ENGINE TEST RESULTS OF FUEL-WATER MICROEMULSION

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Abstract

The emulsion is a mixture of two or more insoluble liquids. Microemulsion is the emulsion with particles dimension in a range of one micrometre and smaller. Such a microemulsion of water and diesel fuel will create a novel quality and allows one to simultaneously achieve environmental and economic effects, as well as eliminate the adverse impact of normal emulsions, or adverse effects of water injection into the engine intake system or directly into the combustion chamber, as well as the sequential injection of water directly into the combustion chamber. Application of microemulsion of water and diesel to fuel diesel engine positively affects the combustion process through the catalytic impact of microparticles of water, and improves the process of preparation of the microemulsion injection into the combustion chamber as a result of water microparticles' microexplosions. This article presents the investigation results of an internal combustion engine fuelled by an emulsion of water and diesel fuel and fuelled by emulsion of FAME and water. It therefore seems appropriate to a strong increase in the degree of dispersion of water droplets in the emulsion by applying the methods to obtain the size of water droplets on nanometric range. This should dramatically improve both the stability of emulsion and its influence on the chemical effects of combustion in diesel engine.

1. Introduction

In the current stage of development of internal combustion engines composition of gases emitted into the atmosphere plays a key role, expressed mainly by emission of carbon dioxide CO_2, which is reflected in the level of fuel consumption and emissions of toxic components in the form of carbon monoxide, CO, NO_x, unburned hydrocarbons THC and particulate matter PM. Due to the lower fuel consumption and therefore lower CO_2 emissions is the growing importance of increasing usage of diesel engines in passenger automobiles.

Even greater and greater reductions of CO_2 emissions and toxic components of exhaust force one to continuously improve the thermal cycle in relation to diesel engine and seek a novel, effective solutions for reducing emissions of toxic exhaust components. Although in this field the major research efforts are undertaken for many years, the achieved results are still insufficient, especially when it comes to the cost of research and development works and the cost of exhaust purification devices.

One example that could be mentioned here is a filter for effectively reducing emissions of exhaust particulate matter (PM), which has so far failed satisfactorily, solves the problem of their recovery.

In addition, the removal of nitrogen oxides from exhaust gases by means of their capture and periodic catalytic reduction raises reservations because of the cost, complexity of control systems and the durability and reliability.

Both the exhaust filters and equipment to reduce nitrogen oxides always have their maximum efficiency of less than 1 and their operating efficiency is significantly lower, depending mainly on the engine conditions and its operating parameters, so it is important to ensure low emissions of toxic components of exhaust at the exit from the cylinder of internal combustion engine.

Among many methods of reducing NO_x emissions, an important option is supply the engine water-fuel microemulsion. Microemulsion's components are exactly dispersed to form a mixture similar to the homogeneous mixture (molecular mixture). The mechanism of micro-emulsion's formation with different degrees of dispersion shows Fig. 1.

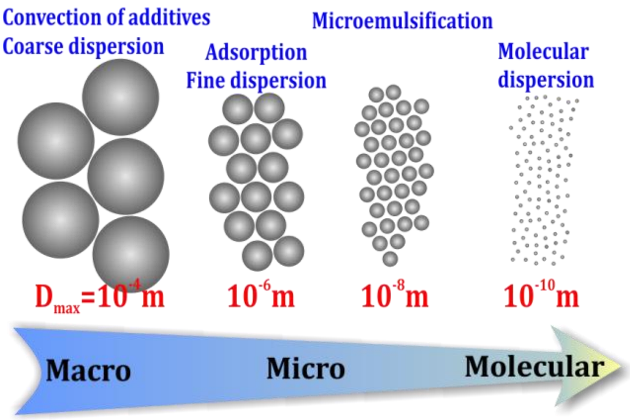

Fig. 1. Mechanism of emulsions` formation with different degrees of dispersion (from the turbulent dispersion via turbulent diffusion to molecular dispersion)

