Article citation info:
Samoilenko D, Savchenko A, Kravchenko S. Improving the performance of diesel engines fueled with water-fuel emulsion. Combustion Engines. 2023;194(3):116-122. https://doi.org/10.19206/CE-169139

Dmytro SAMOILENKO
Anatolii SAVCHENKO
Serhii KRAVCHENKO

Combustion Engines
Polish Scientific Society of Combustion Engines

Improving the performance of diesel engines fueled with water-fuel emulsion

ARTICLE INFO

Received: 31 May 2023
Revised: 27 June 2023
Accepted: 1 July 2023
Available online: 20 July 2023

Due to unique properties, production and operation features, water-fuel emulsion (WFE) could be considered as one of the most promising type of alternative fuels for diesel engines. Experimental research showed that compared to traditional diesel fuel, application of water-fuel emulsion allows to reduce nitrogen oxides and soot emissions, which is due primarily to a decrease in the level of maximum temperatures in the engine cylinder, as well as a more uniform distribution of fuel over the combustion chamber volume thanks to its secondary dispersion (micro-explosion phenomena). To control the stability of water-fuel emulsion properties during engine operation it is recommended to install water content sensor in the fuel supply system.

Key words: *diesel, water-fuel emulsion, combustion process, micro-explosion, water particles size distribution*

1. Introduction

Over a long period of time, internal combustion engines have become widespread in all spheres of human activity, which is explained by their numerous advantages. However, it is the extremely wide application of ICE has caused a number of global problems, related to the depletion of world oil reserves, atmospheric pollution with toxic substances, global warming etc. There is a solution that allows to partially solve the mentioned problems through application of alternative fuels in internal combustion engines [3, 7, 10, 13, 15]. In this content a water-fuel emulsion (WFE) could be treated as one of the most promising type of alternative fuels due to the combination of the unique properties, characteristics, production and operation features [1, 2, 5, 14]. The main advantages of WFE are as follows: reduction of average effective fuel consumption, a significant reduction in emissions of soot and nitrogen oxides in exhaust gases of diesel engines [2, 4, 5, 14], the absence of the need to make changes in the engine design, the possibility of large-scale fuel production and relative simplicity of its production [9, 14].

There is a number of theoretical research on numerical simulations of spark ignition and diesel engines fueled with water-fuel emulsion using AVL Boost simulation software that are shown in [6, 11, 12]. According to numerous studies, the use of WFE makes it possible to reduce emissions of nitrogen oxides by up to 50...80%, reduce soot emissions by up to 35%, and improve diesel fuel efficiency by 3...5% [1, 2, 5].

Experimental studies indicate a noticeable decrease in the temperature of exhaust gases when water-fuel emulsion is used [4, 14]. This is mainly due to additional heat consumed for heating and evaporation of water contained in the WFE (compared to original diesel fuel), as well as an increase in the mass and specific heat capacity of the combustible fluid inside of the cylinder. Decrease in the exhaust gas temperature at the inlet to the turbine of the turbocharger can potentially cause a drop in air pressure in the intake manifold of the diesel engine. As a result, the air excess factor should decrease as well, which in turn has a strong influence on the combustion process. However, experimental studies showed improvement in fuel combustion characteristics when WFE with a moderate water content (no more than 20...25%) is used. Thus, the potential reduction in the amount of fresh air delivered (due to the decrease in boost pressure) is fully compensated by the improvement in uniformity of liquid fuel distribution over the volume of the combustion chamber thanks to the micro-explosion phenomenon [8].

2. The influence of the properties of the water-fuel emulsion on the performance of the diesel engine

To determine the effect of WFE on diesel engine performance, experiments were conducted on compression ignition engine fueled with standard diesel fuel and water-fuel emulsions. WFE was characterized by 15 % of water content (by mass units). The specification of the experimental diesel engine is given in Table 1. The properties of diesel fuel and WFE, that were used in the study, are shown in Table 2.

Table 1. Technical characteristics of the experimental engine

Engine parameter	Value
Number of cylinders	4 (in-line)
Cylinder diameter, mm	120
Piston stroke, mm	140
Compression ratio	15.5
Nominal power, kW	100
Nominal crankshaft rotational speed, rpm	2000
Maximum torque, N·m	632

Table 2. Physical, chemical properties of DF and WFE used in the study

Parameter	Diesel Fuel	Water-fuel emulsion
Density at temperature of 15ºC, kg/m^3	829	857
Heat capacity, kJ/kg·K	2.02	2.37
Low calorific value of the fuel, kJ/kg	42,500	35,100
The ignition temperature in a closed crucible (no lower than), ºC	70.5	ignition is missing
Water content by mass, %	0	15
Kinematic viscosity at temperature of 20ºC, mm^2/s	5.15	6.19

The results of experimental study where the effect of using WFE on fuel efficiency and toxic substances emissions were established are given in Table 3 and Table 4. Effective efficiency of the engine was chosen as a criterion of fuel efficiency in this study.

