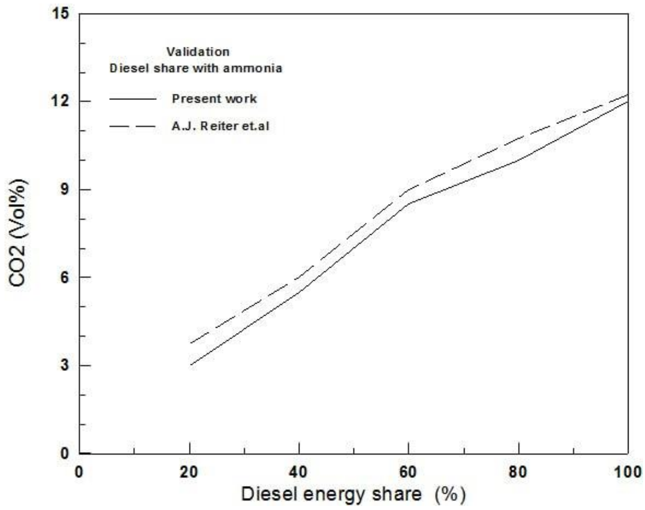

Figure 3. Validation of CO_2 concentration per % diesel energy

5. RESULTS AND DISCUSSION

The present study examines the impact of using two different hybrid fuels on the diesel engine's parameters. Previously explained that first hybrid fuel consists of diesel, water ammonia solution and DME and the other on involves diesel, water ammonia solution and algae biodiesel. The full load point is considered at constant rotational speed of 1500 rpm. Other operating conditions are listed in Table 5. The scenario scheduled is described in Table 6.

Table 5. Engine operating conditions

Conditions	Range
Load	Full
Speed	Constant 1500 rpm
Compression ratio	Constant 15.5:1
Injection timing	20 deg. BTDC
Injection duration	30 deg. BTDC
Initial pressure	1 bar
Initial temperature	300 K

Table 6. Coverage of engine thermal parameters

Present Study Plan	Details
Combustion parameters	Pressure history, peak cylinder pressure, peak temperature, heat release profile,
Performance parameters	Brake specific consumption, brake thermal efficiency, exhaust gas temperature.
Emission parameters	NO_x, Bosch smoke number, Particulate matter, summary of pollutant emissions

5.1 Combustion study

The history of cylinder pressure through 360° crank angle which represents complete power cycle is shown in Figure 4. All fuels showed same profiles except the peak value and the start of ignition. It can be seen that employing hybrid fuel 1 or hybrid fuel 2 reduced combustion pressure compared to the operation of plain diesel. the reason for the reduction is due to the difference in the density, viscosity, and heating values of the tested fuels. The results reported higher pressure for diesel followed by hybrid 2 then hybrid 1 comes last. Since the heating energy of biodiesel and NH_4OH is higher than heating energy of NH_4OH and DME, the pressure for hybrid 2 is greater than hybrid 1.

