Fuel 311 (2022) 122578

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Experimental investigation of the effect of urea addition to fuel on engine performance and emissions in diesel engines

Usame Demir [a,*], Avni Kozan [b], Salih Özer [c]

[a] Department of Mechanical Engineering, Bilecik Şeyh Edebali University, Bilecik, Turkey
[b] Institute of Science, Bingöl University, Bingöl, Turkey
[c] Department of Mechanical Engineering, Muş Alparslan University, Muş, Turkey

ARTICLE INFO

Keywords:
Addition Urea, AdBlue and Citric Acid to Diesel Fuel
Engine Performance
Diesel Engine
Exhaust Emission

ABSTRACT

Today, exhaust emissions have become a critical issue with the increasing number of vehicles due to greenhouse gas. Engine manufacturers carry out R&D studies due to emission limitations imposed on engines that use fossil fuels. Selective Catalytic Reactor and AdBlue injection systems have been used significantly to reduce NO_x emissions in diesel engines. For this reason, AdBlue is sprayed in the exhaust manifold to reduce emissions with a second injector in diesel engines. In this study, the effects of commercial AdBlue, Urea-pure water mixture and urea- pure water-citric acid mixtures as additives to diesel fuel on exhaust emission and performance in a diesel single-cylinder engine were investigated. In-cylinder pressure, exhaust gas temperature, fuel consumption, air consumption and exhaust emissions were measured experimentally to examine the effects of 3 different mixtures added to diesel fuel at 8 different loads. As a result, urea-citric acid–water mixtures added to diesel fuel worsened combustion. Brake fuel specific consumption has increased 8% for diesel + urea + citric acid mixtures due to the presence of water in mixtures. CO_2 emissions increased by 38% with the addition of AdBlue, while an increase of 53% was observed with the addition of diesel + urea + citric acid. With the addition of urea + citric acid to diesel fuel, CO emissions decreased by 233%, while under the same conditions, HC emissions decreased by 300% and NOx emissions decreased by a maximum of 19%.

1. Introduction

From 2000 to 2019, the number of produced vehicles increased by 54% [1]. In addition, the number of passenger cars has also increased day by day. 28 % of the vehicles produced in 2020 were diesel-fueled vehicles. As it can be understood from here, there is still a demand for diesel vehicles [2].

The use of vehicles defined as heavy vehicles in the world has increased considerably and this situation has caused environmental pollution in diesel engines. AdBlue used in new-generation diesel engines is a chemical mixture consisting of 30% urea and 70% pure water. The using purpose of AdBlue was environmental factors and it was aimed to prevent harmful greenhouse gas from diesel engine exhaust systems. Carbon monoxide (CO) and unburned hydrocarbon (HC) -rich gases released from fuel combustion first enter catalytic converter. And then, CO gas and unburned hydrocarbons are converted into harmless carbon dioxide (CO_2) gas and water in a catalytic converter. However, Nitrogen oxid (NO_x) gases cannot be filtered in any way here. Exhaust gases exit from the catalytic converter enters Selective Catalytic Reactor (SCR). AdBlue liquid sprayed on the gases.just before entering the SCR system. NO_x gases are converted into harmless nitrogen gas and water vapor to a large extent at the SCR outlet. After the harmful CO and NO_x components are converted to CO_2, nitrogen, and water vapor. Exhaust gases finally enter diesel particulate filter (DPF). After filtering various harmful particles in DPF. Exhaust gases are released into atmosphere as CO_2, nitrogen, and water vapor. As a result of this process, NO_x gases, which are the most harmful component of exhaust gases to humans and the environment are filtered by 90%. Fontanarosa et al. [3] investigated the effect of adding liquid urea and water vapor to jet A-1 fuel on performance and emissions in a 300 kW gas turbine. With the addition of 2.5% water and 2% urea, the combustion performance remained the same, resulting in a 31% improvement in NO_x emission. Ström et al. [4] studied as an example of the modeling of the urea experiment in the simulation environment. They took part in its application within Computational Fluid Dynamics (CFD) system. The accuracy of the results obtained for the Euler-Lagrangian CFD simulations of the urea-SCR

* Corresponding author.
E-mail address: usame.demir@bilecik.edu.tr (U. Demir).

https://doi.org/10.1016/j.fuel.2021.122578
Received 24 August 2021; Received in revised form 12 October 2021; Accepted 10 November 2021
Available online 19 November 2021

systems of the modeling selections confirmed that urea decomposition limited heat transfer and occurred at a constant temperature (425 K) by applying an AdBlue system to the exhaust pipe wall and the exhaust gas flow. Varna et al. [5] used an SCR system for the interior of the engine cylinder, which aims to lower the combustion temperature. In this system, exhaust gas flow through reducing agent ammonia is provided by catalysts known as Vanadia or Zeolite. It has been seen that low engine temperature has a good thermodynamic advantage as it reduces NO_x emission with the techniques used in the cylinder and also reduces engine efficiency. Liao et al. [6] argued that reducing NO_x emission for performance in diesel engines is possible with further optimization and improvement of existing urea-SCR systems. Jeong et al. [7] revealed that urea entered a homogeneous gas-phase reaction by dissolving urea in the gas phase and separating the urea in three-dimensional modeling [8,9]. In a sample study, a study has been made about the effect of nano additives and particulate filters on the performance and emission characteristics of a diesel engine with biodiesel fuel blended with urea within the SCR system. Koebel et al. [10] showed that urea in a diesel engine does not cause nitrogen dioxide, nitrogen oxide, hydrogen cyanide and isocyanic acid emissions. Miller et al. [11] applied urea-SCR system to a test setup equivalent to a 350 HP heavy vehicle engine. As a result, they proved that it showed NOx reduction in the motor cell. Xin et al. [12] measured the pressure loss values of urea in the engine by using CFD and BOOST software in the simulation environment. It has been observed that it has a slightly positive effect on fuel economy and exhaust pressure. Guo and others [13] Urea solution was used for emission analysis in Euro 4 diesel, Euro 5 diesel and CNG buses. As a result, for CNG buses, the urea system resulted in NO_x reduction, high exhaust temperature and high NO_2/NO_x ratio, while for diesel buses, these data resulted in lower results. This resulted in extremely low NO_x emissions from CNG buses. In order to examine the fuel economy of urea-SCR, they have studied on a 12-liter heavy vehicle engine. As a result of the study, it was seen that a saving rate of 7.5% was achieved [14]. An et al. [15] applied an analysis system according to NO_x by injecting aqueous urea into a 3D designed 2400 rpm diesel engine in a CFD simulation. They found that NO_x emission reached the best emission value at 50% when various percentages of aqueous urea were injected. Xu et al. [16] observed that NO_x absorption was at the highest levels at low temperatures (below 2500) by giving urea to the diesel engine with ammonia in an experiment. Solaimuthu et al. [17] studied the behavior of urea as SCR from full motoring to full load in an experimental diesel test engine. The engine was run at 250 bar with biodiesel fuel. Combustion, emissions and engine performance were measured. As a result, they have seen that there is a decrease in HC and NO_x emissions and a reduction of 5.8% to 1.18% at full load. Sharma et al. [18] Similar to the studies described in the literature, urea was sprayed from the exhaust system. The difference is, Fe-ZSM5 was used as the catalyst. The diesel engine was tested both without and using this system. As a result, it was seen that urea and Fe-ZSM5 catalysts came forward in performance, emission and thermal efficiency values [19]. In an important experiment for engine efficiency, fuel economy and emission values in diesel vehicles, a test study was conducted on Ford's hybrid electric vehicle Prodigy, which was developed under the PNGV (Partnership for a New Generation of Vehicles) program. Within the scope of the program, an emission test consisting of a urea-SCR system was carried out after a diesel particulate filter (0.2 g/mi NO_x, 0.04 g/mi particulate matter (PM)) to comply with ultra-low-emission vehicle (ULEV) emission standards. As a result of the test, it has been confirmed that emissions and performance yield efficient results both in fuel economy and high exhaust gas temperatures. Blakeman et al. [20] observed the emission values in a light vehicle using a urea solution. The aim was to tackle CO, HC and volatile organic fraction (VOF) issues. They achieved a NO_x conversion of 73% at the highest load condition. The exhaust emission values of the urea solution were tested using a high-pressure six-cylinder (7.6 L) diesel engine [21]. It was revealed that NOx emission decreased by increasing the urea content up to 30%. The NH_3 amounts showed an increasing graph compared to the urea water solution with high urea content. Lee et al. [22] conducted a urea study on a high speed, 2.8 L and 4-cylinder diesel engine in light vehicles. The results show that there is less NO_x efficiency at low temperature and N_2O emission needs to be characterized. They argued that longer performance and emission results could be achieved if the mixture of urea with a mixer was increased. Chaudhuri et al. [23] observed the injection of urea solution into the exhaust pipe of a diesel engine containing Pongamia pinata methyl ester (PPME), an alternative fuel type, by injecting 0% 10%, 20% urea solution into a four-stroke, single-cylinder, water-cooled and fixed RPM diesel engine. As a result, an average of 64% NO_x reduction was observed. Due to the ecological problems in today's technology, more useful and economical fuel research has been started. One of them is the very prominent Ammonia fuel. This type, which is also used as hydrogen energy, has a higher octane number than gasoline and has been found to provide more efficient compression ratios at high rpm. It is certain that we will see it frequently in the coming years. The Marangoni Toyota GT86 ECO, which works with ammonia fuel, was introduced for the first time in the world at the 2013 Geneva motor show. In the tests, it performed very well at 180 km and 2,800 rpm of ammonia. In 1966 Gray et al. [24] succeeded in starting a two-stroke engine with diesel-ammonia. They achieved very good compression ratios (such as 35:1–15.2:1 etc.) However, engine misfires occurred due to ammonia injection, which is slower than diesel injection speed. The compression ratio, on the other hand, was found to be proceeding correctly with the cetane number.