Table 3. Indices of the CI engine fueled with a standard diesel fuel

n, rpm	P_e, MPa	η_e	W_{NOx}, ppm	W_{CO}, ppm	W_{CH}, ppm	Soot, opacity in %
2000	0.95	0.3873	850	260	90	16.90
	0.7	0.3687	520	240	100	13.7
	0.474	0.3359	350	250	120	10.8
	0.24	0.2611	210	300	135	5.5
	0.099	0.1541	145	430	170	3.4
1500	1.076	0.4117	1380	300	90	24.2
	0.809	0.4088	1255	170	115	13.8
	0.544	0.3791	840	130	140	9.4
	0.279	0.3099	365	200	175	5.1
	0.14	0.2223	190	320	210	2.6
1000	0.752	0.3962	1410	620	105	40
	0.558	0.3892	1180	430	120	27.5
	0.377	0.3642	940	330	150	11
	0.181	0.291	305	440	195	4.5
	0.098	0.2138	175	570	240	2.2

Table 4. Indices of the CI engine fueled with WFE

n, rpm	P_e, MPa	η_e	W_{NOx}, ppm	W_{CO}, ppm	W_{CH}, ppm	Soot, opacity in %
2000	0.95	0.4072	725	180	100	11.9
	0.7	0.4025	425	150	105	7.7
	0.474	0.3615	270	170	120	5.1
	0.24	0.2731	120	240	140	2.6
	0.099	0.1611	70	330	180	1.5
1500	1.076	0.4414	1145	220	90	16.1
	0.809	0.433	995	140	100	10.1
	0.544	0.4108	697	110	135	5.2
	0.279	0.3393	257	160	175	1.9
	0.14	0.2416	128	250	200	1.2
1000	0.752	0.4188	845	490	125	29.5
	0.558	0.4168	690	350	135	16.5
	0.377	0.3906	514	250	160	8.4
	0.181	0.3105	160	400	210	3.6
	0.098	0.218	60	490	265	1.8

As it can be seen from Table 3 and Table 4 application of WFE makes it possible to reduce soot from exhaust gases by 18...56%. Moreover, at a high crankshaft rotation speed, the positive effect of WFE application on soot emission is greater than at a low crankshaft rotation speed.

At all investigated modes, the concentration of nitrogen oxides decreased by 14...66% when WFE was used. The maximum reduction in nitrogen oxide emissions refers to low-load modes. It can be also seen that the use of water-fuel emulsion helps to increase the effective efficiency from 0,7 to 3,4% depending on the load and crankshaft rotation speed.

3. The influence of the application of the water-fuel emulsion on mixture formation and combustion process in diesel engine

The influence of application of WFE on the processes of mixture formation, combustion and exploitation of the diesel engine was evaluated by comparing a number of indicators of the engine cycle in ICE running on WFE and traditional diesel fuel at the same operating modes.

As it can be seen from the indicator diagrams (Fig. 1) the maximum pressure in the cycle is greater for diesel running on traditional DF when compared to WFE. At the same time, there are differences in pressure increase rate that could be observed from the moment of the start of combustion till the moment of reaching the maximum pressure. To identify the reasons for these differences, the processes of fuel injection and combustion were analyzed. From the given dependences of the change in fuel pressure at the injector inlet on the crankshaft rotation angle (Fig. 2), it can be seen that the start of injection for WFE and DF is almost the same. A little earlier start of DF injection could be explained by its lower compressibility. Injection of WFE lasts longer for 3…5 degrees of crank angle. It could be explained by increased fuel supply per cycle for the same power. As a result of increased fuel supply in one cycle and higher fuel viscosity, the maximum injection pressure of WFE increases by 14–18%, which can lead to an improvement in the fuel atomization process.

In-cylinder temperature dependences for diesel engine running on DF and WFE are shown in Fig. 3. It can be seen that the maximum temperature in the cylinder decreases by 15–30 K when WFE is used. The specified decrease in temperature level is explained by the increased heat capacity of the water-fuel emulsion (Table 2) which will be resulted in the increased amount of heat consumed for fuel heating and its evaporation. Reduction in the maximum temperature of the cycle has a positive effect on nitrogen oxide emissions that was confirmed by the previous experimental studies where WFE was used as a fuel for diesel engines.

