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Impact of water content in fuel for smoke opacity

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The development of internal combustion engines is focused at solving problems like: fulfilment with increasingly stringent requirements regarding exhaust emissions and elimination of threats to the natural environment. The subject of this thesis is to assess the impact of supplying a compression-ignition engine with hydrocarbon mixtures and to examine the impact of water on external parameters of the engine, such as smoke opacity. The main tests were carried out on a 4-cylinder VW 1.9 TDI internal combustion engine at a constant engine crankshaft speed of 3000 rpm and a variable load of 0, 30, 60, 90, 120, 150 and 180 Nm. The tests were carried out using an innovative mixture of hydrated fusel oils, ethyl alcohol and ionic and/or non-ionic emulsifiers, from which was made of microemulsions with a water content in diesel oil of 5, 10, 15, 20 and 25%. The tests carried out showed a beneficial effect of the water content in the diesel oil on the reduction of the average value of smoke opacity, which systematically decreases with the increase in the percentage of water in the diesel oil.

Key words: *combustion engines, fuel, water, microemulsion, smoke opacity*

1. Introduction

The development of internal combustion engines is primarily aimed at meeting the increasingly stringent requirements for exhaust emissions.

Currently, one of the conditions determining the use of internal combustion engines is the composition of exhaust gases emitted into the atmosphere. This is expressed in the emission of carbon dioxide CO_2, which is reflected in the level of fuel consumption, as well as the emission of toxic exhaust components in the form of carbon monoxide CO, nitrogen oxides NO_x, unburned hydrocarbons HC and particulate matter PM [8].

More and more attention is now paid to cheaper ways to reduce emissions by exploiting the potential of modifying the fuel used by shaping its composition and properties. In this way, the composition of the exhaust gas leaving the cylinder can be influenced more directly, partially eliminating the need for exhaust gas purification, thereby relieving the after-treatment equipment. One of the ways to reduce the emission of harmful compounds from diesel engines is the use of water emulsions to power them. Water in the fuel affects lower temperature in the cylinder, which has a positive effect on NO_x emissions. On the other hand, lowering the temperature should in theory cause an increase in soot in the exhaust gases.

Research on the use of water emulsions to power internal combustion engines has been conducted around the world for many years, but the scientific basis developed so far does not allow for wider technical applications. The reason is usually unfavorable results, in particular: stability of fuel-water emulsions, sensitivity to ambient temperature, possibility of corrosion of precision elements of injection equipment [8].

Currently, scientists in Asian countries are the most intensively engaged in the subject of feeding diesel engines with mixtures of fuels containing hydrocarbons and water. Over 70% of India's energy is heavily dependent on imported non-renewable fuels. This situation motivated various researchers in India to look for an alternative energy source that should be renewable and non-polluting.

In Europe, the topic was also studied. For example, in Switzerland, experimental tests and numerical calculations were carried out using standard emulsion fuel with a water content of 3 to 12%. This allowed to conclude that the use of the emulsion leads to a reduction in the emission of NO_x and CO and a reduction in the consumption of the primary fuel. The maximum reduction of emissions by 12.32 and 35.16% for CO and NO_x, respectively, and the reduction of fuel consumption by 5.46% were recorded [7, 13, 15].

In Poland, the subject of research on the impact of supplying internal combustion engines with emulsion fuels was dealt with by Jankowski [8–11]. As a result of research done by Jankowski showed that microemulsions retain the usability of the emulsion while minimizing the negative features of this type of fuel. The results of the research concerning the reduction of the emission of toxic exhaust components, in particular nitrogen oxides and particulate matter. A clear reduction of the aforementioned exhaust gas components occurs by increasing the percentage of water in the fuel. It was concluded that microemulsion fuels may contain a maximum of 30% water concentration. Above this value, liquids cease to maintain their properties and begin to stratify. Oil-water emulsions cause a simultaneous decrease in the emission of NO_x and a decrease in the smoke opacity level in the exhaust gases [2, 5, 6, 14].

2. Microemulsion of water in fuel

2.1. Obtaining microemulsions of water and fuel

One of the main problems with emulsions is that they are not stable and tend to stratify spontaneously over time. This reduces the economic viability and practical use of these fuels. There are many ways to improve the stability of fluids, including new mixing techniques, the addition of nanoparticles, and the addition of other fluids.

The mechanical method of producing a microemulsion consists in the mechanical fragmentation of a drop of water to the size appropriate for a microemulsion (micrometres). Obtaining such an effect is possible in devices of the cavitation type or in devices with counter-rotating discs at high speed. The production of microemulsions by physicochemical methods usually consists in adding surfactant additives to the produced emulsion, which reduce the surface tension at the water-oil interface and form a layer on the water microdroplets that prevents the microdroplets from merging into larger drops. In both cases, the pre-formed oil-water emulsion contains an additive package. Depending on the type of additives and the microemulsion production technique, the additive package is introduced into water or oil [1, 3, 4, 16, 17].