The microemulsion, in contrast to a macroemulsion, has properties of a single-phase fuel [1]. Furthermore, an additional advantage of the microemulsion use is catalytic effect of the water, which does not occur at macroemulsion supply and water injection into combustion chamber of the engine.
The use of microemulsion of water-fuel improves the combustion process through the interaction of microparticles of water and improves the process of preparing the mixture as a result of microexplosion of water microparticles [3].
The use of microemulsion of water-fuel has a positive effect to the stability and anticorrosion properties. The water molecules, which form supercritical water phase, have the property of catalytic effective due to the large cross-sectional area of the particles causing change the position orbit of oxygen.
Supercritical water particles catalyse a chemical reaction involving the transfer of an electron or a reactive constituent, or from the reactive constituent. The oxidation of coal, which is the combustion of hydrocarbon compound in the presence of water under conditions close to or above the critical point, the orbits of the water molecules formed on the carbon oxygen can easily overlap with the orbits of reactive carbon accelerating oxidation. Water is a source of oxygen during the combustion of rich mixture, causing, among others, lowering the temperature in the flame zone, which reflects the thermal mechanism (Zeldovich mechanism) and reduces emissions of NO_x formation [5].

2. Mechanism of fuel stream creating

Many theoretical and research works were devoted to this problem. However, they did not allow for the determination of conclusive solutions. The most widespread hypothesis assumes that the disintegration of the stream is connected with disturbances on its surface due to external and internal forces. Fuel droplets can be further disintegrated when they are in areas of variable dynamic pressure that increase with increasing relative velocity, which occurs especially at high injection pressures. Aerodynamic forces and surface tension also influence the disintegration of droplets. Deformation and further disintegration occurs with increasing aerodynamic forces [2].
The disintegration criterion that will result in the secondary disintegration of droplets is the critical Weber Number. When the Weber Number is greater than the critical Weber Number, i.e. $W_e \geq W_{ekr}$, the fuel stream disintegrates, wherein the Weber Number We is described by the equation:

$$W_e = \frac{\varsigma \cdot w^2 \cdot d}{\sigma} \tag{1}$$

where: w – relative velocity drops;
ς – gas density;
d – average droplet diameter;
σ – fuel surface tension.

At high injection pressures, as in common rail systems, the relative velocity of droplets increases, which affects secondary disintegration. The fuel viscosity and surface tension also have a significant influence on the size and distribution of droplets. The increase in dynamic viscosity results in increased range of the stream and reduction of its volume. Viscosity and surface tension affect the size of the droplet diameter, according to the empirical relationship:

$$r = \frac{3\sigma}{Ep - A\mu \cdot w} \tag{2}$$

where: Ep – pulsation energy;

μ, σ – dynamic viscosity and surface tension of fuel.

The equations presented above refer to averaged values. Under the working conditions of the self-ignition engine, the fuel injection is variable, which is caused by the change of the delivery speed, wave phenomena accompanying the fuel outflow, disturbances caused by the compressibility of the fuel, as well as system vibrations. The high injection pressure at distribution pipe used in fuel systems (Common Rail) and some fuel properties such as viscosity and surface tension thus affect significantly on the fuel injection process. The test results allowing the qualitative assessment of the impact of these factors on the droplet size in the fuel stream are presented below.

3. Fuel-water emulsions

The emulsion is a mixture of two or more insoluble liquids. Microemulsion is the emulsion with particles dimension in the order of one micron and smaller. Such a microemulsion of water and diesel fuel will create a novel quality and allows one to simultaneously achieve environmental and economic effects, as well as eliminate the adverse impact of normal emulsions, or adverse effects of water injection into the engine intake system or directly into the combustion chamber, as well as the sequential injection of water directly into the combustion chamber.

In addition, the usage of microemulsion is beneficial for the reliability of engine components by eliminating emulsion stratification, which is always present in the application of ordinary emulsion of water and diesel fuel.