In this study, natural urea (50% urea + 50% water by volume), commercially available Adblue for diesel vehicles (30% urea by volume-70% pure water) and natural urea + citric acid (The effects of adding three different mixtures containing 50% natural urea + 25% pure water + 25% citric acid by volume) to diesel fuel were investigated. For this purpose, 5% by volume of urea was added to the prepared three mixtures and diesel fuel. With the studies carried out, it is seen that in the technological methods developed commercially, urea is effective on emissions by spraying the burned gases in the exhaust manifold. However, the creation of this injection device and the continuity of the injection are an extra expense for engine manufacturers. In addition, it causes confusion for consumers to buy both diesel and Adblue. In order to eliminate this complexity and costs, the effects of adding urea as a direct additive to diesel fuel were investigated in this study.

2. Material and method

2.1. Test fuels

The urea used in the experiments was obtained from the fertilizer factory in solid form. The obtained solid fertilizer was tried to be dissolved in pure water at the maximum rate. For this purpose, a certain amount of fertilizer by mass was added to one liter of pure water and mixed in a magnetic stirrer heater for 24 h each time. After each mixing, it was observed whether there was precipitation in the solutions that were rested for 24 h. The results obtained showed that 550 gr of fertilizer was dissolved in one liter pure water without any problems. Due to the high water content, it is predicted that some problems may occur in the mixture with diesel fuel. For this reason, citric acid was added to the mixtures. The effects of the addition of citric acid with this new mixture were tried to be examined. For this purpose, a new fuel mixture was formed by adding 20 ml of citric acid to the resulting mixture. These two urea mixtures were compared with a commercial product for diesel vehicles in Turkey. The product sold to limit exhaust gas emissions in diesel vehicles is generally known as AdBlue. AdBlue consists of 30% Urea-70% pure water combination. Commercial AdBlue purchased consists of a combination of 30% Urea and 70% pure water. Experimental fuels were obtained by adding 5% of these three mixture ratios into diesel fuel. The properties of the fuel mixtures used in the experiments are given in Table 1.

Table 1
Properties of test fuels.

Fuels	Viscosity	Density	Calorific Value
Diesel Fuel	3.8	845	43.106
Diesel + 5% Urea	2.7	831	45.328
Diesel + 5% AdBlue	2.69	831	45.330
Diesel + 5% Urea + Citric Acid	2.7	831	45.328

2.2. Test setup

The resulting fuel mixtures were tested in a single-cylinder, direct injection, air-cooled, compression ignition engine. For this purpose, in-cylinder and fuel line pressure changes were recorded by sensors on the engine. The technical specifications of the engine used in the experiments are given in Table 2. All experiments were repeated three times with four different fuel mixtures (Diesel, diesel + 5% AdBlue, diesel + 5% urea, diesel + 5% urea + citric acid). The average of the obtained data was taken. During all experiments, the exhaust gas temperature was measured with a K-type thermocouple. The fuel consumption value was measured in mass with a precision balance. The exhaust emission values of the engine were measured with a Bosh BEA 350 brand gas analyzer.

The measurement ranges and measurement uncertainties of the devices used in the experiments are given in Table 3.

In-cylinder pressure of test engine was measured with an air-cooled a piezo-resistive pressure sensor (Kistler, 6052C). In addition; Fuel line pressure is measured by an air-cooled pressure sensor (Oprand, OPTD 32288GPA). FNC brand optical crank encoder determined crankshaft position. The schematic view of engine test setup is given in Fig. 1.

2.3. Experimental procedures

All engine tests were carried out at a constant engine speed of 3000 rpm. The engine was loaded at this stage with loads of idling, 0.5 kW, 1 kW, 1.5 kW, 2 kW, 2.5 kW, 3 kW and 3.5 kW. In-cylinder pressure values were recorded for every 0.1 °CA position of the crankshaft. Each in-cylinder pressure graph was created by averaging 100 cycles. Heat release analysis was also performed using 100 cycles average cylinder pressure data. The heat release rate was calculated through an analytical model by applying the first law of thermodynamics and the ideal gas law. Using the in-cylinder pressure and cylinder volume values, the formula for the heat release rate per °CA is Eq. It is given in (1) [25].

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1}P\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dP}{d\theta} \quad (1)$$

Here; $\frac{dQ_n}{d\theta}$ net heat release rate (J/°CA), θ crank angle (°CA), γ is the specific heat ratio,V is the cylinder volume (m^3), and P is the cylinder pressure (bar). The total uncertainties of the measurements performed in the experimental study were calculated according to the Kline and McClintock method [26,27]. The accuracy of the measurements and the total uncertainties are given in Table 4.

3. Experimental results

Figures drawn from the data obtained from experimental test results are given in this section. The important issues in obtained figure results were tried to be explained together with literature. Variation of in-cylinder pressure values with crank angle (°CA) under different engine loads is given in Fig. 2. It is seen that all fuel mixtures have a similar in-cylinder pressure profile with diesel fuel. While the maximum in-cylinder pressure value was determined at 39.75 bar with using diesel fuel at 3.5 kW engine load, the lowest pressure value was measured with diesel + 5% urea at 37.2 bar at motoring. The maximum in-cylinder pressure value is obtained very close to top dead center (TDC) with diesel fuel. It can be easily seen in the in-cylinder pressure graphs that combustion becomes partially irregular with addition of urea and Adblue. In this case, combustion partially extends towards exhaust stroke. Because maximum in-cylinder pressure takes place far ahead of the TDC. In-cylinder pressure values of diesel + urea and diesel + AdBlue fuel mixtures decreased compared to diesel fuel at all engine loads. The best fuel mixture performance at all engine loads was obtained with diesel + urea + citric acid mixture after diesel fuel. In internal combustion engines, the heating value of fuel is very important for the pressure formed after combustion [28]. It has been reported in the literature that fuels with higher calorific value exhibit better combustion performance [29].For this reason, it is expected that the in-cylinder pressure values will decrease. As given in the previous section, it has been determined that the mixtures added to diesel fuel reduce calorific value. In the literature on the addition of urea to diesel fuel, there are studies stating that the in-cylinder pressure value increases [30] compared to diesel fuel, while some studies state that it decreases [31]. Researchers who reported a rise in in-cylinder pressure, increase the oxygen and water in the fuel due to supporting it with mineral content.

Table 2
Technical specifications of the engine.

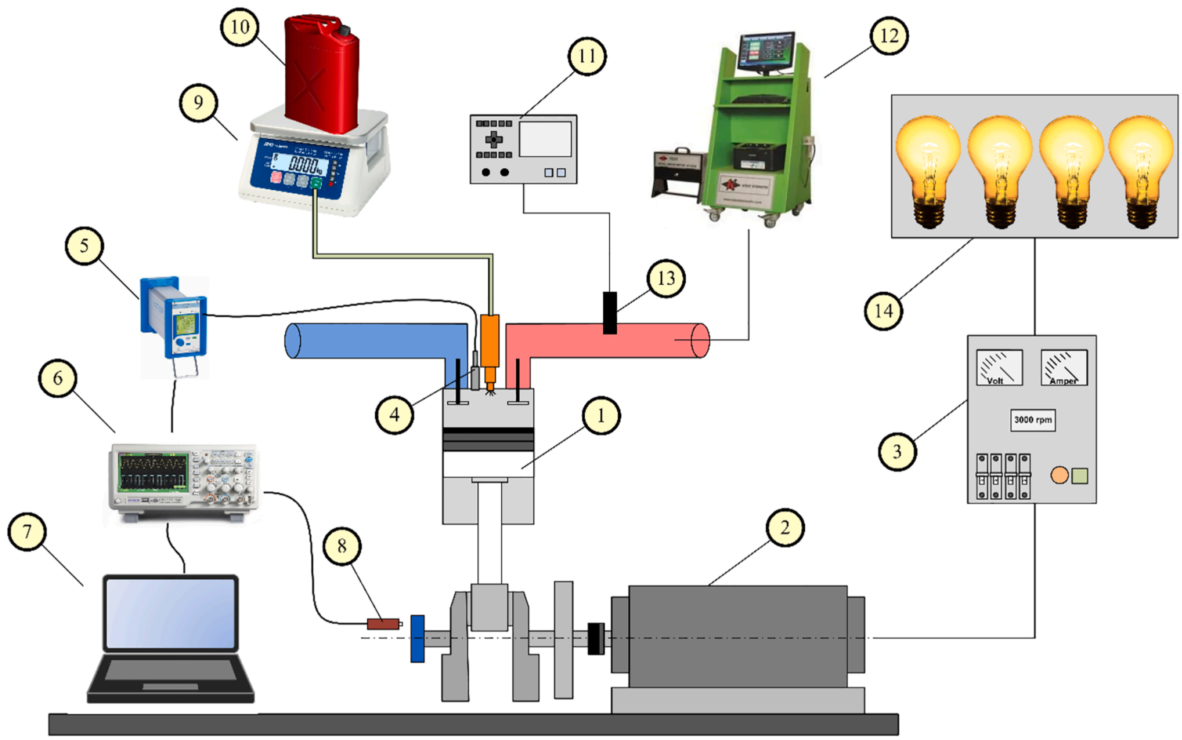
Model	186 FAG
Type	Air Cooled – 4 Stroke
Cylinder Displacement	418 cm^3
Compression ratio	18:1
Maximum Output Power	7 kW (3000 rpm)
Injection pressure	200 bar
Maximum torque	21 Nm (2600 rpm)
Injector Opening	21 °CA BTDC

Table 3
Measurement range of gas analyzer and calculated uncertainties.

Component	Measurement Range	Resolution	Accuracy %
CO (% vol.)	0–10.00	0.001	±0.01
CO_2 (% vol.)	0–18.00	0.01	±0.05
HC (ppm)	0–9999	1	±0.01
O_2 (% vol.)	0–22.00	0.01	±0.04
Lambda	0.50–9.99	0.001	±0.0001
NO (ppm)	0–5000	≤1	±0.1
Smoke Opacity (%)	0–100	0.1	±0.1

For this reason, they explained that better combustion occurs with the explosion of excess oxygen. Researchers declaring that it is decreasing, on the other hand, describe it with the heating value and partial irregularity of combustion. However, studies in the literature also report that the maximum combustion pressure moves away from the TDC with urea. In addition, with the addition of urea, an increase in viscosity and density value and a decrease in cetane number were observed. It is known that the deterioration in these values also has an effect on combustion [32].It is thought that these values have an effect on decrease of maximum in-cylinder pressure values by partially worsening combustion. It has been observed that the urea additive with citric acid addition has less pressure drop than the fuel mixture without the addition of citric acid. This can be expressed by the fact that the amount of oxygen in citric acid partially improves combustion. This may have provided some improvement over pure urea. It has been reported that oxygen content can partially improve combustion in studies with oxygen-rich fuels [33].