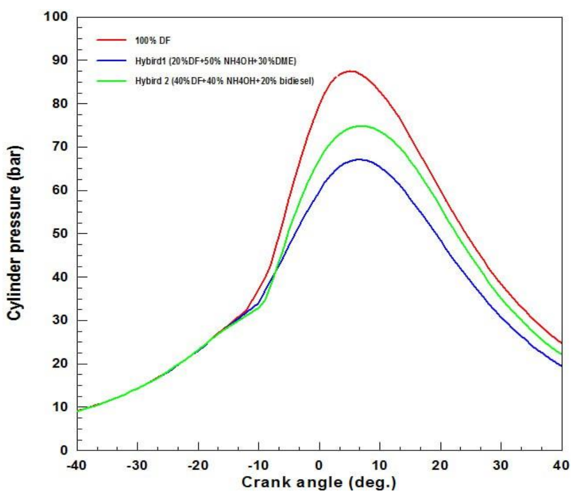

Figure 4. Pressure history per crank angle

Using hybrid fuels delayed the occurrence of combustion because the presence of aqueous ammonia lowered the speed of combustion as well as resisted self-ignition. While the degree of pressure rise is (4.6626 bar/deg.) for diesel, it was (2.5108 bar/deg.) and (4 bar/deg.) for hybrid 1 and hybrid 2 respectively. The present findings are matched with studies conducted by Abdulwahid et al. [47]. The values of peak pressures for the tested fuels are illustrated in Figure 5. Compared to the operation of neat diesel, the use of hybrid 1 reduces the pressure by 23.04% while it reduced by 14.74% with the use of hybrid 2. It is evident that the ignition delay rises, and maximum cylinder pressure lowers as additional diesel fuel is substituted with ammonia. There are two basic theories concerning why the ignition delay has increased. Firstly, less diesel fuel is sprayed, which reduces the velocity of the fuel for efficient atomization and blending that leads to ignite. Secondly due to ammonia's great capacity to resist auto ignition, it is harder for ignition to happen as the quantity grows [43].

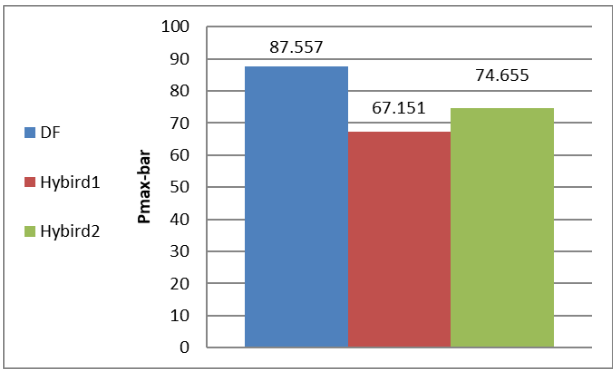

Figure 5. Peak pressure for the tested fuels

Figure 6 illustrates the values of average maximum combustion temperature at full load for tested fuels. Induction of NH_4OH and DME noticeably reduces the peak temperature. Ignition delay was observed to increase during the injection of Ammonia. However, Ammonia injection reduces peak pressure of the cylinder and temperature in-cylinder. The peak temperature is decreased from 2051 K for neat diesel to 1504 K and 1704 K for hybrid 1 and hybrid 2 respectively.

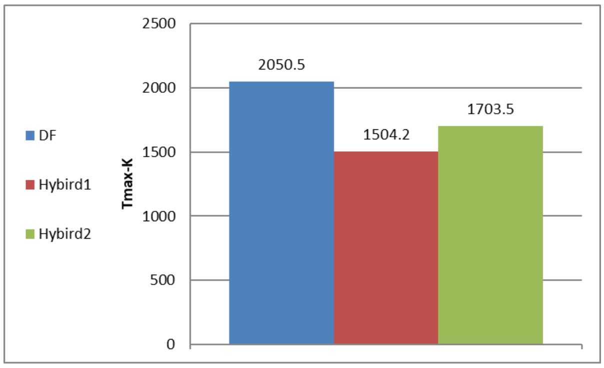

Figure 6. Peak temperature for the tested fuels

The profile of heat release per crank angle is presented in Figure 7. Since significant changes take place within the allotted time, the calculation's step is a 0.2o crankshaft angle. As is evident, introducing ammonia, biodiesel, and DME lowers the pressure and heating content of diesel/NH_4OH mixes, which lowers the rate at which heat is released. Heat is released at a peak rate of 57.37 J/deg. for diesel while for hybrid 1 and hybrid 2, it’s 22.36 and 36, J/deg., respectively.