Application of microemulsion of water and diesel to fuel diesel engine positively affects the combustion process through the catalytic impact of microparticles of water and improves the process of preparation of the microemulsion injection into the combustion chamber because of water microparticles microexplosions. The result of the application of microemulsions will reduce emissions of nitrogen oxides, particulate matter PM and increasing the efficiency of the engine.

Application of microemulsion of water and diesel fuel will favourably affect its stability and anticorrosion properties. The catalytic effect of water microparticles will also benefit the reduction of hydrocarbons emissions. Water molecules, which form a supercritical water phase have catalytic properties due to the large effective cross sections of the particles reactive surface that cause changes in the position of oxygen orbits.

Water will be a temporary source of oxygen during the combustion of rich mixtures at the same time lowering the temperature in the flame zone, which affects the thermal mechanism (Zeldovich) formation of nitrogen oxides, NO_x.

By direct microemulsions injection into the combustion chamber the adverse events occurring during water injection alone are eliminated. The advantage of microemulsion injection over water injection realized in any way lays in its application comfort and outcomes relating to both reduction of toxic components emissions of exhaust gases, and the specific fuel consumption. A novel element of microemulsion usage is the water catalytic effect, which does not exist in the macroemulsion injection and the water injection alone.

4. Methods of water supply into the combustion chamber

There are four main ways to supply water to the engine's combustion chamber:

- Injection of water into the engine intake manifold.
- Direct injection of water into the engine through a separate injector.
- Sequential injection of water and diesel oil fuel.
- Direct injection of water and diesel oil fuel macroemulsion.

All known methods of using water to fuel the diesel engine have a beneficial impact on emissions of nitrogen oxides, however, they cause adverse effects associated with an increased emission of hydrocarbons, particulates and the increase in specific fuel consumption. They also

cause adverse effects associated with the corrosive effects of water on the essential elements of the engine. In turn, use of water injection into the engine as such, limits the use of these methods for stationary applications. For example, the use of water injection in winter conditions eliminates this way of the compression ignition engine fuelling under these conditions.
Attempts to apply macroemulsion to fuel the diesel engine did not yield a satisfactory result because of very low emulsion stability caused by its stratification. Applications of microemulsion of water and diesel oil fuel can be interesting because it will be possible to obtain a stable microemulsion, in which there will be no stratification. Furthermore, the advantage of microemulsion injection over water injection realized in any way lays in its application comfort and outcomes relating to both reduction of toxic components emissions of exhaust gases, and the specific fuel consumption.
Furthermore, a novel element of microemulsion usage is the water catalytic effect, which does not exist in the macroemulsion injection and the water injection alone. A new problem in the world is thus the catalytic aspect of use of water and diesel oil fuel microemulsion, as well as the proposed methodology of research in relation to the microemulsion based on PDPA laser techniques. It is worth mentioning, that the microemulsions will have the properties of a single-phase fuel as opposed to macroemulsion.

5. Engine researches

Engine researches were aimed at suitability determination of a novel method of a fuel-water emulsion preparation using a helical mixer and explanation of the effects of water content in the emulsion on the properties of compression ignition engine, and particularly on its environmental and economic parameters.
Supplementing these studies were comparative measurements of the motorized injection apparatus alone, connected with the visualization of the atomized fuel streams. Measurements were carried out for the two fuels: diesel oil fuel manufactured from crude oil and rapeseed FAME (Fatty Acid Methyl Ester) fuel.

Fig. 2 shows a diagram of helical fuel and water mixer used during the tests.