Further analysis was conducted based on heat release rate dependences that are shown in Fig. 4. As it can be seen from the Fig, the release of heat in the engine cylinder starts with a 3..5 crank angle delay when WFE is used. Taking into account the almost identical moment of the start of injection for both types of fuels, the increase in the ignition delay period by 2…4 crank angles can be explained by an increase in activation energy of fuel combustion and a decrease in temperature and pressure inside of the cylinder at the beginning of fuel injection process when WFE is used.

According to Fig. 4, the heat release rate as well as the area under the heat release curve at the second combustion phase (premixed combustion) is greater for WFE. It can be explained by the fact that a larger amount of diesel-water emulsion fuel will evaporate during a comparatively longer ignition delay period. Accordingly, the share of fuel burning during the second combustion phase and the rate of heat release during this phase increases.

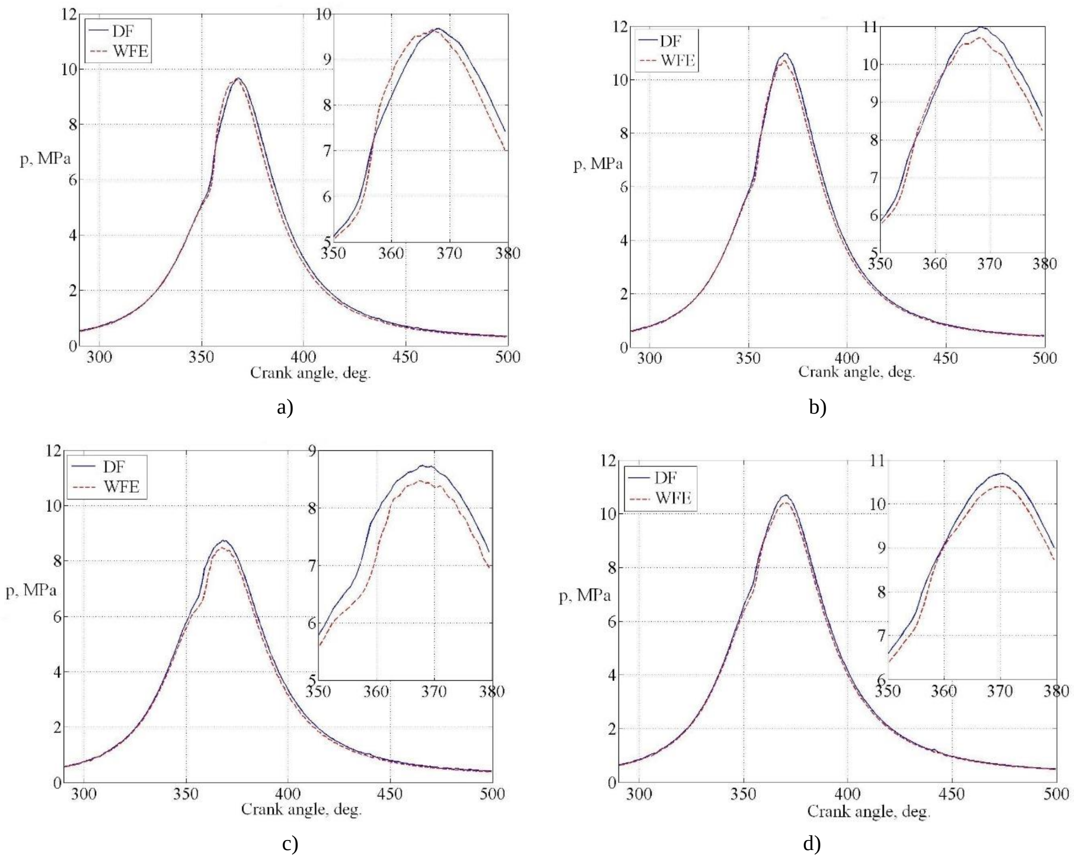

Fig. 1. Indicator diagrams of a diesel engine running on DF and WFE: a) n = 1500 rpm, P_e = 0.809 MPa; b) n = 1500 rpm, P_e = 1.076 MPa; c) n = 2000 rpm, P_e = 0.71 MPa; d) n = 2000 rpm, P_e = 0.95 MPa