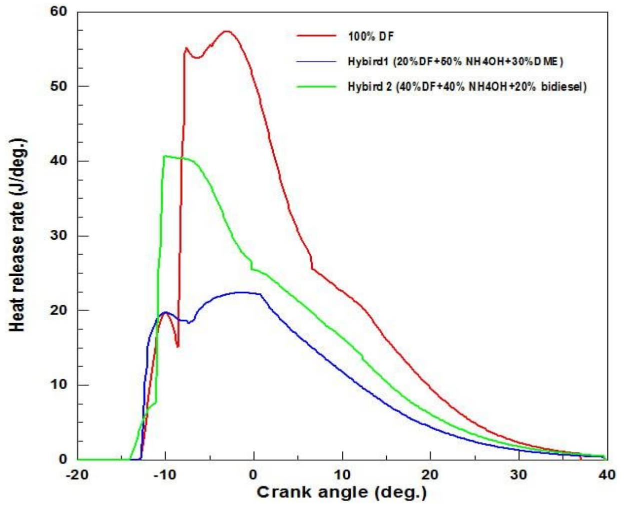

Figure 7. Heat release per crank angle

5.2 Performance study

A comparison of BSFC for plain diesel, hybrid 1 and hybrid 2 are shown in Figure 8. The operation of diesel engine on dual-fuel system of diesel, NH_4OH and DME (hybrid 1) or diesel, NH_4OH and biodiesel (hybrid 2) showed clear increase in BSFC because of the difference in the lower calorific values of NH_4OH, and DME compared to diesel as well as the reduction in brake power. In order to meet required power, more fuel will be consumed. The obtained results look similar to the study conducted by Auti and Rathod [28]. The hybrid 2 showed less increase in BSFC compared to hybrid 1 because the liberated energy of biodiesel is higher than DME as seen in Table 1. For comparison the presence of 30% DME showed increased BSFC by 15.27% due to the difference in the energy content of the tested fuels [48].

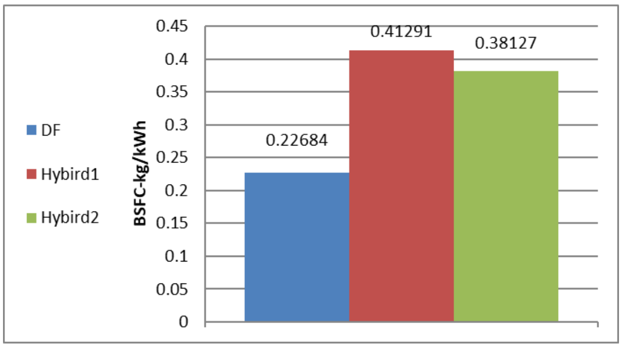

Figure 8. BSFC values for the tested fuels

The values of BTE for the proposed blends is shown in Figure 9. The results indicated that BTE decreases with use of hybrid 1 and hybrid 2 compared to the mono fuel mode (pure diesel). As the amount of diesel fuel reduced, a noticable reduction in the flame-temperature was observed, leading to reduction in the efficiency of combustion. Therefore, the process needs more fuel to gain similar useful power, which results low BTE. The BTE values for hybrid 1 and hybrid 2 are 31.2% and 31.4% respectively, which compared to (34.6%) for pure diesel fuel.

Figure 10 illustrates how the operation of dual fuel diesel engine on hybrid 1 and hybrid 2 impact the exhaust gas temperature (EGT) with respect to the operation on solo fuel (diesel). Inducting the aqueous ammonia and DME with diesel lead to reduce the EGT remarkably. Replacing diesel with water ammonia solution and DME or biodiesel resulted in decrease in combustion temperature and EGT. Using NH_4OH with DME reduces EGT by 23.8% while the use of NH_4OH with biodiesel drops EGT by 17.33%. Same results are noticed with findings of Al-Dawody et al. [49].