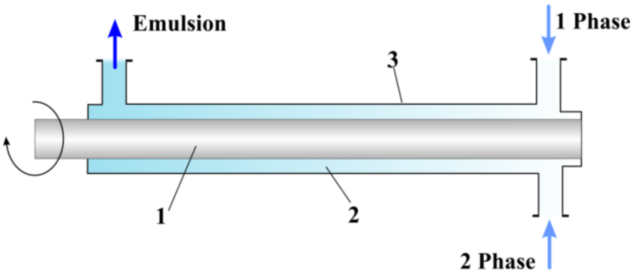

Fig. 2. Schematic of the helical mixer:
Phase 1 – diesel oil or FAME fuel,
Phase 2 – water with the possible surfactant content; 1 - rotor, 2 - the fuel-water emulsion, 3 - cylinder

Helical flow in the annular gap apparatus consists of imposing axial flow on the rotational flow caused by a rotating motion of the internal cylinder (rotor – 1). A characteristic feature of this flow is the loss of its stability, which occurs above the critical value of the rotor rotational speed. Then under the influence of inertia occurs the secondary motion of fluid in the form of so-called Taylor vortices. The presence of these vortices and the combination of axial flow with the rotational flow makes that the helical flow can be used in the emulsification of two immiscible liquids. The structure of this movement (the average diameter of emulsified phase droplet) depends, inter alia, on the viscosity and density of both phases and the interfacial tension. The fuel-water emulsions produced by this method were characterized by relatively low durability, what makes this fuel practically impossible to store. In order to avoid these difficulties, attempts were carried out with the changes, including rotor speed and the thickness of the gap between the rotor and the outer cylinder, but the obtained improvement was not satisfactory.
Depending on the various mixers operating parameters the average diameter size of the water droplets obtained in diesel fuel ranged from 5 to 15 microns. Such degree of water in fuel dispersion was too small for sufficient stability of emulsions. Marked increase in emulsion stability was possible only with the aid of a surfactant (as such a measure Rokafenol was used).

However, due to the complexity of the emulsion manufacturing process and the fuel costs, this method to increase emulsion durability was dropped. In this context, during investigations the fuelling of the engine with emulsion directly from the helical emulsifier was assumed.
Trials were carried out on 1-cylinder high-speed version of the direct fuel injection diesel engine with a power rating of 23 kW at 2200 rpm.
Measurements were made on the external engine characteristics. The most interesting results were obtained in relation to exhaust emissions. On Fig. 3 and Fig. 4 is shown the effect of water content in the emulsion of diesel oil and FAME fuels and water to the emission of unburned hydrocarbons THC.

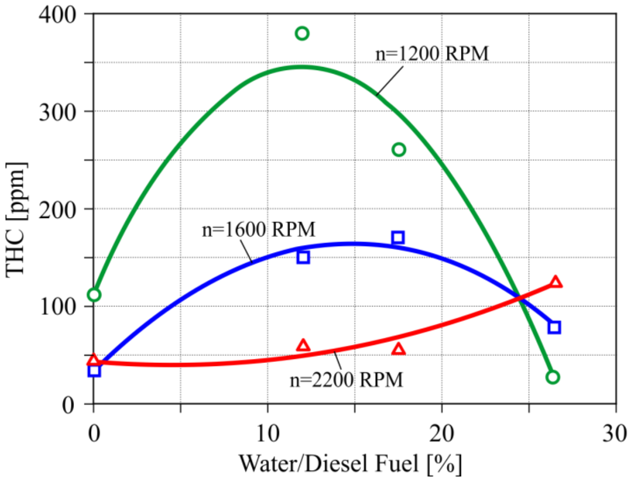

Fig. 3. Effect of water content of the fuel oil - water emulsion on the emission of unburned hydrocarbons THC

Generally, a tendency to a slight increase in THC emissions is observed, together with increased water content in the emulsions.
The reason for this is probably the reduction in combustion temperature caused by water (the influence of heat of evaporation of water contained in the emulsion).
For both fuels used, the impact of the water is broadly similar.

Much more pronounced impact of water in the emulsion has been found for carbon monoxide emissions of CO, shown in Fig. 5 and Fig. 6. One might expect that the above-mentioned reduction in combustion temperature by water must also result here in deterioration of fuel oxidation.