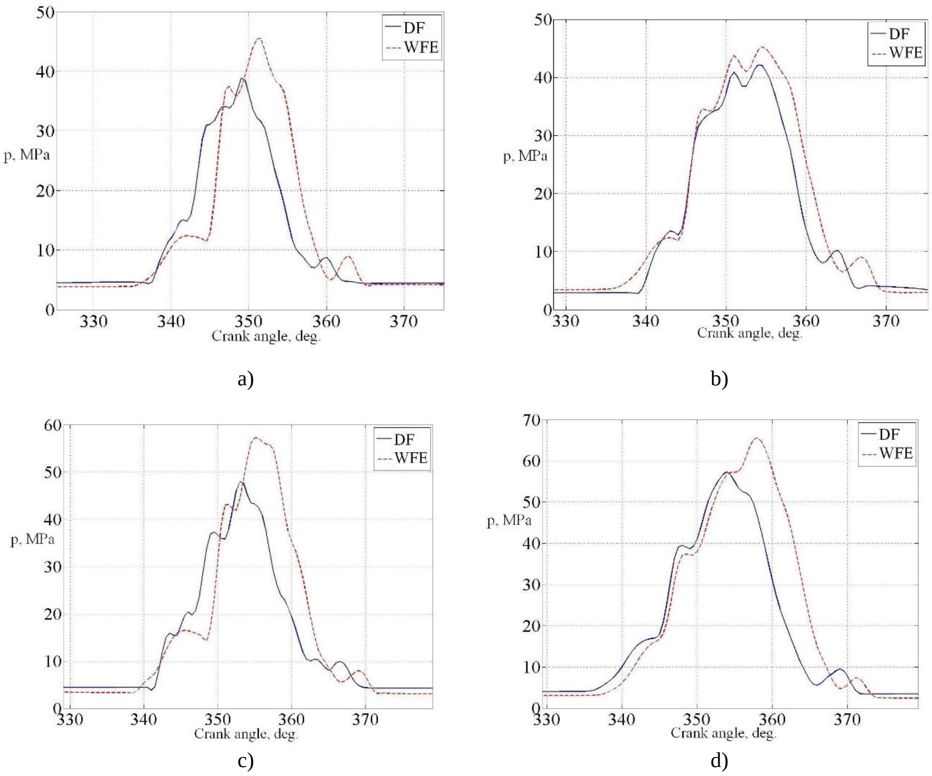

Fig. 2. Fuel pressure at the injector inlet for diesel engine running on DF and WFE: a) n = 1500 rpm, P_e = 0.809 MPa; b) n = 1500 rpm, P_e = 1.076 MPa; c) n = 2000 rpm, P_e = 0.71 MPa; d) n = 2000 rpm, P_e = 0.95 MPa

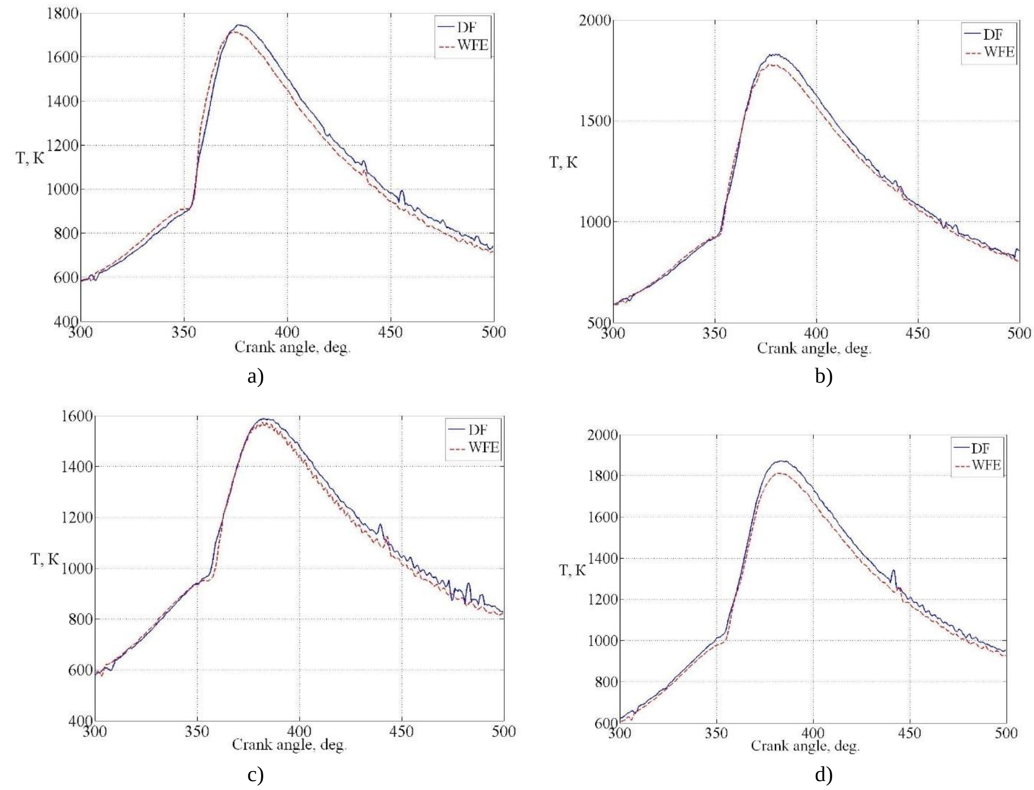

Fig. 3. In-cylinder temperature for diesel engine running on DF and WFE: a) n = 1500 rpm, P_e = 0.809 MPa; b) n = 1500 rpm, P_e = 1.076 MPa; c) n = 2000 rpm, P_e = 0.71 MPa; d) n = 2000 rpm, P_e = 0.95 MPa