Fig. 3 shows the curves of the heat release rate calculation for diesel fuel and three different mixtures addition on diesel fuel for different loads. Again, the highest values in heat release rates were obtained with diesel fuel and diesel + urea + Citric acid mixtures. At low engine loads (motoring, 0.5 kW, 1 kW and 1.5 kW), the maximum heat release rate was obtained with diesel fuel, while at medium and high engine loads, the maximum heat release rate was obtained with citric acid added urea additive fuel mixtures. The highest heat release rate with 27.3 J/°CA was obtained with mixture of diesel + urea + citric acid at 3 kW engine



1) Diesel engine, 2) Generator, 3) Generator control panel, 4) Cylinder pressure sensor, 5) Charge amplifier, 6) Oscilloscope, 7) Computer, 8) Crank encoder, 9) Precision scale, 10) Fuel tank, 11) Data logger, 12) Exhaust gas analyzer, 13) K-type thermocouple, 14) Lamp load unit

Fig. 1. Experimental test setup schematic diagram.

Table 4
Uncertainty of measuring device.

Measured parameter	measurement device	Accuracy
Engine speed	Incremental encoder, rpm	±1%
Cylinder pressure	Pressure sensor, bar	±0.5%
Fuel line pressure	Pressure sensor, bar	±1%
Fuel mass	Precision scale, g	±0.1%
Exhaust gas temperature	Thermocouple, °C	±1%
Time measurement	Digital chronometer, s	±1%
Calculated results	**Uncertainty value**	
Power	±1.17%	
BSEC	±1.54%	

load. Especially, it is seen that diesel fuel with AdBlue additive draws different heat release rates from other mixtures and combustion is prolonged. It is possible to explain this situation with the amount of water in the fuel mixtures. It is thought that increased water in fuel mixtures worsens the combustion [34].

Thus, a decrease in the heat release rate occurs. Heat release rate increased with engine load increasing. An increase in engine load in a diesel engine is possible with an increase in fuel amount in the cylinder. Increasing fuel amount also causes an increase in the heat release rate. With the increasing amount of fuel, fuel/air mixture ratio in the cylinder gets richer. Thus, imbalances in air/fuel ratio partially worsen the combustion.

As engine load increases, amount of water taken into cylinder in diesel fuels with AdBlue and urea mixture also increases. For this reason, combustion worsens with AdBlue and urea added diesel fuels and heat release rates decrease. Fuel mixture with citric acid added almost similar values with diesel fuel. It can be explained by the fact that the diesel + urea + citric acid mixture is partially higher in calorific value than other fuel mixtures. The results of the study are similar to the [31] study with urea.

Fig. 4 shows the graphs of the cumulative heat release calculation for four different mixtures for different loads. In motoring load, diesel fuel reached the highest cumulative heat release value 432 J and the lowest cumulative heat release value of diesel + AdBlue mixture reached 265 J maximum. It was observed that the highest cumulative heat release value of 970 J at 0.5 kW load for diesel + urea + citric acid mixture, while diesel fuel reached 638 J. cumulative heat release. Cumulative heat release value of diesel + AdBlue mixture reached 800 J and it has reached the lowest cumulative heat value of 648 J for diesel fuel at 3.5 kW load.

The variation of the pressure rise rate with °CA for diesel and 3 different fuel additives at different loads is given in Fig. 5. The pressure rise rate is used in diesel engines to understand whether the fuels are knocking. The knock is an important parameter that can change with fuel properties. In motoring (no load), pressure rise rate value has reached a maximum value of 1.09 bar/deg at 18 °CA Before Top Dead Center (BTDC). There was a maximum pressure rise rate of 1.14 bar/deg for other load cases at 11 °CA BTDC. It can be stated that these values do not pose a knock risk, especially for diesel engines.

The variation of CO_2 emission values with different load is given in Fig. 6 for diesel fuel and three different additive mixtures. CO_2 emissions in diesel engines represent formation of complete combustion products [35]. When CO_2 emission values are examined, Diesel + Urea + Citric Acid mixture reached the highest emission value in motoring (no load). As the load increased, CO_2 emission values decreased in all cases.

Since diesel engines operate with a high excess air coefficient, they partly affect the formation of CO_2 emissions as combustion efficiency. With the ideal air/fuel mixture in the cylinder, combustion partially increases and CO_2 emissions increase. However, as the air/fuel ratio goes towards the rich mixture, the combustion efficiency decreases and CO_2 emissions decrease. In studies conducted with the addition of

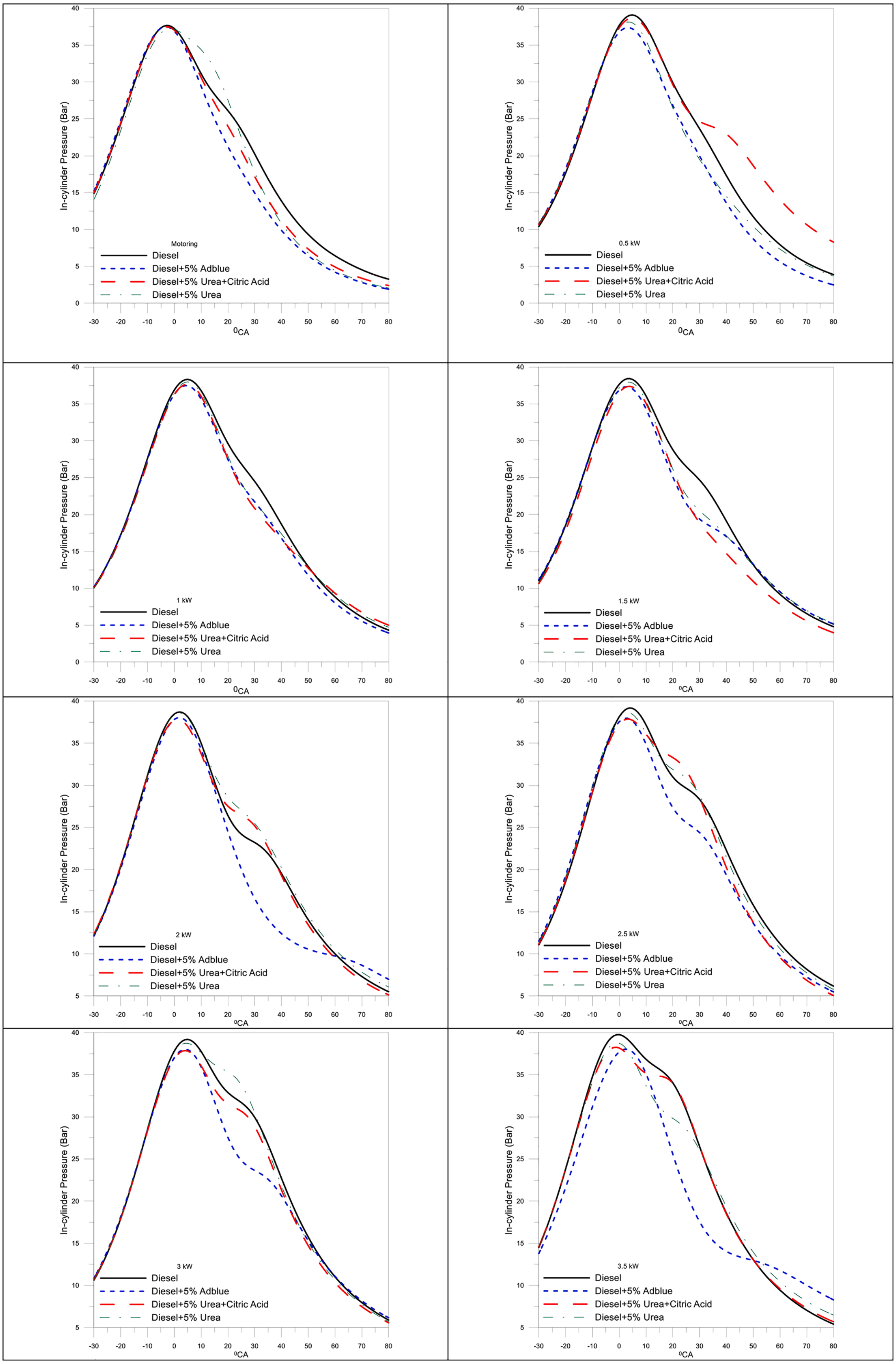


Fig. 2. Variation of in-cylinder pressure values depending on crank angle for different loads.