2.2. Water supplying to the engine

Since the 1930s, water supplied with the fuel has been used to control the combustion process in the knocking range. As a result of adding water to the air-fuel mixture, the time of its combustion in the cylinders is reduced, which naturally prevents the conditions for detonation. The mass fraction of the fuel increases due to the microdroplets of water and steam, while the non-evaporated water increases the compression ratio. The reduction of fuel combustion temperature during the injection of water into the cylinder reduces the concentration of nitrogen oxides formed.

For the most beneficial effect, water must be supplied to the right place and at the right time to those spaces in the combustion chamber where the highest temperatures prevail. Injection of water into the intake system or direct injection of water using a separate injector may be disadvantageous because they also supply water to areas where it is inefficient [12].

Another way to put water in the combustion chamber is to feed it along with the fuel. The emulsion fuel particles sprayed as a result of the injection process contain a certain amount of water droplets in the fuel cloud. During the combustion process in the engine cylinder there are high temperatures, in which the emulsion molecule is overheated and its composition changes. As a result of the difference in boiling points, the fuel part of the droplet remains initially in a liquid state, while the other component – water – turns into a vapor state. With further heating, such a particle is atomized into finer droplets as a result of the so-called micro explosions. This phenomenon has a very positive effect on the process of mixing fuel with air. Combustion is more complete because the large amount of water vapor in the combustion chamber (in a situation of relative oxygen deficiency) promotes cracking of the fuel and gasification of the released coal, thereby reducing the number of soot particles. The addition of water has the strongest effect on reducing the emission of nitrogen oxides and this effect is maintained with an increase in the percentage of water content [9].

However, the water content in the diesel fuel must be optimized due to the overall efficiency of the engine, the degree of engine smoke and changes in the emission of toxic exhaust components. The amount of water required for a specific NO_x reduction is twice as much when injecting water into the engine's intake system than when injecting water via a diesel injector into the combustion chamber. This excess amount of water reduces the temperature level in the combustion chamber to a range where soot oxidation is inhibited, thereby increasing the level of hydrocarbon emissions, which may result in increased PM emissions. Therefore, the most advantageous method of supplying water to the combustion chamber is direct injection of the fuel-water emulsion directly into the combustion chamber [11].

3. Tests for microemulsion of water in fuel

3.1. Preparation of the microemulsions

The first tests using water microemulsions was conducted under the supervision of prof. Antoni Jankowski. As a result of the research, it was found that among all the emulsifier additives used, the best results were obtained with an ecological, hydrated fuel additive, protected by Polish patent No. PL202335. For the aforementioned research on microemulsions, this additive was modified: the fusel alcohols were removed and replaced with salts of waste fatty acids. Based on the additive prepared in this way, after mechanical mixing with fuel and water, microemulsions with a water content of 5 to 25% were created, which were then used in the research described in this article.

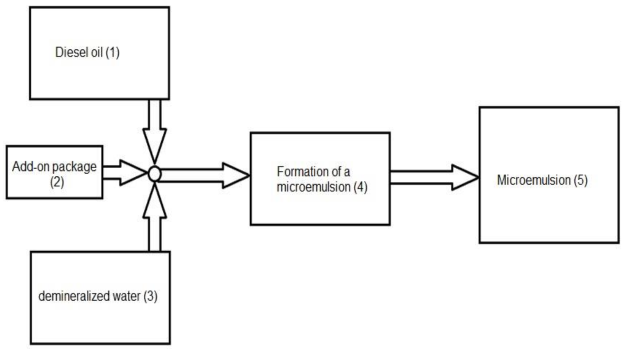

Fig. 1. Microemulsion preparation procedure

The procedure for producing the diesel oil-water microemulsion is shown in Fig. 1:

1. introduced 20 dm^3 of diesel from the tank (1) oil into the tank (4) using a drain device operating by gravity;
2. the introduced diesel fuel was then heated in the mixer (4) to the temperature of 50ºC;
3. to tank (4) containing the heated and mixed with a low-speed mechanical agitator, diesel oil was introduced from tank (2) using a gravitational drain device through a metering device: 250, 500, 750, 1000 and 1250 cm^3 (in the case of a microemulsion containing 5, 10, 15, 20, 25% water);
4. after introducing the appropriate amount of the additive package to the mixer (4), demineralized water was added from the tank (3) using a dispenser in an amount appropriate to the target water content in the microemulsion;
5. stirring at 50ºC for 30 minutes;

6. the resulting microemulsion was poured into a tank (5) and cooled to ambient temperature.