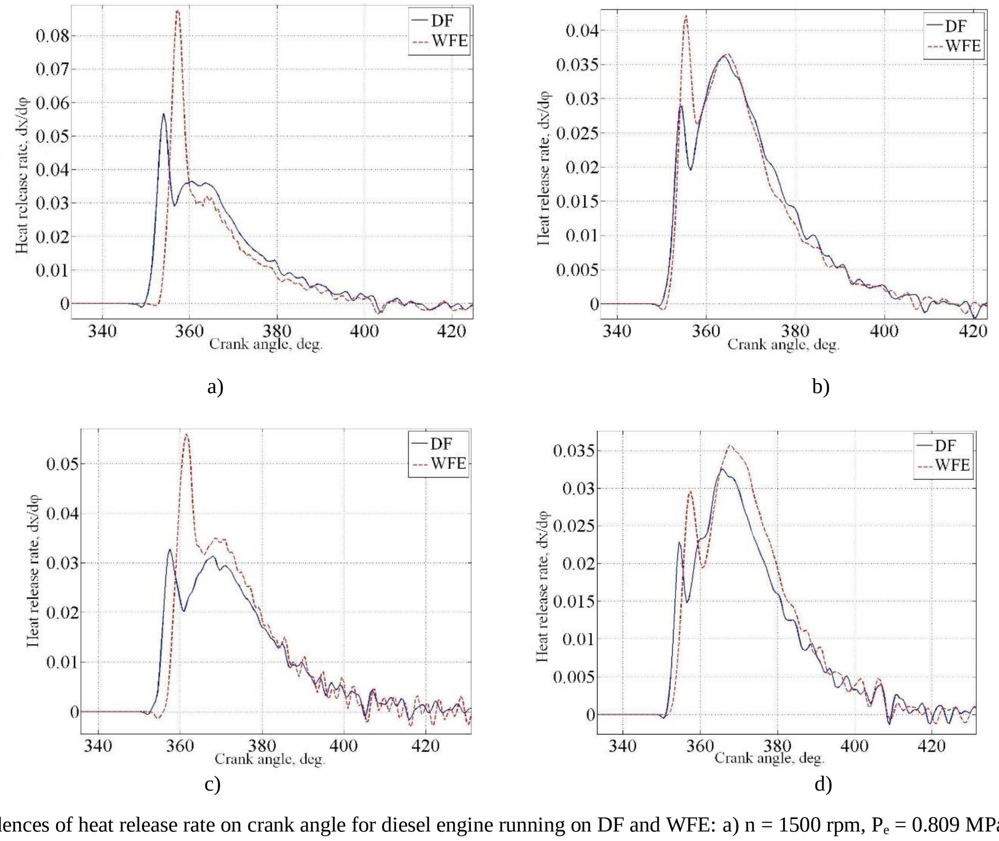

Fig. 4. Dependences of heat release rate on crank angle for diesel engine running on DF and WFE: a) n = 1500 rpm, P_e = 0.809 MPa; b) n = 1500 rpm, P_e = 1.076 MPa; c) n = 2000 rpm, P_e = 0.71 MPa; d) n = 2000 rpm, P_e = 0.95 MPa

The analysis of the mixing-controlled combustion phase shows that the rate of heat release during the combustion of WFE is greater than during the DF combustion in this phase and it is evident for the higher crankshaft rotation speeds.

The moment of the end of combustion (the moment when the rate of heat release is equal to zero) for DF and WFE is approximately the same. Taking into account the later start of heat release in the premixed combustion phase (for WFE), it can be concluded that the duration of the combustion of WFE is shorter than the diesel fuel combustion duration despite the fact that the heat capacity of WFE is greater than that of DF. Thus, an increased combustion rate of WFE could be observed compared to DF combustion.

There are several theories that explain the influence of WFE on combustion processes in compression ignition engines. For example, in one theory the influence of WFE is primarily explained by the catalytic effect of water dissociation products on the fuel combustion process. Under high temperature conditions in the combustion chamber of a diesel engine, water vapor dissociates into hydrogen and oxygen, as well as into hydrogen radicals and hydroxyl groups. The presence of hydrogen radicals in the combustion chamber accelerates chemical reactions and results in a more complete combustion of hydrocarbons.

Another theory suggests that there is a secondary atomization of fuel in the combustion chamber due to the boiling of water (micro-explosions phenomena) stored inside a water-fuel emulsion droplet.