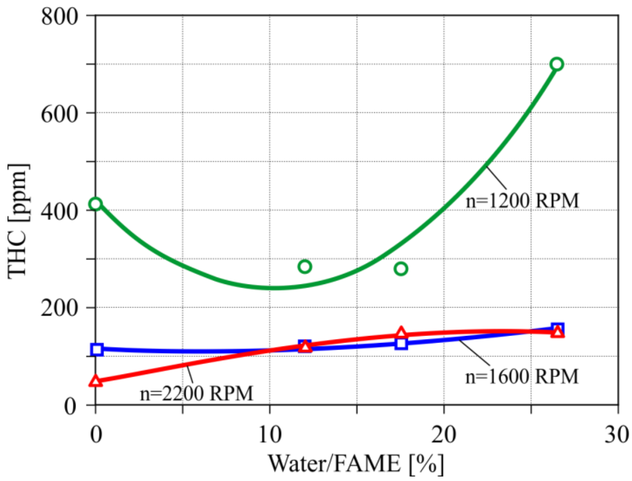

Fig. 4. Effect of water content of the FAME fuel – water emulsion on the emission of unburned hydrocarbons THC

However, for both fuels is a significant drop in CO emission with increasing water content in the emulsion at any speed. It seems that this phenomenon is the result of the dissociated steam impact and more active oxygen atoms and OH radicals. It is characteristic that for the FAME fuel is a clear minimum CO content for the water level in emulsion of approximately 20%.

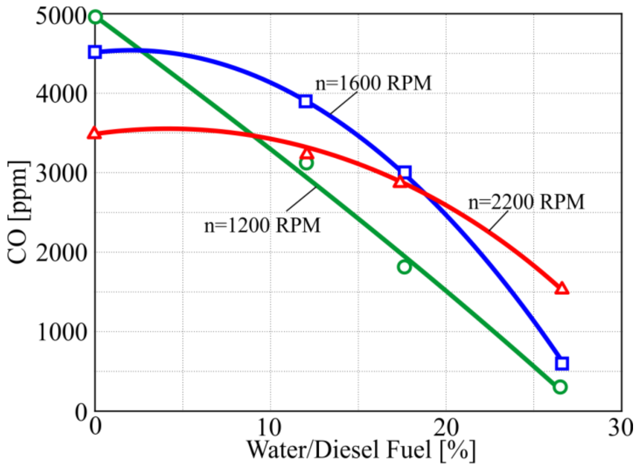

Fig. 5. Effect of water content of the fuel oil – water emulsion on the emission of carbon monoxide CO

Typically, the use of fuel-water emulsion in a diesel engine is connected with the hope of a dramatic reduction in emissions of NO_x.
NO_x emissions were obtained with a water increase in emulsion.

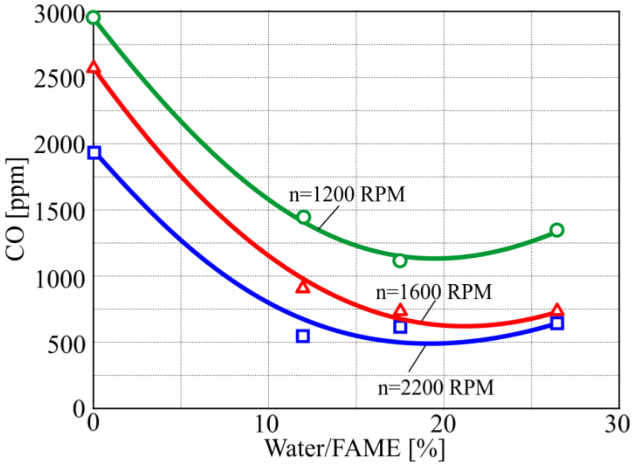

Fig. 6. Effect of water content of the emulsion FAME – water on the emission of carbon monoxide CO

However, there is a clear difference between the effectiveness of emulsion for diesel and FAME fuels.

As is clear from Fig. 7 and Fig. 8, for both fuels used in the tests almost linear decrease in. For the first type of the fuel, the water level in emulsion at 26.5% resulted in a decrease in NO_x emissions by only 21% – 25%, while in the case of FAME fuel slightly lower water content (22.6%) resulted in an emission cut of 60% – 85%.