3.2. Parameters of the produced microemulsions

Fuel samples with water content of 5, 10, 15, 20 and 25% obtained in the manner described above were tested for compliance with the requirements of the standard PN-EN 590. Table 1 below presents the results of the conducted fuel tests.

Table 1. Comparison of results from laboratory tests of fuel

Tested parameter	Standard requirements PN-EN 590	Tests results for water content					
		0%	5%	10%	15%	20%	25%
Density in 15ºC [g/cm^3]	0.820–0.845	0.830	0.875	0.896	0.901	0.910	0.900
Viscosity in 40ºC [mm^2/s]	2.00–4.50	3.25	8.07	10.04	11.54	12.77	12.46
Cold filter plugging temperature [ºC]	max –22ºC	–22	–10	–6	–5	–4	–6
Ash residue [% (m/m)]	max 0.010	0.009	0.019	0.020	0.023	0.029	0.039
Water content [% (m/m)]	max 0.020	0.010	8.71	12.53	16.03	21.14	22.3
Heat of combustion [MJ/kg]	–	44.71	41.96	38.67	36.99	34.67	35.54
Calorific value [MJ/kg]	–	41.80	38.86	35.48	33.72	31.72	32.11

As can be seen, parameters such as density, viscosity at 40°C, cold filter plugging temperature and ash residue are not within the ranges provided for by the aforementioned standard.

The water content in the fuel, measured according to the PN-EN ISO 9029 standard, slightly differs from the calculated values obtained during the emulsion production process.

3.3. Measuring station and tests methodology

The basic tests were carried out on the Volkswagen 1.9 TDI engine. Engine technical data are presented in Table 2.

Table 2. Technical and operational parameters of the VW 1.9 TDI engine

Number of cylinders	4
Number of strokes	4
Cylinder diameter	95.5 mm
Piston stroke	79.5 mm
Stroke volume	1896 cm^3
Compression ratio	18.0:1
Rated power/speed	85 kW/4000 rpm
Maximum torque/speed	285 Nm/1900 rpm
Engine powered by	pump injectors
Engine type	AJM

The tests were carried out on the engine dynamometer stand at the Department of Vehicle Engineering at the Wroclaw University of Technology. This stand was placed in an isolated measuring box, where the motor and the brake were mounted on a common foundation plate. Figure 2 shows the appearance of the discussed test stand.

During the tests, one constant engine crankshaft rotational speed of 3000 rpm was used. The engine was loaded with torques of 0, 30, 60, 90, 120, 150, 180 Nm. Exhaust gas opacity was measured using an AVL type 415S G002 smoke meter. Detection limit of this device 20 µg/m^3 or 0.002 FSN. At each measurement point, the collection of concentrations of individual exhaust gas components lasted 4 minutes. The measurements at each operating point of the engine were repeated six times.

Fig. 2. Research station

Comparative tests were carried out with the engine fueled with standard diesel oil and then with microemulsion fuels with water content in diesel oil at the level of 5, 10, 15, 20 and 25%.

All tests were carried out with the factory settings of the engine, and its fuel equipment was not interfered with.

4. Smoke opacity level for tested microemulsions

The results of the tests show that for each tested engine load, the smoke opacity value for samples with water content systematically decreases with the increase in the percentage of water in the diesel oil. The addition of 5% of water in the fuel resulted in a significant decrease in smoke opacity. For loads in the range of 0 to 60 Nm, it was a decrease of about 41–51%, while for loads from 90 to 180 Nm – a decrease of about 63–72%.

Figure 3 presents graphs for all seven tested fuels, showing changes in smoke opacity level in relation to the applied rotational speeds of the test engine.

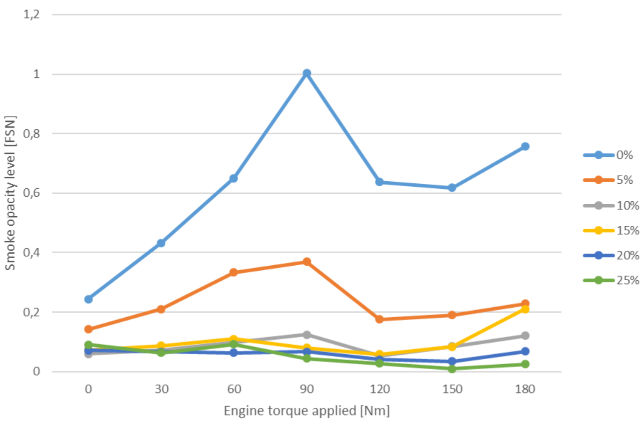

Fig. 3. The average smoke opacity values for an engine fueled with fuels with different water content depending on the engine loading torque

The Gaussian distribution is the most commonly used distribution in statistics. This is due to the fact that if a quantity is used by many random providers, then according to their distribution, its distribution will be close to normal. If we take a closer look at the values of the Gaussian distribution, we will notice that the results obtained during the tests were close to the average values presented in Fig. 3. Especially for fuels with a water content of 10% and above, it can be concluded that the test results obtained provide a good basis for further tests on these microemulsions.