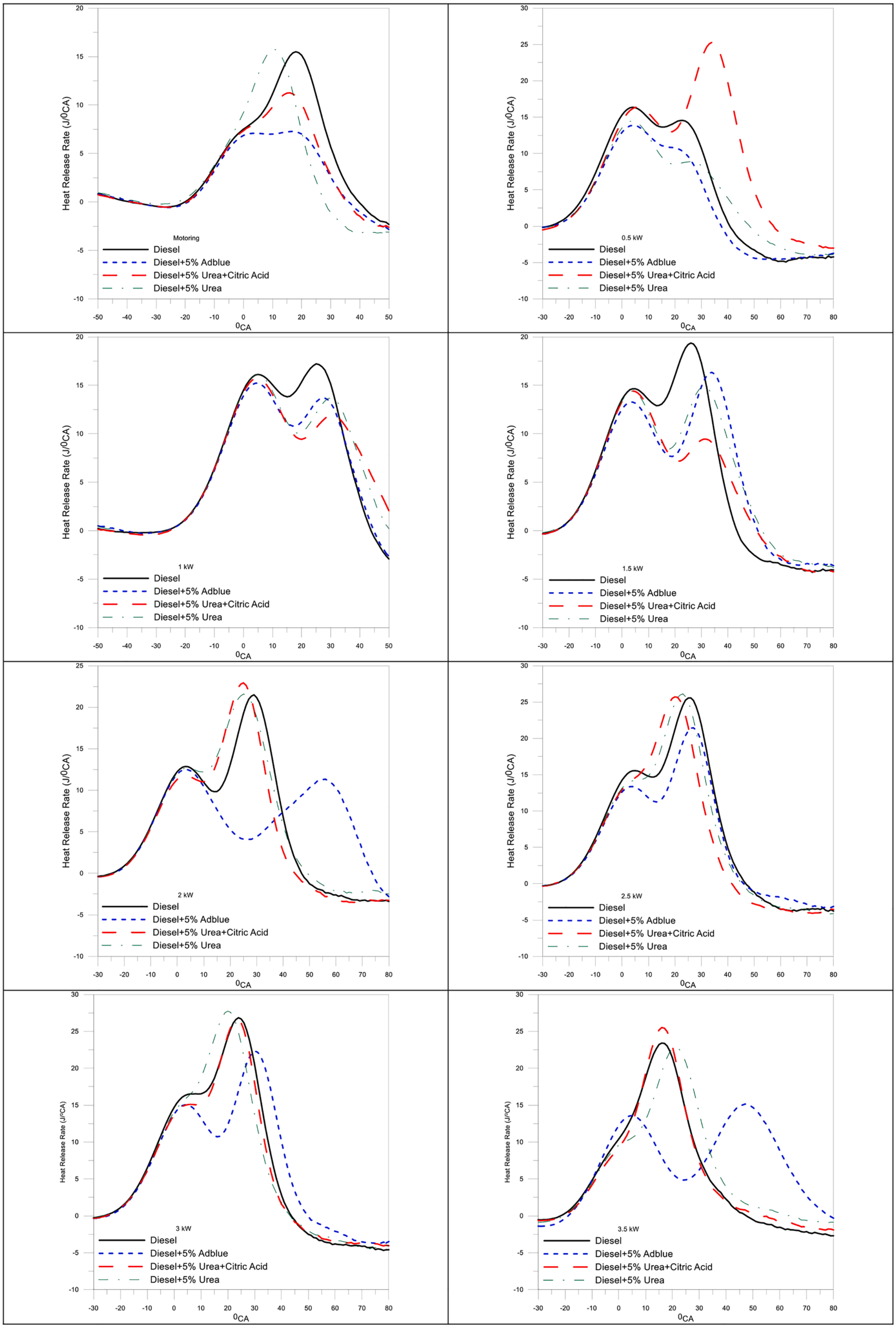


Fig. 3. Variation of heat release rates depending on crank angle at different loads.

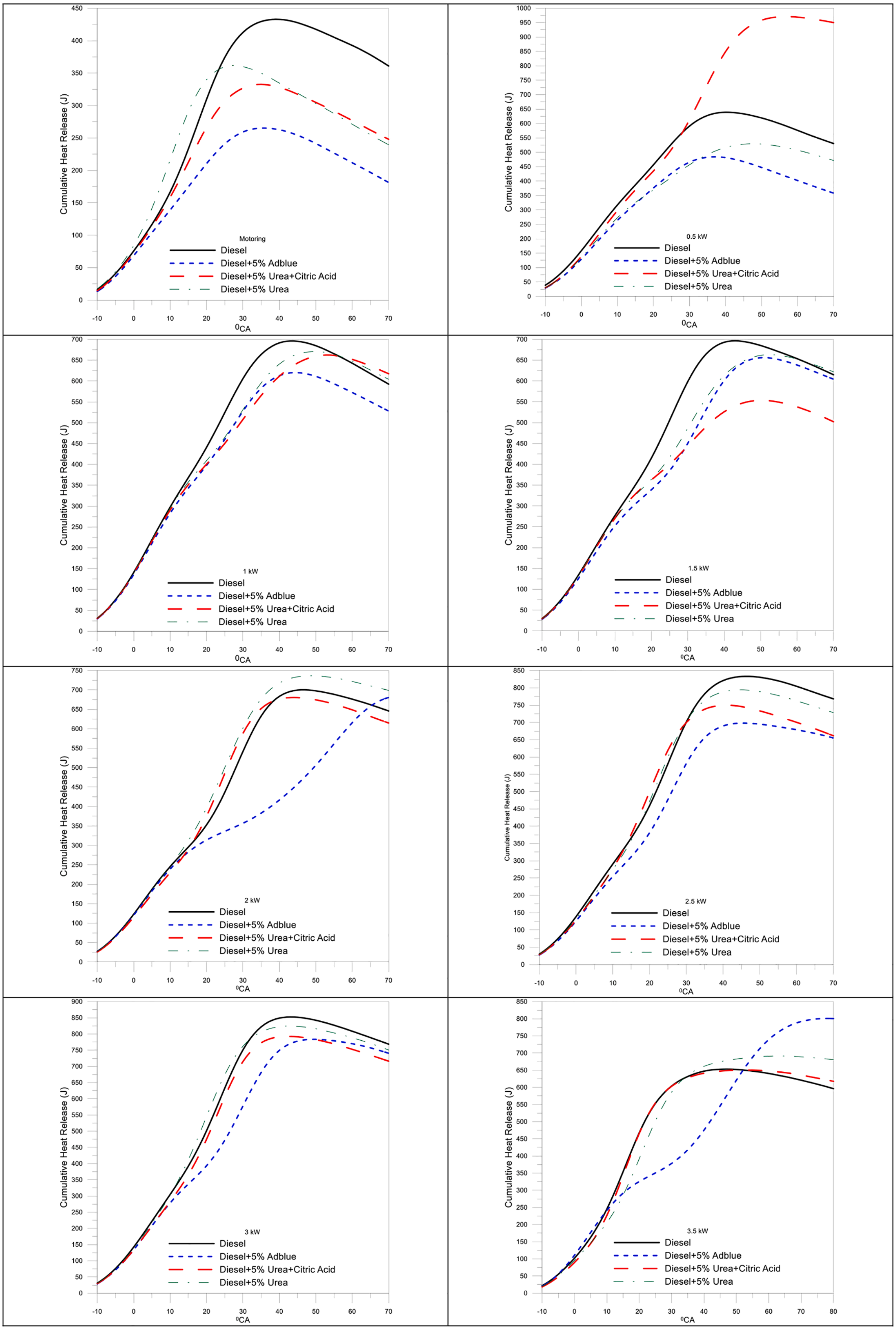


Fig. 4. Variation of cumulative heat release depending on crank angle at different loads.

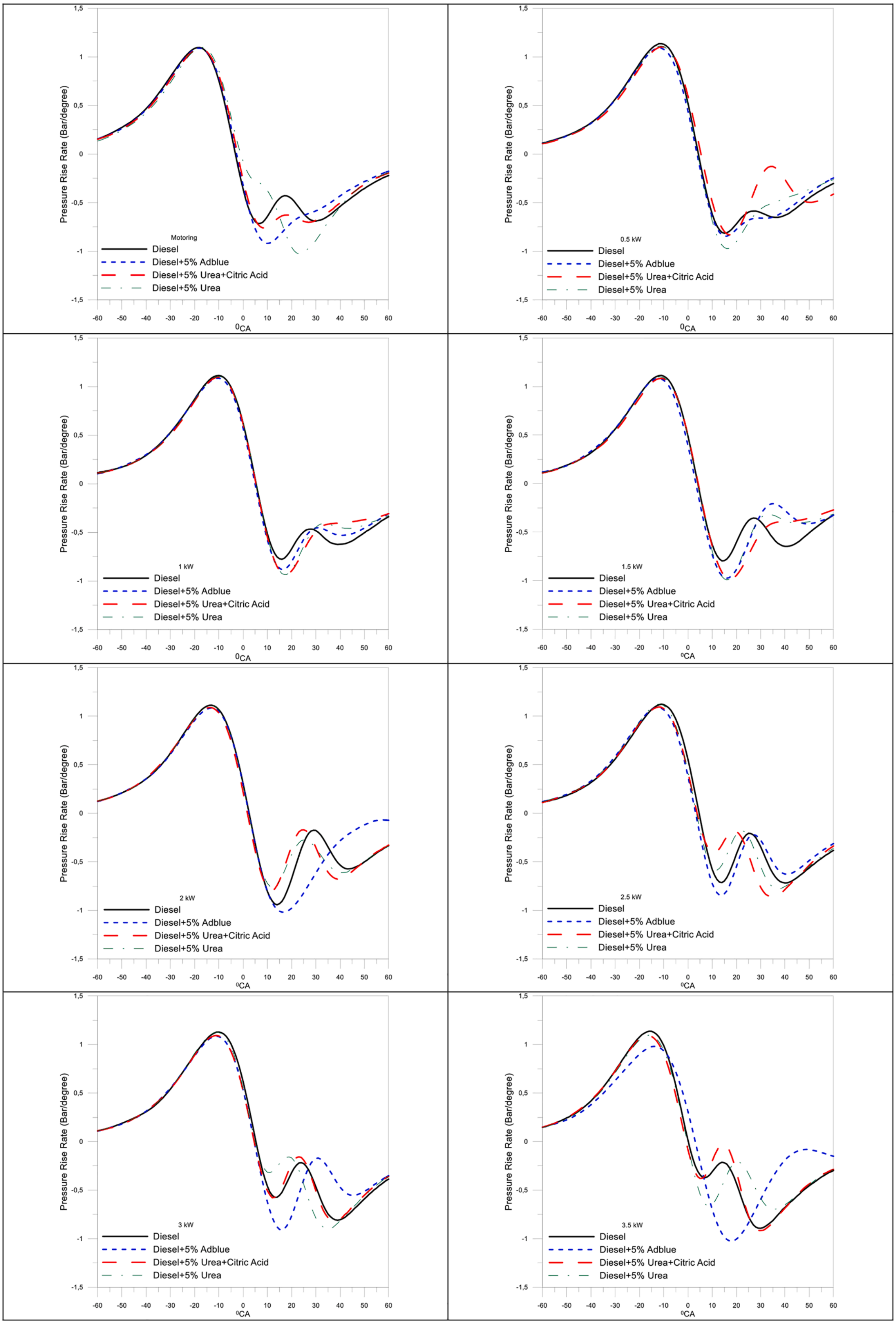


Fig. 5. Variation of pressure rise rate depending on crank angle at different loads.