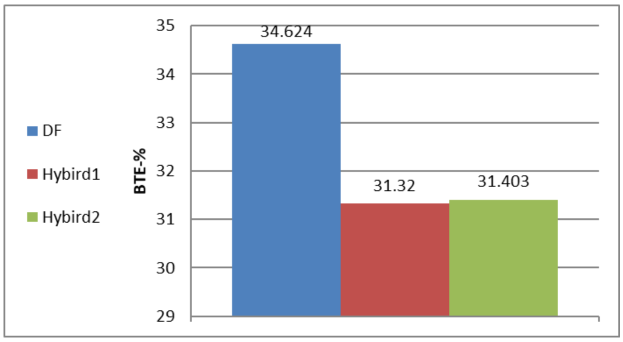

Figure 9. BTE values for the tested fuels

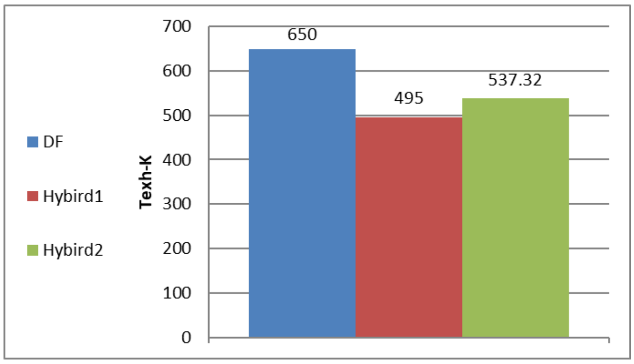

Figure 10. EGT values for the tested fuels

5.3 Emissions study

The NO_x and Bosch smoke number (BSN) are chosen to indicate how the use of hybrid fuel 1 and hybrid fuel 2 can impact the emission parameters of dual fuel diesel engine. Figure 11 shows the values of NO_x foe the tested fuels. The results proved that introducing the aqueous ammonia and DME along with diesel (hybrid 1) reducing the combustion temperature which directly produced lower NO_x by 48.12% compared to pure diesel. Also, the use the aqueous ammonia and algae biodiesel (hybrid 2) has the same effect by reducing NO_x emissions by 37%. An excellent convergence is reported with the results of the study of Abdulwahid et al. [47].

Figure 12 shows the values of BSN for diesel, hybrid 1 and hybrid 2 accordingly. The results showed plain diesel produces high amount of soot due to the low ratio of (H/C) as well as the nature of combustion-process in diesel fuel. On the other hand, impressive reduction in BSN for both hybrid fuels is reported. The reason for this attitude is the partial replacement of diesel by water ammonia solution which has no carbon it its structure as well as in case of biodiesel and DME the lower C/H ratio and higher oxygen quantity are responsible for this excellent reduction. Same findings are capture in the study of Öner and Altun [50]. The hybrid 1 recorded 51.27% reduction in the BSN while the use of hybrid 2 reported 53.5% reduction in BSN.

Increased use of fossil fuels has had a negative effect on the environment, particularly on climate change, as a result of widespread pollution It deserves mention that the results of present study highlight the use of hybrid fuels that lead to reduce NO_x and BSN simultaneously which can be considered as a good strategy to face the trade-off relation between NO_x-BSN. The effect of using such hybrid fuels on the thermal characteristics of dual fuel diesel engine can impact future energy prices and technology progress.

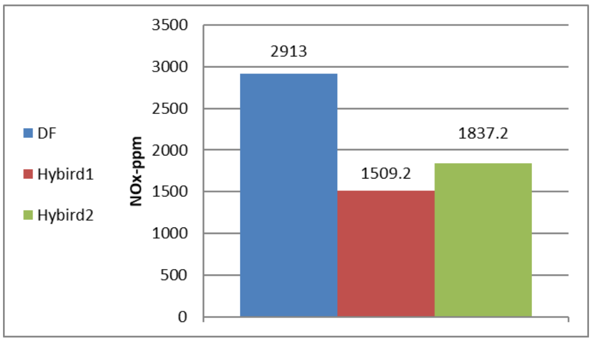

Figure 11. NO_x values for the tested fuels

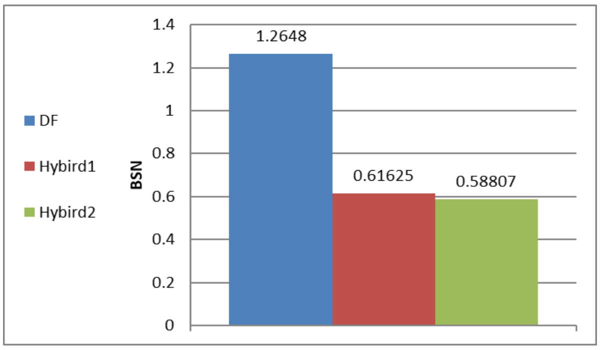

Figure 12. BSN values for the tested fuels

6. CONCLUSIONS

The numerical software Diesel-RK is used to simulate diesel engine working on two modes, first one refers to the base line operation on plain diesel and the dual fuel mode with the use two hybrid fuels. The hybrid fuels involve different combination on energy basis of aqueous ammonia, DME, and biodiesel in addition to neat diesel. The overall conclusions are summarized as follows:

1. The Pressure, and heat release dropped when engine turned to dual fuel mode whether hybrid 1 or hybrid 2 is used.
2. The presence of NH_4OH in both hybrid fuels attends to prolong the delay-period because it has a lower cetane-number and a slower combustion-reaction.
3. Clear increase in the BSFC with use of hybrid 1 and hybrid 2 as well as slight decrease in BTE.
4. Incredible reductions in (NO_x) emissions observed as follows: 48.12% for hybrid 1 and 37% for hybrid 2.
5. The BSN is strikingly reduced by 51.2% and 53.2%, when hybrid1 and hybrid 2 is respectively.
6. The findings point out that using hybrid 2 (40% DF+40% NH_4OH+20% biodiesel) is preferable more than hybrid 1 (20% DF+50% NH_4OH+30% DME).
7. Further numerical simulation is suggested to indicate how these hybrid blends can response under variable engine speed, compression ratio and injection timing accordingly.
8. An experimental investigation is suggested to study the influence of utilizing such hybrid fuels on the performance, combustion, and emissions characteristics of the engine.
9. The economic, maintenance and cost analysis with the use of such fuels in dual fuel diesel engine is suggested.

REFERENCES

[1] Silitonga, A.S., Masjuki, H.H., Ong, H.C., Yusaf, T., Kusumo, F., Mahlia, T.M.I. (2016). Synthesis and optimization of Hevea brasiliensis and Ricinus communis as feedstock for biodiesel production: A comparative study. Industrial Crops and Products, 85: 274-286. http://doi.org/10.1016/j.indcrop.2016.03.017

[2] Alptekin, E., Canakci, M., Ozsezen, A.N., Turkcan,A., Sanli, H. (2015). Using waste animal fat-based biodiesels–bioethanol–diesel fuel blends in a DI diesel engine. Fuel, 157: 245-254. http://doi.org/10.1016/j.fuel.2015.04.067

[3] Maheshwari, P., Haider, M.B., Yusuf, M., Klemeš, J.J., Bokhari, A., Beg, M., Al-Othman, A., Kumar, R., Jaiswal, A.K. (2022). A review on latest trends in cleaner biodiesel production: Role of feedstock, production methods, and catalysts. Journal of Cleaner Production, 355: 131588. http://doi.org/10.1016/j.jclepro.2022.131588

[4] Ji, C.W., Wang, S.F., Zhang, B. (2010). Combustion and emissions characteristics of a hybrid hydrogen–gasoline engine under various loads and lean conditions. International Journal of Hydrogen Energy, 35(11): 5714-5722. http://doi.org/10.1016/j.ijhydene.2010.03.033

[5] Ji, C.W., Wang, S.F. (2010). Combustion and emissions performance of a hybrid hydrogen–gasoline engine at idle and lean conditions. International Journal of Hydrogen Energy, 35(1): 346-355. http://dx.doi.org/10.1016/j.ijhydene.2009.10.074

[6] Ma, S., Zheng, Z.Q., Liu, H.F., Zhang, Q.C., Yao, M.F. (2013). Experimental investigation of the effects of diesel injection strategy on gasoline/diesel dual-fuel combustion. Applied Energy, 109: 202-212. http://doi.org/10.1016/j.apenergy.2013.04.012

[7] Hanson, R.M., Kokjohn, S.L., Splitter, D.A., Reitz, R.D. (2010). An experimental investigation of fuel reactivity controlled PCCI combustion in a heavy-duty engine. SAE International Journal of Engines, 3(1): 700-716. http://doi.org/10.4271/2010-01-0864

[8] Kokjohn, S.L., Hanson, RM., Splitter, D.A., Reitz, R.D. (2009). Experiments and modeling of dual-fuel HCCI and PCCI combustion using in-cylinder fuel blending. SAE International Journal of Engines, 2(2): 24-39. http://doi.org/10.4271/2009-01-2647