Figures 4 to 6 show the Gaussian distributions for the results obtained from the tests were repeated six times with the engine load at 30, 90 and 150 Nm. In each of the described cases, the best results were obtained for fuel with 25% water content (green line in the graphs).

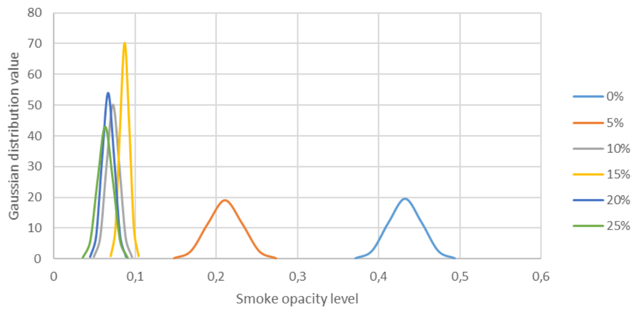

Fig. 4. Gaussian distributions for smoke opacity by the engine loaded with a torque of 30 Nm

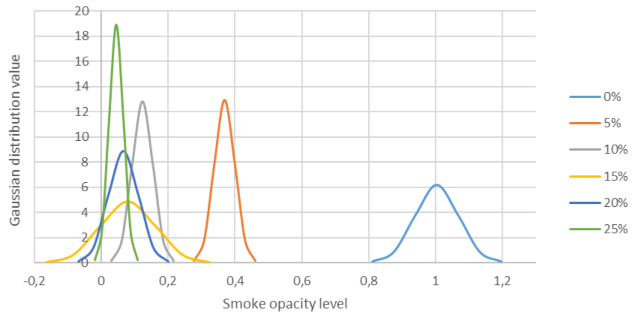

Fig. 5. Gaussian distributions for smoke opacity by the engine loaded with a torque of 90 Nm

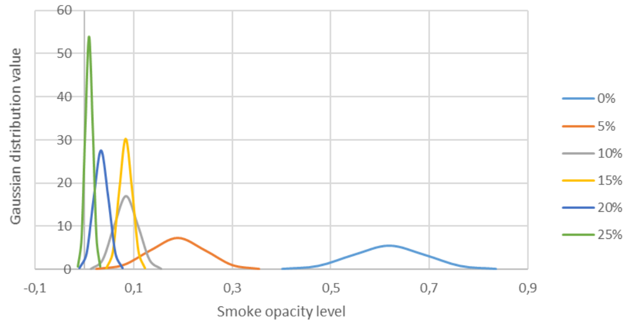

Fig. 6. Gaussian distributions for smoke opacity by the engine loaded with a torque of 150 Nm

5. Conclusions

The subject of this article was to check the effect of supplying a compression-ignition engine with hydrocarbon mixtures and to examine the effect of water on exhaust gas opacity.

Based on the research results, the following conclusions can be drawn:

– the greatest reduction of smoke opacity was obtained for the microemulsion with 25% water addition, at the engine load with a torque of 150 Nm. This value was lower by 98.5% compared to the engine fueled with standard diesel fuel
– the smallest changes in smoke opacity were recorded for tests with the engine unloaded
– tests with a set low value of the engine torque showed the highest values between the minimum and maximum for diesel fuel and emulsion with 5% water. It is shown in Fig. 4, 5, and 6 in the form of more flatter curves than for the other fuels in this test
– for the other emulsions tested, similar results were obtained, so the graphs almost overlap
– a further increase of the torque loading the engine showed similar results as in the previous tests.

Due to the reduction of smoke opacity obtained in the tests, further tests with the described emulsions are considered. The expectations regarding the addition of water in the fuel, set at the beginning of the tests, have been confirmed, which prompts further research in this area.

Nomenclature

CO	carbon monoxide
CO_2	carbon dioxide
HC	unburned hydrocarbons
NO_x	nitrogen oxides
PM	particulate matter

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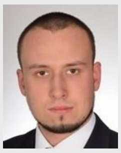

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