Based on analysis of heat release rate dependences shown in Fig.4 it could be assumed that both mechanisms occur during water-fuel emulsion combustion in CI engine. Thus, the micro-explosion phenomenon can have a significant impact on the combustion processes at its initial stage because the high dispersity of fuel atomization has the greatest positive effect on the initiation of the combustion process, and secondary atomization of fuel due to the micro-explosion phenomenon can contribute to the improvement of fuel atomization characteristics. From another point, the catalytic effect of hydrogen radicals and hydroxyl groups (water dissociation products) presented in WFE allows to increase in combustion rate during the mixing-controlled combustion phase and even in the late combustion phase. During these combustion stages, the local concentration of active radicals is significant in the immediate vicinity to unburned fuel droplets and it contributes to its rapid combustion. Thus, application of WFE in diesel engines makes it possible to simultaneously improve fuel efficiency and environmental characteristics of the ICE.

Considering the above-mentioned differences in the combustion process for CI engine running on diesel fuel and water-fuel emulsion, and in order to achieve maximum efficiency when WFE is used, special attention should be paid to the stability of water-fuel emulsion. In order to ensure the reliable operation of the diesel engine fueled with WFE, a study on the stability behavior of WFE samples with different water content was conducted. The Zeta-Sizer device was used to determine the size of water particles in the water-fuel emulsion. For this experiment, a number of WFE samples were produced with the water content from 0 to 15% (by mass).

4. Study on the stability behavior of water-fuel emulsion

To study the stability behavior of the WFE, a number of measurements of the size distribution of water particles in the fuel for specified time intervals were performed. Based on the results of these measurements, the relative change in the average size of water particles as a function of time was plotted (Fig. 5).

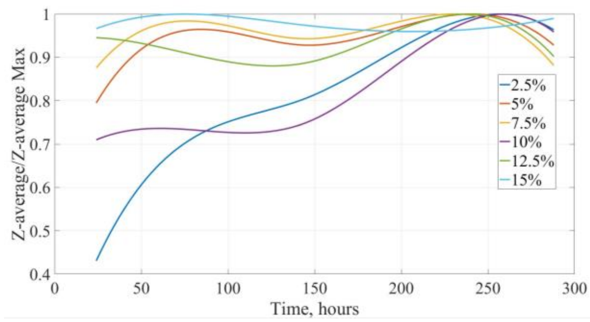

Fig. 5. The relative change in the average size of water particles depending on the time since the sample was made

It can be seen from the chart that the size of water particles increases during the first 200 hours after WFE production, and then it stabilizes. The size distribution of water particles in WFE with different water content is shown in Fig. 6. It can be seen from the Fig.6 that the size of water particles in the emulsified fuel increases with an increase in water content. In this content the risk of loss of WFE stability increases and fuel stratification problems could arise as well.

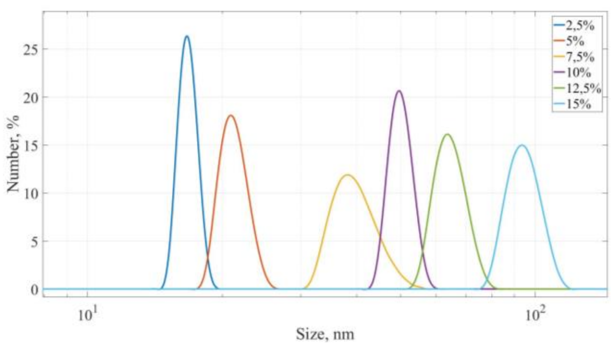

Fig. 6. Size distribution of water particles in water-fuel emulsion for samples with different water contents

The currently mentioned problem is mostly solved through the proper manufacturing technology and specified storage conditions applied to emulsified fuels. But, in order to minimize the risk of WFE stratification during engine exploitation it is recommended to introduce a water content sensor in the fuel delivery system for real-time control of water-fuel emulsion stability. The main requirements for the sensor are sufficiently high precision, high response, compactness, reliability, and relatively low price. Sensors based on absorption spectroscopy meet these requirements to the greatest extent. Such a sensor was used in the research. The results of the study of WFE samples with different water content are shown in Fig. 7. It can be seen from Fig.7 that in several wavelength ranges, the correlation between absorption by the WFE sample and water content in it is clearly traced. Thus, the specified regularity can be used to determine the water content in WFE. In commercial applications, the sensor must determine absorption in one or several relatively narrow wavelength ranges. This will help to simplify and reduce the price of solution without any loss of accuracy of the obtained data on the emulsified fuel composition.