[9] Curran, S., Prikhodko, V., Cho, K., Sluder, C., Parks, J., Wagner, R., Kokjohn, S., Reitz, R.D. (2010). In-cylinder fuel blending of gasoline/diesel for improved efficiency and lowest possible emissions on a multi-cylinder light-duty diesel engine. SAE International. http://doi.org/10.4271/2010-01-2206

[10] Roh, H.G., Lee, D., Lee, C.S. (2015). Impact of DME-biodiesel, diesel-biodiesel and diesel fuels on the combustion and emission reduction characteristics of a CI engine according to pilot and single injection strategies. Journal of the Energy Institute, 88(4): 376-385. http://doi.org/10.1016/j.joei.2014.11.005

[11] Alruqi, M., Sharma, P., Deepanraj, B., Shaik, F. (2023). Renewable energy approach towards powering the CI

engine with ternary blends of algal biodiesel-diesel-diethyl ether: Bayesian optimized Gaussian process regression for modeling-optimization. Fuel, 334(p2): 126827. http://doi.org/10.1016/j.fuel.2022.126827
[12] Dhana Raju, V., Soudagar, M.E.M., Venu, H., Nair, J.N., Reddy, M.B.S.S., Reddy, J.S., Rao, T.S., Khan, T.M.Y., Ismail, K.A., Elfasakhany, A. (2022). Experimental assessment of diverse diesel engine characteristics fueled with an oxygenated fuel added lemon peel biodiesel blends. Fuel, 324(A): 124529. http://doi.org/10.1016/j.fuel.2022.124529
[13] Devaraj Naik, B., Meivelu, U., Thangarasu, V., Annamalai, S., Sivasankaralingam, V. (2022). Experimental and empirical analysis of a diesel engine fuelled with ternary blends of diesel, waste cooking sunflower oil biodiesel and diethyl ether. Fuel, 320: 123961. http://doi.org/10.1016/j.fuel.2022.123961
[14] Zhu, J.L., Wang, Z., Li, R.N., Liu, S., Hua, Y. (2023). Experimental study and prediction model of combustion stability and combustion mode variation of burning methanol/biodiesel blends for diesel engines. Fuel, 335: 127038. http://doi.org/10.1016/j.fuel.2022.127038
[15] Luo, Y., He, Y., Liu, C.Z., Liao, S.Y. (2023). Combustion characteristics of biodiesel with different dimethyl ether blending strategies. Fuel, 332: 126078. http://doi.org/10.1016/j.fuel.2022.126078
[16] Wu, G., Wang, X., Abubakar, S., Li, Y.Q. (2022). A skeletal mechanism for biodiesel-dimethyl ether combustion in engines. Fuel, 325: 124834. http://doi.org/10.1016/j.fuel.2022.124834
[17] El-Seesy, A.I., Waly, M.S., He, Z.X., El-Batsh, H.M., Nasser, A., El-Zoheiry, R.M. (2021). Influence of quaternary combinations of biodiesel/methanol/n-octanol/diethyl ether from waste cooking oil on combustion, emission, and stability aspects of a diesel engine. Energy Conversion and Management, 240: 114268. http://doi.org/10.1016/j.enconman.2021.114268
[18] Prasad, S.S., Singh, A., Prasad, S. (2020). Degummed Pongamia oil – Ethanol microemulsions as novel alternative CI engine fuels for remote Small Island Developing States: Preparation, characterization, engine performance and emissions characteristics. Renewable Energy, 150: 401-411. http://doi.org/10.1016/j.renene.2019.12.150
[19] Taghavifar, H., Nemati, A., Walther, J.H. (2019). Combustion and exergy analysis of multi-component diesel-DME-methanol blends in HCCI engine. Energy, 187: 115951. http://doi.org/10.1016/j.energy.2019.115951
[20] Yesilyurt, M.K., Aydin, M. (2020). Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends. Energy Conversion and Management, 205: 112355. http://doi.org/10.1016/j.enconman.2019.112355
[21] Jeevanantham, A.K., Nanthagopal, K., Ashok, B., Al-Muhtaseb, A.H., Thiyagarajan, S., Geo, V.E., Ong, H.C., Samuel, K.J. (2019). Impact of addition of two ether additives with high speed diesel- Calophyllum Inophyllum biodiesel blends on NO_x reduction in CI engine. Energy, 185: 39-54. http://doi.org/10.1016/j.energy.2019.07.013