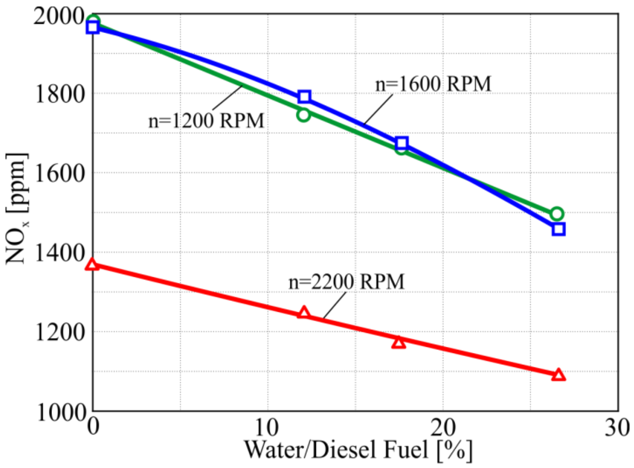

Fig. 7. Effect of water content in the fuel oil – water emulsion on the emission of NO_x

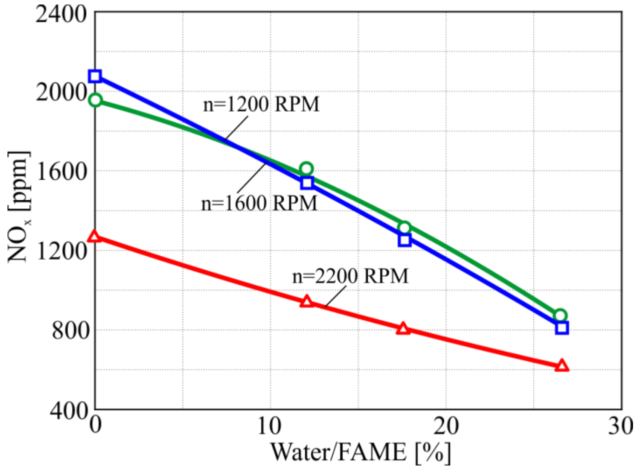

Fig. 8. Effect of water content of the FAME fuel – water emulsion on the emission of NO_x

Overall, the heat discharge ratio from the combustion is lower for FAME fuel (fatty acid methyl esters did not burn slower than the hydrocarbons of diesel oil) and maybe then lowering the local temperature in the combustion chamber due to the presence of a drop of water is more effective in terms of inhibition of the process of nitrogen oxidation.

It should be noted, however, that in the case of diesel fuel reduction of NO_x emissions obtained here by using the water-fuel emulsion at around 25% is far too small compared to the results obtained in other research centres.

The reason for this may be associated with too small dispersion of water droplets in the emulsion, which is also expressed by the above mentioned much lower durability of emulsions used in the studies presented here.

Very characteristic is the influence of water content in emulsion on the exhaust smoke – d, which clearly can be seen from Fig. 9 and Fig. 10. Generally, exhaust smoke decreased significantly with increasing water content in the emulsion for both fuels. We must pay attention to the similarity of the course of the curves d = f (% water in emulsion) separately for diesel oil fuel and FAME fuel.

Especially in the case of FAME fuel the smoke curves show the course of a similar nature as carbon monoxide (Fig. 10 and Fig 6), where the water content of about 20% is a minimum of smoke and CO. The data contained in Fig. 9 and Fig. 10 clearly show the beneficial effect of water content in emulsion on the course of combustion of both fuels. Unfortunately, the water content in the emulsion causes the deterioration of the economics of operating the engine for both diesel oil fuel and FAME fuel.