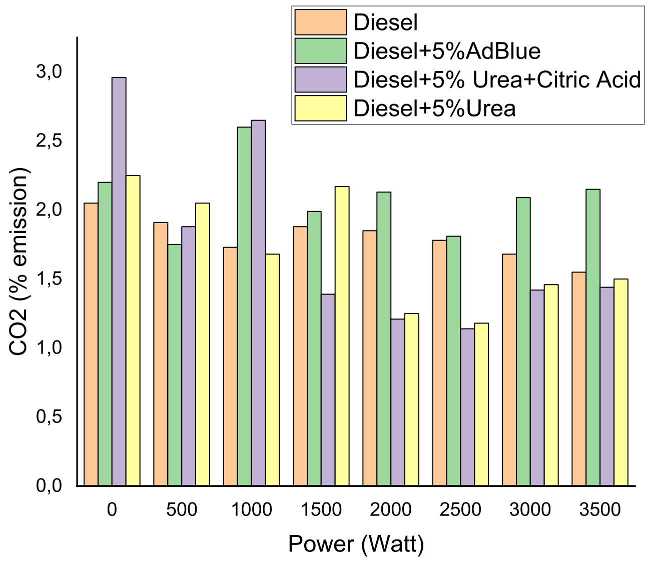


Fig. 6. Variation of CO2 emission values with load.

chemicals to diesel fuels, it is observed that the combustion efficiency of the chemicals with oxygen-rich content increases and there is an improvement in exhaust emissions [36]. In addition, it is mentioned that the addition of water to diesel fuels causes a micro-explosion during spraying and this improves the combustion efficiency [37].

At 3 and 3.5 kW load values, diesel + AdBlue mixture produced more CO_2 emissions than the other fuel mixtures. While CO_2 emission for diesel fuel was around 1.9%, Diesel + Urea + Citric Acid mixture reached its maximum level at motoring (no load) and 1 kW load. In the case of 0.5 kW load, Although diesel + urea + citric acid mixture produced the same CO_2 emission with diesel fuel, it produced less CO_2 emission than diesel fuel at 1.5 kW and higher load values. Diesel + AdBlue mixture produced higher CO_2 emissions than diesel fuel in all load conditions except 0.5 kW load. Diesel + Urea mixture has same level of CO_2 emissions as diesel fuel at motoring, 0.5, 1, 1.5 and 1.5 kW load conditions, while low CO_2 emissions have occurred in other situations.

Fig. 7 shows the variation of CO emissions at different engine loads. As it is known, diesel engines work with a large amount of air. Therefore, CO emissions are almost non-existent. However, according to the fuel mixtures used, partially unburned areas are formed in the combustion chamber. At the same time, CO emissions may occur as a result of the incomplete combustion of fuel particles hitting cylinder walls [38]. With the addition of urea to diesel fuel, CO emissions tended to decrease at all engine loads and in all fuel mixtures.

Studies have shown that CO emissions tend to decrease with the use of oxygen-rich chemicals in diesel engines [39]. In addition, studies on the addition of water-containing mixtures to diesel fuels underline that water provides an ideal air/fuel mixture by making a micro-explosion effect during spraying [40]. It is thought that this situation, combined with oxygen-rich fuels, causes a decrease in CO emissions.

CO emission formed the highest emission value for diesel fuel except for 1 kW engine load. The lowest CO emission value was 0.03% in Diesel + Urea + Citric Acid mixture at 3.5 kW engine load. The highest CO emission was 0.25% at 0.5 kW engine load for diesel fuel. Diesel + Urea + Citric Acid mixture provided the best CO emission level. Diesel + Urea + Citric Acid mixture compared to diesel fuel improved 233% CO emission at 2.5 kW and above engine load. In general, CO emission levels decreased as engine load increased. As it is known, engine load increasing is regulated by the amount of fuel taken into the cylinder. Combustion end temperature increases with increased fuel consumption. Thus, complete combustion of the fuel mixtures taken into the cylinder is ensured. The reduction in CO emissions with the addition of urea can be explained by the reduction in the total carbon number, the partial explosion effect of the water content in the fuel, and the formation of a near-ideal air/fuel mixture in the cylinder. The effect of fuel mixtures with citric acid addition and the reduction of further CO emissions can also be explained by the amount of oxygen in the citric acid. It can be stated that increasing oxygen relative to urea reaches freedom in the cylinder, increasing oxidation and thus reducing CO emissions. Similar studies in the literature with fuel mixtures with a high water content also mention a decrease in CO emissions [18].

Fig. 8 shows the NO_x (Nitrogen Oxide) emission variation with engine load for different fuel mixtures. Uncontrolled $_{NOx}$ emissions in diesel engines are an undesirable emission value. It is formed as a result of the reaction of nitrogen in the air with oxygen under high temperatures [41].

While the diesel + urea mixture provides the lowest emission value, the minimum NO_x emission value has occurred in the diesel + AdBlue fuel mixture with the increase in engine load. Studies report that NO_x emissions tend to increase when very rich fuel/air mixtures are formed in the cylinder or when combustion increases suddenly by accumulation [42,43]. It is possible to explain the reason for the increase compared to diesel fuel, with the increasing number of oxygen atoms in the fuel

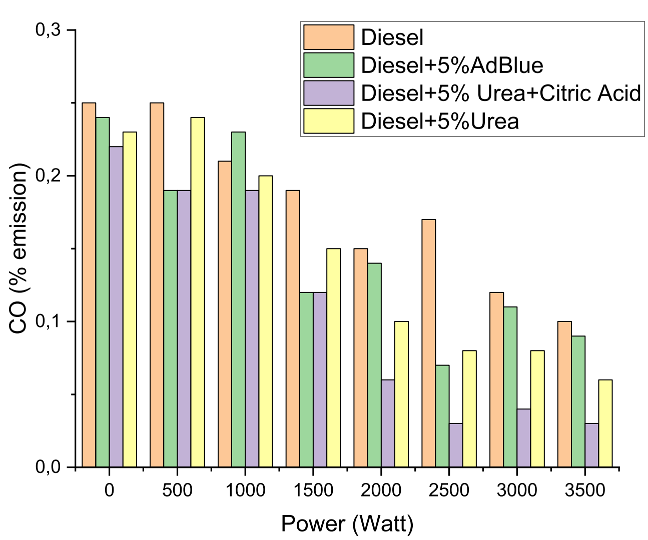


Fig. 7. Variation of CO emission values with load.

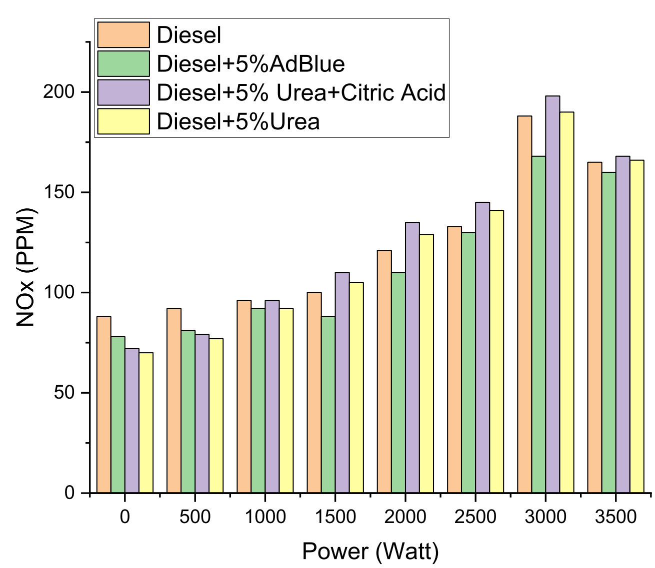


Fig. 8. Variation of NO_x emission values with load.

mixture and the sudden burning of the fuel by accumulating in the cylinder. Because urea and citric acid are oxygen-rich fuels. In addition, a slight increase in NO_x emissions can be expected due to the fact that the water content can cause the formation of partially rich regions with the effect of micro-explosion. It is possible to explain the reduction in NO_x emissions with the amount of water in the urea fuel mixtures. Studies on the addition of water to diesel fuels indicate that the addition of water reduces NO_x emissions [44]. It is thought that the amount of water in the urea-added fuel causes similar effects with the studies carried out and causes a decrease in NO_x emissions [45,46].

The lowest NO_x emission occurred in the diesel + urea mixture with 70 ppm at motoring. The highest NO_x emission was 198 ppm in diesel + urea + citric acid mixture at 3 kW load. In general, it is seen that the mixtures show the highest NO_x emission at 3 kW. NO_x values increased in direct proportion to engine load in all fuel mixtures. While diesel + urea mixture has the lowest emission at low loads, diesel + AdBlue has the lowest NO_x emission at high loads. It is possible to explain the reduction in NO_x emissions with the amount of water in urea for fuel mixtures. In studies on the addition of water to diesel fuels, it is mentioned that water reduces NO_x emissions [44].

It is thought that the amount of water in the urea-added fuel also causes a decrease in NO_x emissions by causing similar effects with the studies carried out.

Exhaust gas temperature values with different engine loads for diesel fuel and three different fuel mixtures in Fig. 9. Exhaust gas temperature emerges as an indicator of combustion in the cylinder [47]. Exhaust gas temperature decreased with the addition of urea to diesel fuel.

The heating values of fuel mixtures in diesel engines are an important parameter that affects the combustion end temperature. In addition, the physical and chemical properties of fuels such as cetane number, density and viscosity are also determinative at the end of combustion temperature [48,49]. In this study, the heating value and cetane number of the fuel mixture tended to decrease with the addition of urea to the diesel fuel. For this reason, a decrease in exhaust gas temperature is expected in all mixtures and engine loads.