[22] El-Seesy, A.I., Hassan, H. (2019). Combustion characteristics of a diesel engine fueled by biodiesel-diesel-n-butanol blend and titanium oxide additives. Energy Procedia, 162: 48-56. http://doi.org/10.1016/j.egypro.2019.04.006
[23] Erdoğan, S., Balki, M.K., Aydın, S., Sayin, C. (2019). The best fuel selection with hybrid multiple-criteria decision making approaches in a CI engine fueled with their blends and pure biodiesels produced from different sources. Renewable Energy, 134: 653-668. http://doi.org/10.1016/j.renene.2018.11.060
[24] Dey, S., Reang, N.M., Majumder, A., Deb, M., Das, P.K. (2020). A hybrid ANN-Fuzzy approach for optimization of engine operating parameters of a CI engine fueled with diesel-palm biodiesel-ethanol blend. Energy, 202: 117813. http://doi.org/10.1016/j.energy.2020.117813
[25] Silitonga, A.S., Masjuki, H.H., Ong, H.C., Sebayang, A.H., Dharma, S., Kusumo, F., Siswantoro, J., Milano, J., Daud, K., Mahlia, T.M.I., Chen, W.H., Sugiyanto, B. (2018). Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine. Energy, 159: 1075-1087. http://doi.org/10.1016/j.energy.2018.06.202
[26] Das, A.K., Mohapatra, T., Panda, A.K. (2023). Multiple response optimization for performance and emission of a CI engine using waste plastic oil and biogas in dual fuel mode operation. Sustainable Energy Technologies and Assessments, 57: 103170. http://doi.org/10.1016/j.seta.2023.103170
[27] Viswanathan, V.K., Kaladgi, A.R., Thomai, P., Ağbulut, Ü., Alwetaishi, M., Said, Z., Shaik, S., Afzal, A. (2022). Hybrid optimization and modelling of CI engine performance and emission characteristics of novel hybrid biodiesel blends. Renewable Energy, 198: 549-567. http://doi.org/10.1016/j.renene.2022.08.008
[28] Auti, S.M., Rathod, W.S. (2021). Effect of hybrid blends of raw tyre pyrolysis oil, karanja biodiesel and diesel fuel on single cylinder four stokes diesel engine. Energy Reports, 7: 2214-2220. http://doi.org/10.1016/j.egyr.2021.04.007
[29] Rawat, J.S., Bhowmik, S., Panua, R., Madane, P.A., Triveni, M.K. (2023). Investigation of performance, emission and exergy parameters of a compression ignition engine fuelled with ethanol-jatropha biodiesel blend under varying hydrogen strategies. International Journal of Hydrogen Energy, 48(95): 37415-37426. http://doi.org/10.1016/j.ijhydene.2023.06.128
[30] Murad, M.E., Al-Dawody, M.F. (2020). Biodiesel production from spirulina microalgae oil. IOP Conference Series: Materials Science and Engineering, 928(2): 022127. http://doi.org/10.1088/1757-899X/928/2/022127
[31] Mohsen, M., Al-Dawody, M.F. (2022). The combustion characteristics of compression ignition engine fuelled partially by LPG-Diesel blends (Simulation study). Al-Qadisiyah Journal for Engineering Sciences, 15: 157-164. http://doi.org/10.30772/qjes.v15i3.828
[32] Duynslaegher, C. (2011). Experimental and numerical study of ammonia combustion. https://www.academia.edu/1093080/Experimental_and_numerical_study_of_ammonia_combustion.
[33] Şanlı, A., Yılmaz, I.T., Gümüş, M. (2020). Experimental evaluation of performance and combustion

characteristics in a hydrogen–methane port fueled diesel engine at different compression ratios. Energy Fuels, 34(2): 2272-2283. http://doi.org/10.1021/acs.energyfuels.9b03033

[34] Guido, C., Alfè, M., Gargiulo, V., Napolitano, P., Beatrice, C., Giacomo, N.D. (2018). Chemical/physical features of particles emitted from a modern automotive dual-fuel methane–diesel engine. Energy Fuels, 32(10): 10154-10162. http://doi.org/10.1021/acs.energyfuels.8b01011