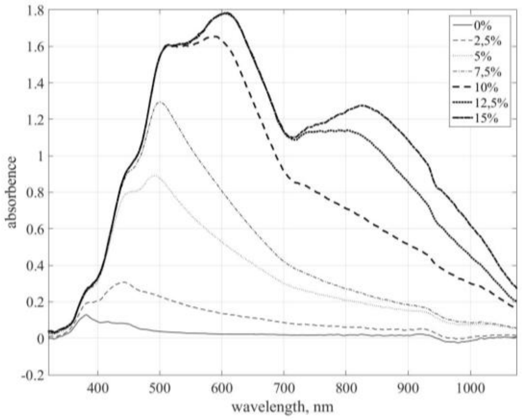

Fig. 7. Results of the study with WFE samples at different water content using absorption spectroscopy method

The use of a water content sensor in the fuel delivery system will make it possible to increase the reliability of operation in diesel engines running on WFE. It can be achieved by analyzing the dynamics of changes in the fuel absorption characteristic over time. Laboratory tests showed that water-fuel emulsion with high homogeneity of the volume structure is characterized by high stability of absorption in each range of wavelength. In the event of a loss of WFE stability (fuel stratification), the absorption value will change rapidly that will be detected by the sensor. Thus, it is possible to implement an algorithm where in emergency mode fuel delivery system will be switched from WFE fuel supply to the traditional diesel fuel supply. The engine should have the reserve fuel tank filled with traditional diesel fuel in this case.

Thus, the implementation of the above-mentioned concept of the adaptive management system with the water content sensor for diesel engine running on WFE would improve not only its reliability but also increase its fuel and environmental performance.

5. Conclusion

1. Application of water-fuel emulsion in diesel engines is a promising solution that could accelerate transformation from traditional fuels to alternative ones accompanied by reduction in engine NO_x and soot emissions.

2. Experimental studies on the influence of the physical and chemical properties of water-fuel emulsions on the environmental and fuel performance of diesel engine were carried out. It was established that concentration of `nitrogen oxides decreased by 14...66% when WFE was used. The maximum reduction in nitrogen oxide emissions refers to low-load modes. At the same time, application of WFE makes it possible to reduce soot formation in exhaust gases by 18...56%. Moreover, at high crankshaft rotation speed, the positive effect of WFE application on soot is greater than at a low crankshaft rotation speeds. The use of water-fuel emulsion helps to increase the effective efficiency from 0.7 to 3.4% depending on the load and crankshaft rotation speed as well.

3. The maximum temperature in the cylinder decreases by 15–30 K when WFE is used. The specified decrease in temperature level is explained by the increased heat capacity of the water-fuel emulsion that will be resulted in increased amount of heat consumed for fuel heating and its evaporation during the combustion process. Reduction in the maximum temperature of the cycle has a positive effect on nitrogen oxide emissions.

4. Based on experimental research results it was established that the ignition delay period and the intensity of combustion during the premixed combustion phase slightly increase for CI engine running on WFE (compare to diesel fuel). At the same time, the moment of the end of the combustion for both types of fuel is the same, despite the longer duration of the water-fuel emulsion fuel supply and increased ignition delay period. It can be explained by the intensification of combustion in mixing-controlled phase when WFE is used.

5. Based on analysis of heat release rate dependences it could assumed that the micro-explosion phenomenon can have a significant impact on the combustion processes at its initial stage when WFE is used. In this case, a high dispersity of fuel atomization has the greatest positive effect on the initiation of combustion, and secondary atomization of fuel due to the micro-explosion phenomenon can contribute to the improvement of fuel atomization characteristics. From another point, the catalytic effect of hydrogen radicals and hydroxyl groups (water dissociation products) presented in WFE allows to increase in combustion rate during mixing-controlled combustion phase and even in the late combustion phase. During these combustion stages, the local concentration of active radicals in the immediate vicinity to unburned fuel droplets is significant and it contributes to its rapid combustion. Thus, the application of WFE in diesel engines makes it possible to simultaneously improve fuel efficiency and environmental characteristics of the ICE.

6. In order to ensure the reliable operation of the diesel engine running on WFE, a study on the stability behavior of WFE samples with different water content (from 0 to 15% by mass) was conducted. It was established that the size of water particles gradually increasing during the first 200 hours after WFE production, and then it stabilizes. Moreover, the size of water particles in the emulsified fuel increases with an increase in water content.

7. It is recommended to use a water content sensor in the fuel delivery system of CI engines running on WFE because it will increase the reliability of its operation. The sensor should analyze the dynamics of changes in the fuel absorption characteristic over time. In the scenario of fuel stratification, the absorption value will change rapidly. In this case, it will be possible to implement an algorithm where fuel delivery system is switched from WFE fuel supply to the traditional diesel fuel supply.