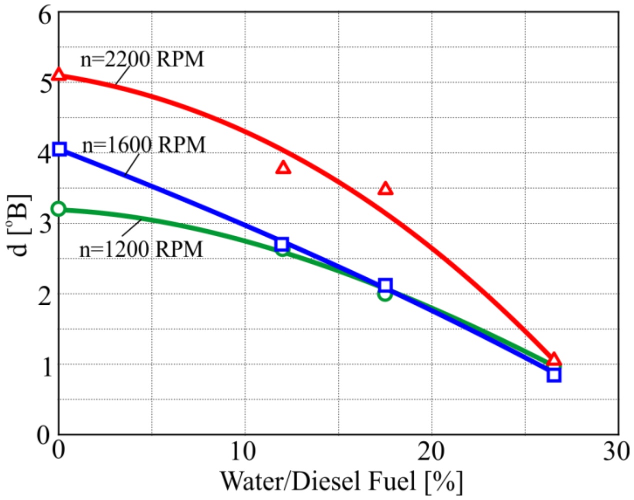

Fig. 9. Effect of water content of the fuel oil – water emulsion on the exhaust smoke – d

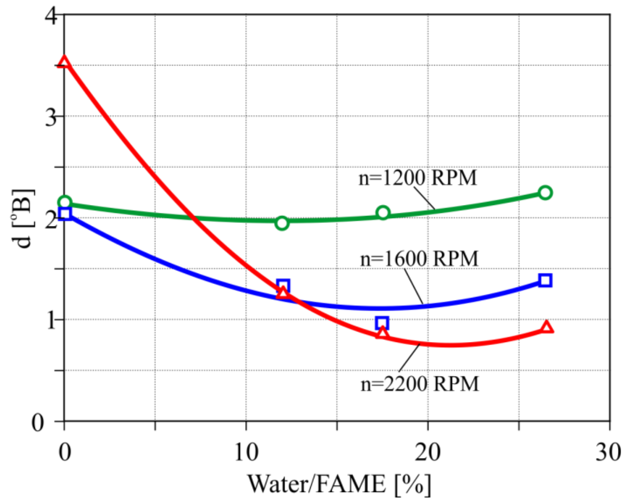

Fig. 10. Effect of water content of the emulsion FAME fuel – water on the exhaust smoke – d

This is evident from the data presented in Fig. 11 and Fig. 12. The reason here is mainly the reduction of combustion temperatures and increasing of an outlet loss (more 3-atomic gases in the exhaust). Partial compensation could be achieved by optimizing the timing angle of the fuel injection.

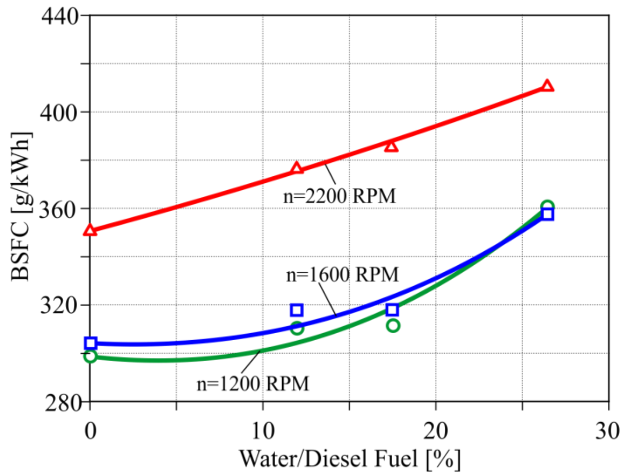

Fig. 11. Effect of water content of the fuel oil – water emulsion on specific fuel consumption – BSFC