[35] Reiter, A.J., Kong, S.C. (2011). Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. Fuel, 90(1): 87-97. http://doi.org/10.1016/j.fuel.2010.07.05

[36] Gill, S.S., Chatha, G.S., Tsolakis, A., Golunski, S.E., York, A.P.E. (2012). Assessing the effects of partially decarbonising a diesel engine by co-fuelling with dissociated ammonia. International Journal of Hydrogen Energy, 37(7): 6074-6083. http://doi.org/10.1016/j.ijhydene.2011.12.137

[37] Lhuillier, C., BREQUIGNY, P., Contino, F., Rousselle, C. (2019). Combustion characteristics of ammonia in a modern spark-ignition engine. SAE International. http://doi.org/10.4271/2019-24-0237

[38] DIESEL-RK as an engine simulation tool. http://diesel-rk.bmstu.ru/Eng/index.php, accessed on Feb. 12, 2024.

[39] Al-Dawody, M.F., Bhatti, S.K. (2013). Optimization strategies to reduce the biodiesel NO_x effect in diesel engine with experimental verification. Energy Conversion and Management, 68: 96-104. http://doi.org/10.1016/j.enconman.2012.12.025

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

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

[42] Al-Amir, Q.R., Al-Dawody, M.F., Abd, A.M. (2022). Design of cooling system for an automotive using exhaust gasses of turbocharged diesel engine. Journal of The Institution of Engineers (India): Series C, 103: 325-337. http://doi.org/10.1007/s40032-021-00787-4

[43] Al-Dawody, M.F., Al-Obaidi, W., Aboud, E.D., Abdulwahid, M.A., Al-Farhany, K., Jamshed, W., Eid, M.R., Raizah, Z., Iqbal, A. (2023). Mechanical engineering advantages of a dual fuel diesel engine powered by diesel and aqueous ammonia blends. Fuel, 346: 128398. http://doi.org/10.1016/j.fuel.2023.128398

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

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

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

[47] Abdulwahid, M.A., Al-Dawody, M.F., Al-Obeidi, W., Al-Farhany, K. (2023). Assessment of diesel engine thermo-characteristics working with hybrid fuel blends. Numerical Heat Transfer, Part A: Applications, 84(7): 659-674. http://doi.org/10.1080/10407782.2023.2237668

[48] Al-Dawody, M.F., Imtiaz, M., Katbar, N.M., Abdulwahid, M.A., Al-Obaidi, W., Al-Farhany, K., Flayyih, M.A., Jamshed, W., Eid, M.R., Alhushaybari, A., Alharthi, A.M. (2024). The effect of biogas and dimethyl ether on the thermal characteristics of a dual-fuel diesel engine: A numerical study. Biofuels Bioproducts and Biorefining, 18(1): 125-138. http://doi.org/10.1002/bbb.2553

[49] Al-Dawody, M.F., Rajak, U., Jazie, A.A., Al-Farhany, K., Saini, G., Verma, T.N., Nashine, P. (2022). Production and performance of biodiesel from Cladophora and Fucus green diesel. Sustainable Energy Technologies and Assessments, 53(D): 102761. http://doi.org/10.1016/j.seta.2022.102761

[50] Öner, C., Altun, Ş. (2009). Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine. Applied Energy, 86(10): 2114-2120. http://doi.org/10.1016/j.apenergy.2009.01.005

NOMENCLATURE

U	current speed of the elementary fuel mass
$U_{\circ}$	the initial speed of the EFM at the nozzle injector
l	the current distance between the EFM and the nozzle injector
l_m	the penetration length of EFM till the end in front of a spray
r_v	rate of relative evaporation in the environment zones and front
r_{wi}	the rate of the relative evaporation through various zones within wall surface flow

Greek symbols

ε_b	air use efficiency [1]
τ_k	travel period for the EFM to amount to the length l from the nozzle injector
τ_m	travel period for the EFM to amount to the spray's front before ending
φ 1,2,3	function that describes the completion of the combustion of fuel vapor in zones
ϕ	the equivalence ratio