The lowest exhaust gas temperature was 241 °C in diesel + AdBlue mixture at motoring load. The highest exhaust gas temperature was 580 °C in diesel fuel at 3.5 kW load. The exhaust gas temperature of diesel fuel has the highest value at all powers. While diesel + AdBlue fuel mixtures had the lowest exhaust gas temperature at loads below 2 kW, the lowest temperature was realized in diesel + urea + citric acid mixture after 2 kW load.

The variation of O_2 emission values with engine load is shown in Fig. 10 for different fuel mixtures. A part of the air taken into the cylinder consists of oxygen atoms. While some of the oxygen atoms taken with the air are burned, the unburned oxygen is thrown out of the exhaust. In studies on mixing oxygen-rich chemicals with water content into diesel fuels, it is seen that the amount of oxygen is released in the cylinder, causing an increase in the amount of oxygen emission [37,50]. The lowest O_2 was 17.05% for the motoring condition in diesel + urea + citric acid mixture. The highest O_2 was 19.85% for diesel + urea + citric acid mixture at 3 kW load. In general, the amount of O_2 as exhaust emission increased with increasing load. Diesel + AdBlue mixture has lower O_2 emissions compared to diesel fuel in all load conditions. On the other hand, other mixtures produced O_2 emissions values close to diesel fuel.

Fig. 11 shows the variation of HC emission values with engine load for different fuel mixtures. HC emissions in internal combustion engines refer to oils and fuels that do not burn in the cylinder. Some researchers frequently state that these emissions are caused by fuel mixtures that do not fully combine with oxygen [51]. Studies explain this situation with low end-of-combustion temperature. In addition, there are many studies reporting that oxygen-rich fuels reduce HC emissions [52,53]. In these studies, it is mentioned that in general, oxygen and fuels with high calorific value are effective in reducing HC emissions by partially increasing the combustion in the cylinder. HC emissions have decreased as the overall trend as engine power increases. It is possible to explain this situation with the combustion end temperature. With the increasing end-of-combustion temperature, the HC emissions in the cylinder continue to decrease. The lowest HC emission was 4 ppm at 3.5 kW engine load for diesel + urea + citric acid mixture. The highest HC emission was 188 ppm at 0.5 kW engine load for diesel + urea mixture. As a general trend, HC emissions decreased with increasing engine load. HC emission of Diesel + Urea mixture increased in all engine load. Diesel + AdBlue and diesel + urea + citric acid mixtures have lower HC emissions compared to diesel fuel.

The variation of particulate emission with load is given in Fig. 12 for different fuel mixtures. PM emissions are extremely important for human health. There are many studies reporting that the oxygen content of chemicals used by mixing with fuel mixtures is effective on these emissions [54]. In general, it has been observed that diesel + urea + citric acid mixture produces the best results in terms of PM emissions at all engine loads. It is possible to explain this situation with the oxygen

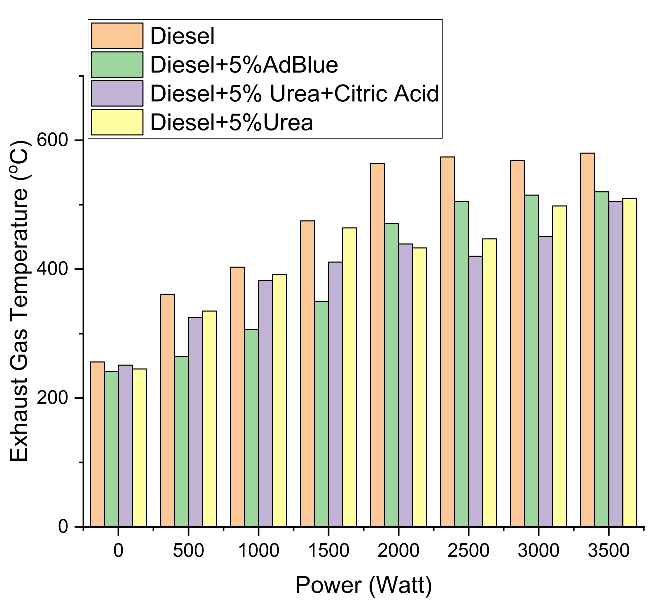


Fig. 9. Variation of Exhaust Gas Temperature values with load.

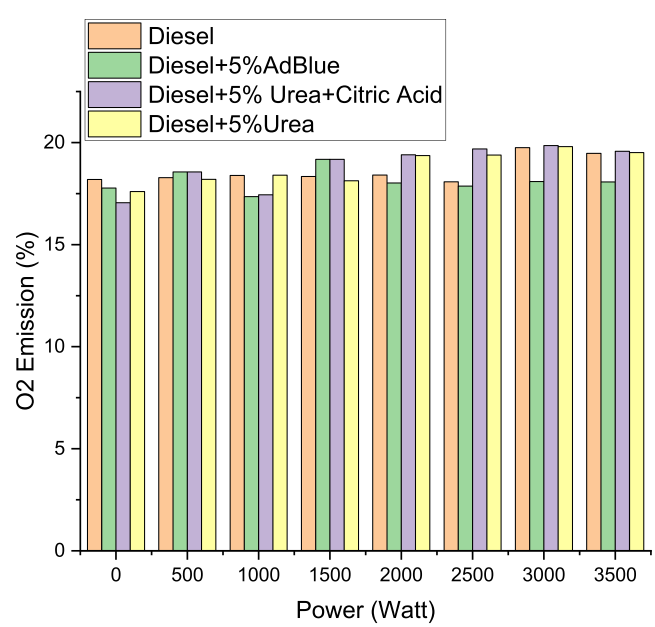


Fig. 10. Variation of O_2 emission values with load.

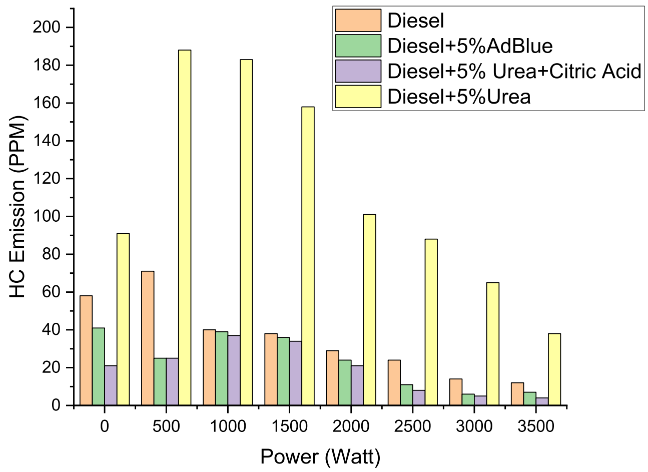


Fig. 11. Variation of HC emission values with load.

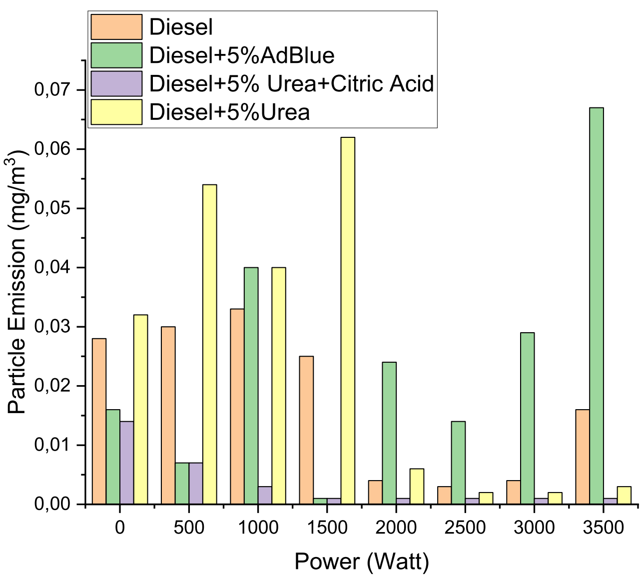


Fig. 12. Variation of Particle emission values with load.

concentration in citric acid and the fact that the heating value does not decrease too much. The lowest PM emission was 0 mg/m3 in diesel and diesel + urea mixtures between 2 and 3.5 kW engine load. The highest PM emission was 0.067 mg/m3 for diesel + AdBlue mixture for 3.5 kW engine load. Diesel + urea mixture has zero particle emission at 2 kW and above loads but has the highest particle emission value between motoring and 1.5 kW load range. Diesel + urea + citric acid mixture created minimum particle emission at low loads. At high loads, it gave very close to zero particle emission.

The variation of brake-specific fuel consumption (BSFC) values with engine load is given in Fig. 13 for different fuel mixtures.

Brake-specific fuel consumption value is an important parameter in alternative fuels studies for diesel engines. Because the fuel is economical, it can be widely used in internal combustion engines in the future. BSFC refers to the amount of fuel required to produce one kW of power for one hour. In this respect, it can be useful to understand how much of the BSFC value is used efficiently in the cylinder because the high combustion efficiency and the use of all the fuel can cause a decrease in the BSFC value. With the addition of water-containing fuel to diesel fuel, there is not much decrease in the heating value. However, a slight increase is observed at low engine loads. This may be due to the water content in the urea and AdBlue fuel mixtures. At low engine loads, low

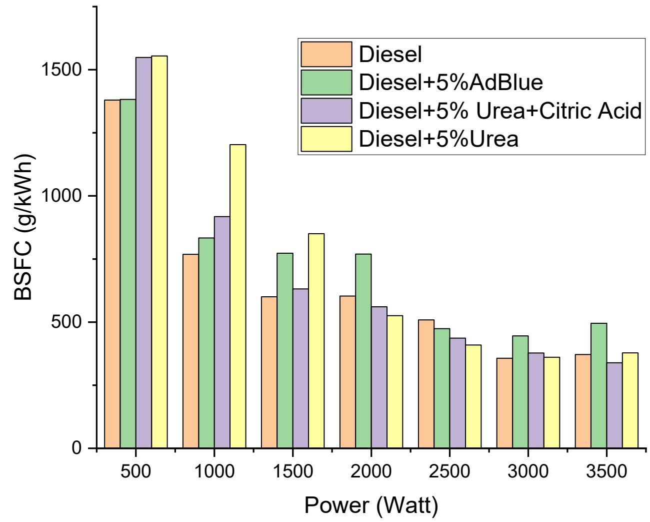


Fig. 13. Variation of Break Specific Fuel Consumption values with load.

end-of-combustion temperature occurs. In this case, the fuel consumption value may have increased since the fuel mixtures could not evaporate completely and the combustion efficiency would decrease. With the increase of the engine load, the BSFC value decreases as a better fuel mixture will be formed with the effect of the oxygen in the fuel content and the end-of-combustion temperature.