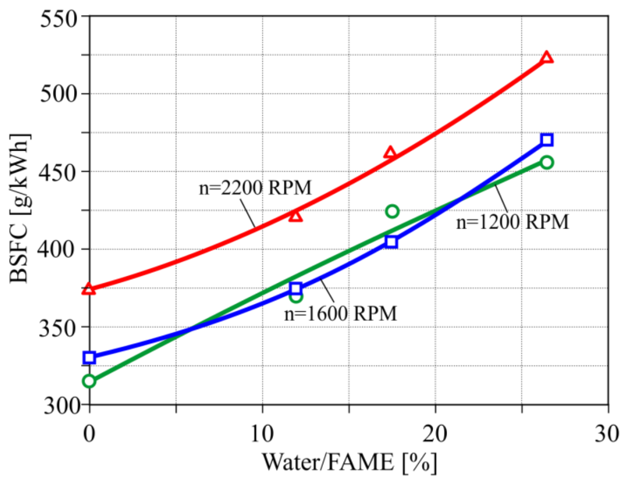

Fig. 12. Effect of water content of the FAME fuel – water emulsion on specific fuel consumption – BSFC

Fig. 13 and Fig. 14 present effect of water content of the fuel oil – water emulsion on the exhaust gases temperature and effect of water content of the emulsion FAME – water on the exhaust gases temperature.

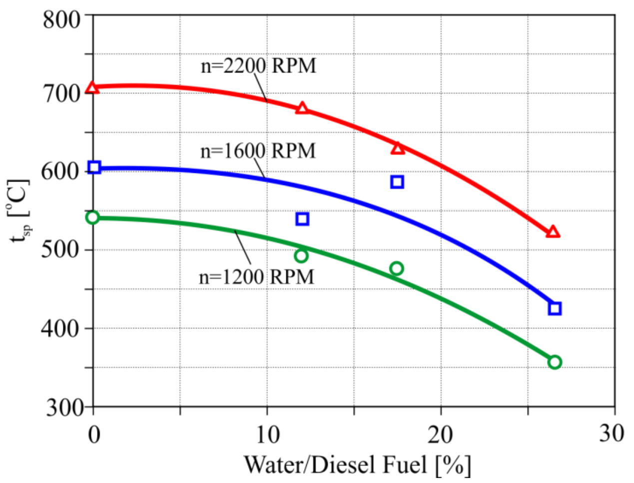

Fig. 13. Effect of water content of the fuel oil – water emulsion on the exhaust gases temperature

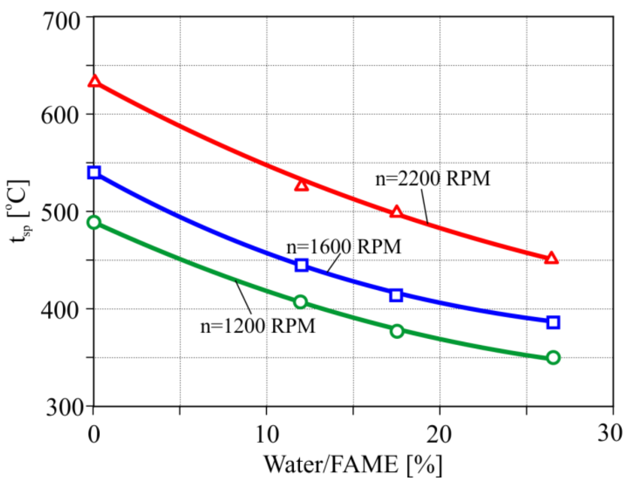

Fig. 14. Effect of water content of the emulsion FAME – water on the exhaust gases temperature

Conclusions

Summarizing the results presented above can be stated generally positive impact of fuel-water emulsion produced by helical mixer on the combustion process and its results in the form of exhaust gas composition.

However, the dispersion of water droplets in the emulsion produced by mixing such a determination is too weak, resulting in one hand a very low durability of the manufactured emulsion and the other a relatively small reduction in emissions of NO_x (especially in the case of diesel oil fuel).

It therefore seems appropriate to a strong increase in the degree of dispersion of water droplets in the emulsion by applying the methods to obtain the size of water droplets on nanometric range. This should dramatically improve both the stability of emulsion and its influence on the chemical effects of combustion in diesel engine. The performed analysis and research is the first stage, which aims to simultaneously reduce emissions of PM and NO_x.

It seems that the simultaneous reduction in emissions is possible with a stable emulsion, i.e. water-fuel microemulsion.

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