Nomenclature

CI	compression ignition
DF	diesel fuel
ICE	internal combustion engine
WFE	water-fuel emulsion

Bibliography

[1] Al-lwayzy SH, Yusaf T, Saleh K, Yousif B. The Influence of emulsified water fuel containing fresh water microalgae on diesel engine performance, combustion, vibration and emission. Energies. 2019;12(13):2546. https://doi.org/10.3390/en12132546

[2] Badran O, Emeish S, Abu-Zaid M, Abu-Rahmaa T, Al-Hasana M, Al-Ragheba M. Impact of emulsified water/diesel mixture on engine performance and environment. International Journal of Thermal and Environmental Engineering. 2011; 3:1-7. https://doi.org/10.5383/ijtee.03.01.001

[3] Belousov E, Marchenko A, Gritsuk I, Savchuk V, Mitienkova V, Bulgakov N et al. Research of the gas fuel supply process on the compression stroke in ship's low-speed gas-diesel engines. SAE Technical Paper 2020-01-2107. 2020. https://doi.org/10.4271/2020-01-2107

[4] Bukkarapu KR, Jyothi Y, Raju L, Babu G, Narayanan K. A review on current trends in water in oil emulsions. International Journal of Mechanical Engineering and Technology. 2017;8:359-371.

[5] Chaichan MT. Enhancement of DI compression ignition engine performance and emission using diesel-water emulsion as fuel. Al-Rafidain Engineering. 2013;4:29-41. https://doi.org/10.33899/rengj.2013.77216

[6] Choi I, Lee C. Feasibility study of emission reduction on marine engine with variation of emulsified water concentration and turbocharger compression ratio. Appl Sci. 2020;10: 1215. https://doi.org/10.3390/app10041215

[7] Marchenko AP, Semenov VG. Alternative biofuel from rape oil derivatives. Chem Tech Fuels Oil+. 2001;37(3):183-185. https://doi.org/10.1023/A:1017976722355

[8] Nissar Z, Rybdylova O, Sazhin SS, Heikal M, Rashid A, Ismael M. A model for puffing/microexplosions in water/fuel emulsion droplets. Int J Heat Mass Tran. 2020;149:119208. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119208

[9] Oo YM, Legwiriyakul A, Thawornprasert J, Somnuk K. Production of diesel–biodiesel–water fuel nanoemulsions using three-dimensional printed rotor–stator hydrodynamic cavitation. Fuel. 2022;317:123445. https://doi.org/10.1016/j.fuel.2022.123445

[10] Parsadanov I, Marchenko A, Tkachuk M, Kravchenko S, Bulgakov N, Tkachuk M et al. Complex assessment of fuel efficiency and diesel exhaust toxicity. SAE Technical Paper 2020-01-2182. 2020. https://doi.org/10.4271/2020-01-2182

[11] Qadiri U, AlFantazi A. Numerical 1-D simulations on single-cylinder stationary spark ignition engine using micro-emulsions, gasoline, and hydrogen in dual fuel mode. Cleaner Chemical Engineering. 2022;2:100009. https://doi.org/10.1016/j.clce.2022.100009

[12] Qadiri U, Pasha AA, Rahman MM, Raheem MA, Abdul Jameel AG, Pillai SN. Parametric investigation on single cylinder spark ignition engine fueled methanol blends; water-based micro emulsions and conventional gasoline. International Journal of Heat and Technology. 2021;39(3):919-924. https://doi.org/10.18280/ijht.390327

[13] Stępień Z. Synthetic automotive fuels. Combustion Engines. 2023;192(1):78-90. https://doi.org/10.19206/CE-152526

[14] Sugeng DA, Zahari MH, Ithnin AM, Yahya WJ. Diesel engine fuel consumption and emission analysis using steam generated non-surfactant water-in-diesel emulsion fuel. International Conference on Mechanical Engineering Research. 2017;4:1-10. https://doi.org/10.1088/1757-899X/257/1/012036

[15] Zacharewicz M, Kniaziewicz T. Model tests of a marine diesel engine powered by a fuel-alcohol mixture. Combustion Engines. 2022;189(2):83-88. https://doi:10.19206/CE-143486

Prof. Dmytro Samoilenko, DSc., DEng. – Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Poland.

e-mail: *dmytro.samoilenko@pw.edu.pl*

Serhii Kravchenko, DEng. – Department of Engines and Hybrid Power Plants, National Technical University "Kharkiv Polytechnic Institute", Ukraine.

e-mail: *serhii.kravchenko@khpi.edu.ua*

Anatolii Savchenko, DEng. – Department of Engines and Hybrid Power Plants, National Technical University "Kharkiv Polytechnic Institute", Ukraine.

e-mail: *anatolii.savchenko@khpi.edu.ua*