The lowest BSFC was 339.12 g/kWh at 3.5 kW engine load in diesel + urea + citric acid mixture. The highest BSFC occurred as 1554.74 g/kWh in diesel + urea mixture at 0.5 kW engine load. As it is known, the low brake-specific fuel consumption value means that the engine is operating at good efficiency. Diesel fuel showed the best efficiency up to 1.5 kW load. Diesel + urea + citric acid fuel mixture from 2 kW to 3.5 kW has a similar BSFC value to diesel fuel. As explained in the previous figures, fuel consumption increased due to the lower calorific value of urea mixtures added to diesel fuel. However, diesel + urea + citric acid mixture has reached a performance close to diesel due to low water content.

4. Conclusion

This study investigated the added effects of AdBlue, urea and urea + citric acid mixtures to diesel fuel on the engine performance and exhaust emissions in a direct injection diesel engine. Experimental study performed at different engine loads on other parameters was investigated.

- It has been observed that urea has a reducing effect on emissions along with its direct addition to fuel. Therefore, perhaps there may be a potential for it to be used as a fuel additive in the future.
- The addition of commercial AdBlue to diesel fuel has reduced the maximum in-cylinder pressure. Addition of commercial AdBlue to diesel fuel caused delay and worsening of combustion. Diesel + urea + citric acid mixture gave performance close to diesel fuel. When heat release rate is evaluated, same situation is observed with in-cylinder pressure graphs. In addition, it is more clearly understood from heat release rate graphs that diesel + urea and diesel + urea + citric acid mixtures accelerate combustion compared to diesel fuel.
- Due to addition of urea and its mixtures to diesel fuel reduces calorific value, the cumulative heat release values decreased compared to diesel fuel. Urea and its mixtures added to diesel fuel did not significantly affect the pressure increase rate.
- When CO_2 emission values are examined, the additions of urea mixtures added to diesel fuel generally reduced CO_2 emission level. However, Diesel + AdBlue fuel mixture has increased CO_2 emissions compared to diesel fuel at all loads. Diesel + AdBlue mixture

increased CO_2 emissions by 38% compared to diesel fuel at 3.5 kW engine load. Compared to diesel fuel, the highest CO_2 emission increase was 53% in diesel + urea + citric acid mixture at 1 kW engine load.

- Diesel + urea + citric acid mixture provided the best 233% improvement in CO emission compared to diesel fuel. In general, it can be said that the addition of urea and its mixtures reduces CO emissions.
- NO_x emission was expected to decrease further with the addition of urea and its mixtures. However, the expected decrease was not fully achieved. The biggest decrease was 12% in diesel + Adblue mixture compared to diesel fuel. The addition of urea and mixtures at different rates may have the expected effect on NO_x emissions. Diesel + urea + citric accid mixture showed the opposite effect of expected and increased NO_x emission at some loads.
- Exhaust gas temperature generally increased as power increased. In general, urea and its mixtures added to diesel fuel as an additive decreased the exhaust gas temperature. Diesel + urea + citric acid mixture showed a 26.82% decrease in 2.5 kW load value compared to diesel fuel.
- When evaluated in terms of HC emission, other mixtures except diesel + urea mixture significantly reduced HC emissions. Especially the diesel + urea + citric acid mixture provided a 300% improvement in maximum power value.
- Adding AdBlue to diesel fuel increased the amount of particulate matter. Other mixture produced particulate matter emissions similar to diesel fuel.
- Addition of AdBlue to diesel fuel increased BSFC except for 2.5 kW engine load. Other mixtures gave a result close to diesel fuel in terms of BSFC. Diesel + urea + citric acid mixture provided the minimum BSFC value at 3.5 kW load. Diesel + urea + citric acid mixture provided an improvement of about 8% compared to Diesel fuel.

As a result, the addition of urea and citric acid to diesel has improved especially HC, CO, and NOx emissions. The use of urea alone significantly increased HC and PM. However, diesel + urea + citric acid seems to be a great combination. Cost reduction can be achieved by eliminating AdBlue injectors used by vehicle manufacturers to avoid exceeding the Euro emission limit. Besides, urea and water mixture in different rates to diesel fuel seems to be a subject to be studied. It is crucial to carry out studies on the effects of the corrosion effect of water and urea on engine parts in future studies.

CRediT authorship contribution statement

Usame Demir: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft, Writing – review & editing. **Avni Kozan:** Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – review & editing. **Salih Özer:** Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] 2020 Statistics | www.oica.net n.d. https://www.oica.net/category/production-statistics/2020-statistics/ (accessed August 20, 2021).

[2] Fuel types of new cars: electric 10.5%, hybrid 11.9%, petrol 47.5% market share full-year 2020 – ACEA – European Automobile Manufacturers' Association n.d. https://www.acea.auto/fuel-pc/fuel-types-of-new-cars-electric-10-5-hybrid-11-9-petrol-47-5-market-share-full-year-2020/ (accessed August 20, 2021).

[3] Fontanarosa D, De Giorgi MG, Ciccarella G, Pescini E, Ficarella A. Combustion performance of a low NOx gas turbine combustor using urea addition into liquid fuel. Fuel 2021;288:119701. https://doi.org/10.1016/j.fuel.2020.119701.

[4] Ström H, Lundström A, Andersson B. Choice of urea-spray models in CFD simulations of urea-SCR systems. Chem Eng J 2009;150(1):69–82. https://doi.org/10.1016/j.cej.2008.12.003.

[5] Varna A, Spiteri AC, Wright YM, Dimopoulos Eggenschwiler P, Boulouchos K. Experimental and numerical assessment of impingement and mixing of urea–water sprays for nitric oxide reduction in diesel exhaust. Appl Energy 2015;157:824–37. https://doi.org/10.1016/J.APENERGY.2015.03.015.

[6] Fluid Dynamic Comparison of AdBlue Injectors for SCR Applications on JSTOR n.d. https://www.jstor.org/stable/26278121?seq=1#metadata_info_tab_contents (accessed August 20, 2021).

[7] Jeong S-J, Lee S-J, Kim W-S. Numerical study on the optimum injection of urea-water solution for SCR DeNOx system of a heavy-duty diesel engine to improve DeNOx performance and reduce NH3 slip. Environ Eng Sci 2008;25(7):1017–36. https://doi.org/10.1089/ees.2007.0224.

[8] Mehregan M, Moghiman M. Effects of nano-additives on pollutants emission and engine performance in a urea-SCR equipped diesel engine fueled with blended-biodiesel. Fuel 2018;222:402–6. https://doi.org/10.1016/J.FUEL.2018.02.172.

[9] López JM, Jiménez F, Aparicio F, Flores N. On-road emissions from urban buses with SCR + Urea and EGR + DPF systems using diesel and biodiesel. Transp Res Part D Transp Environ 2009;14:1–5. https://doi.org/10.1016/J.TRD.2008.07.004.

[10] KOEBEL Manfred, Elsener Martin, Marti Thomas. NOx-reduction in diesel exhaust gas with urea and selective catalytic reduction. Combust Sci Technol 1996;121(1-6):85–102. https://doi.org/10.1080/00102209608935588.

[11] Miller WR, Klein JT, Mueller R, Doelling W, Zuerbig J. The development of urea-SCR technology for US heavy duty trucks. SAE Tech Pap 2000. https://doi.org/10.4271/2000-01-0190.

[12] Pressure loss of urea-SCR converter and its influence on diesel engine performance–《Transactions of the Chinese Society of Agricultural Engineering》2011年08期 n.d. http://en.cnki.com.cn/Article_en/CJFDTOTAL-NYGU201108031.htm (accessed August 20, 2021).

[13] Guo J, Ge Y, Hao L, Tan J, Li J, Feng X, et al. On-road measurement of regulated pollutants from diesel and CNG buses with urea selective catalytic reduction systems. AtmEn 2014;99:1–9. https://doi.org/10.1016/J.ATMOSENV.2014.07.032.

[14] Gekas I, Gabrielsson P, Johansen K, Bjørn I, Kjær JH, Reczek W, et al. Performance of a urea SCR system combined with a PM and fuel optimized heavy-duty diesel engine able to achieve the euro v emission limits. SAE Tech Pap 2002. https://doi.org/10.4271/2002-01-2885.

[15] An H, Yang WM, Li J, Zhou DZ. Modeling analysis of urea direct injection on the NOx emission reduction of biodiesel fueled diesel engines. Energy Convers Manage 2015;101:442–9. https://doi.org/10.1016/J.ENCONMAN.2015.06.008.

[16] Xu L, McCabe RW, Hammerle RH. NOx self-inhibition in selective catalytic reduction with urea (ammonia) over a Cu-zeolite catalyst in diesel exhaust. Appl Catal B Environ 2002;39(1):51–63. https://doi.org/10.1016/S0926-3373(02)00074-7.

[17] Solaimuthu C, Govindarajan P. Performance evaluation of a urea-water selective catalytic reduction (SCR) for a diesel engine with mahua bio diesel. Energy Sour Part A Recover Util Environ Eff 2015;37(13):1424–31. https://doi.org/10.1080/15567036.2011.621012.

[18] Sharma S, Kumar N, Jain S, Kumar S. Scope of Fe-ZSM5 zeolite based urea-scr with fish oil bio-diesel fuel in compressed ignition engine. SAE Tech Pap 2014;1. https://doi.org/10.4271/2014-01-1541.

[19] Lambert C, Vanderslice J, Hammerle R, Belaire R. Application of urea SCR to light-duty diesel vehicles. SAE Tech Pap 2001. https://doi.org/10.4271/2001-01-3623.

[20] Blakeman PG, Chandler GR, John GA, Wilkins AJJ. Investigations into NOx Aftertreatment with Urea SCR for light-duty diesel vehicles. SAE Tech Pap 2001. https://doi.org/10.4271/2001-01-3624.

[21] Kim HJ, Lim Y, Do EM. Study on the exhaust emission characteristics in the diesel engine with the urea-SCR system according various urea contents rate. SAE Tech Pap 2013;1. https://doi.org/10.4271/2013-01-0089.

[22] (12) Effects of B20 fuel and catalyst entrance section length on the performance of urea SCR in a light-duty diesel engine n.d. https://www.researchgate.net/publication/254726186_Effects_of_B20_fuel_and_catalyst_entrance_section_length_on_the_performance_of_urea_SCR_in_a_light-duty_diesel_engine (accessed August 20, 2021).

[23] IJMER n.d. http://www.ijmer.com/pages/vol3-issue2.html (accessed August 20, 2021).

[24] Gray JT, Dimitroff E, Meckel NT, Quillian RD. Ammonia fuel – Engine compatibility and combustion. SAE Tech Pap 1966. https://doi.org/10.4271/660156.

[25] Alloune R, Balistrou M, Awad S, Loubar K, Tazerout M. Performance, combustion and exhaust emissions characteristics investigation using Citrullus colocynthis L. biodiesel in DI diesel engine. J Energy Inst 2018;91(3):434–44. https://doi.org/10.1016/j.joei.2017.01.009.

[26] Karagöz Y, Sandalcı T, Koylu UO, Dalkılıç AS, Wongwises S. Effect of the use of natural gas–diesel fuel mixture on performance, emissions, and combustion characteristics of a compression ignition engine: Http://DxDoiOrg/101177/1687814016643228 2016;8:1–13. https://doi.org/10.1177/1687814016643228.

[27] Deb M, Sastry GRK, Bose PK, Banerjee R. An experimental study on combustion, performance and emission analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation. Int J Hydrogen Energy 2015;40(27):8586–98. https://doi.org/10.1016/j.ijhydene.2015.04.125.

[28] Özener O, Yüksek L, Ergenç AT, Özkan M. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel 2014; 115:875–83. https://doi.org/10.1016/J.FUEL.2012.10.081.

[29] Venu H, Madhavan V. Influence of diethyl ether (DEE) addition in ethanol-biodiesel-diesel (EBD) and methanol-biodiesel-diesel (MBD) blends in a diesel engine. Fuel 2017;189:377–90. https://doi.org/10.1016/J.FUEL.2016.10.101.

[30] Sarvestani NS, Abbaspour-Fard MH, Tabasizadeh M, Nayebzadeh H, Van TC, Jafari M, et al. Synthesize of magnetite Mg-Fe mixed metal oxide nanocatalyst by urea-nitrate combustion method with optimal fuel ratio for reduction of emissions in diesel engines. J Alloys Compd 2020;838:155627. https://doi.org/10.1016/j.jallcom.2020.155627.

[31] Venu H, Appavu P. Al2O3 nano additives blended Polanga biodiesel as a potential alternative fuel for existing unmodified DI diesel engine. Fuel 2020;279:118518. https://doi.org/10.1016/j.fuel.2020.118518.

[32] Espinosa EAM, Rodríguez RP, Sierens R, Verhelst S. Emulsification of waste cooking oils and fatty acid distillates as diesel engine fuels: An attractive alternative. Int J Sustain Energy Plan Manage 2016;9:3–16. https://doi.org/10.5278/IJSEPM.2016.9.2.

[33] Emiroğlu AO, Şen M. Combustion, performance and exhaust emission characterizations of a diesel engine operating with a ternary blend (alcohol-biodiesel-diesel fuel). Appl Therm Eng 2018;133:371–80. https://doi.org/10.1016/J.APPLTHERMALENG.2018.01.069.

[34] Özer S. The effect of diesel fuel-tall oil/ethanol/methanol/isopropyl/n-butanol/fusel oil mixtures on engine performance and exhaust emissions. Fuel 2020;281: 118671. https://doi.org/10.1016/j.fuel.2020.118671.

[35] Awad OI, Mamat R, Ali OM, Yusri IM, Abdullah AA, Yusop AF, et al. The effect of adding fusel oil to diesel on the performance and the emissions characteristics in a single cylinder CI engine. J Energy Inst 2017;90(3):382–96. https://doi.org/10.1016/j.joei.2016.04.004.

[36] Yesilyurt MK, Yilbasi Z, Aydin M. The performance, emissions, and combustion characteristics of an unmodified diesel engine running on the ternary blends of pentanol/safflower oil biodiesel/diesel fuel. J Therm Anal Calorim 2020;140(6): 2903–42. https://doi.org/10.1007/s10973-020-09376-6.

[37] Rosid R, Sudarmanta B, Atmaja L, Özer S. An experimental study of the addition of air mass flow rate using a 30% emulsion-fueled diesel engine at high load. Automot Exp 2020;3:57–67. https://doi.org/10.31603/ae.v3i2.3618.

[38] Aghbashlo M, Tabatabaei M, Mohammadi P, Khoshnevisan B, Rajaeifar MA, Pakzad M. Neat diesel beats waste-oriented biodiesel from the exergoeconomic and exergoenvironmental point of views. Energy Convers Manage 2017;148:1–15. https://doi.org/10.1016/J.ENCONMAN.2017.05.048.

[39] Ganesan S, Devarajan Y. Emission investigation of higher alcohol and biodiesel blends in constant speed diesel engine. Https://DoiOrg/101080/01430750201815176695 2018;42:11–4. https://doi.org/10.1080/01430750.2018.1517695.

[40] Hoseini SS, Sobati MA. Performance and emission characteristics of a diesel engine operating on different water in diesel emulsion fuels: optimization using response surface methodology (RSM). Front Energy 2019;13(4):636–57. https://doi.org/10.1007/s11708-019-0646-7.

[41] Giakoumis EG, Rakopoulos CD, Dimaratos AM, Rakopoulos DC. Exhaust emissions of diesel engines operating under transient conditions with biodiesel fuel blends. Prog Energy Combust Sci 2012;38(5):691–715. https://doi.org/10.1016/j.pecs.2012.05.002.

[42] Krishna MVSM, Prakash TO, Ushasri P, Janardhan N, Murthy PVK. Experimental investigations on direct injection diesel engine with ceramic coated combustion chamber with carbureted alcohols and crude jatropha oil. Renew Sustain Energy Rev 2016;53:606–28. https://doi.org/10.1016/J.RSER.2015.09.011.

[43] Tamilvanan A, Balamurugan K, Ashok B, Selvakumar P, Dhamotharan S, Bharathiraja M, et al. Effect of diethyl ether and ethanol as an oxygenated additive on Calophyllum inophyllum biodiesel in CI engine. Environ Sci Pollut Res 2021;28 (26):33880–98. https://doi.org/10.1007/s11356-020-10624-3.

[44] Ağbulut Ü, Yeşilyurt MK, Sarıdemir S. Wastes to energy: Improving the poor properties of waste tire pyrolysis oil with waste cooking oil methyl ester and waste fusel alcohol – A detailed assessment on the combustion, emission, and performance characteristics of a CI engine. Energy 2021;222:119942. https://doi.org/10.1016/j.energy.2021.119942.

[45] Khatri D, Goyal R. Performance, emission and combustion characteristics of water diesel emulsified fuel for diesel engine: a review. Mater Today Proc 2020;28: 2275–8. https://doi.org/10.1016/J.MATPR.2020.04.560.

[46] Tamilvanan A, Balamurugan K, Vijayakumar M. Effects of nano-copper additive on performance, combustion and emission characteristics of Calophyllum inophyllum biodiesel in CI engine. J Therm Anal Calorim 2019;136(1):317–30. https://doi.org/10.1007/s10973-018-7743-4.

[47] Nour M, Attia AMA, Nada SA. Combustion, performance and emission analysis of diesel engine fuelled by higher alcohols (butanol, octanol and heptanol)/diesel blends. Energy Convers Manage 2019;185:313–29. https://doi.org/10.1016/J.ENCONMAN.2019.01.105.

[48] IŞIK MZ. Comparative experimental investigation on the effects of heavy alcohols-safflower biodiesel blends on combustion, performance and emissions in a power generator diesel engine. Appl Therm Eng 2021;184:116142. https://doi.org/10.1016/j.applthermaleng.2020.116142.

[49] Sheng Y, Brindhadevi K, Eed EM, Xia C, Chi NTL. Enzymatic lipase-based methyl esterified Citrullus colocynthis L. biodiesel for improved combustion, performance and emission characteristics. Fuel 2022;307:121899. https://doi.org/10.1016/j.fuel.2021.121899.

[50] Vellaiyan S. Enhancement in combustion, performance, and emission characteristics of a biodiesel-fueled diesel engine by using water emulsion and nanoadditive. Renew Energy 2020;145:2108–20. https://doi.org/10.1016/J.RENENE.2019.07.140.

[51] Pitchamuthu G, Gokulnath R. Effect of additives on emissions of DI CI engine fuelled with algae/Mangifera indica blends. Https://DoiOrg/101080/0143075020201839552 2020. https://doi.org/10.1080/01430750.2020.1839552.

[52] Hasan AO, Al-Rawashdeh H, Al-Muhtaseb AH, Abu-jrai A, Ahmad R, Zeaiter J. Impact of changing combustion chamber geometry on emissions, and combustion characteristics of a single cylinder SI (spark ignition) engine fueled with ethanol/gasoline blends. Fuel 2018;231:197–203. https://doi.org/10.1016/J.FUEL.2018.05.045.

[53] Yuvarajan D, Dinesh Babu M, BeemKumar N, Amith Kishore P. Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine. Atmos Pollut Res 2018;9(1):47–52. https://doi.org/10.1016/j.apr.2017.06.003.

[54] Park W, Park S, Reitz RD, Kurtz E. The effect of oxygenated fuel properties on diesel spray combustion and soot formation. Combust Flame 2017;180:276–83. https://doi.org/10.1016/J.COMBUSTFLAME.2016.02.026.