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STUDY OF THE DROPLET SIZE OF THE DISCRETE PHASE OF A FUEL-WATER EMULSION

Badanie wielkości kropel fazy dyskretnej emulsji paliwowo-wodnej

Abstract: *In the era of increasing care for the earth's climate, numerous scientific studies are being conducted looking for alternative fuels with reduced emissions. One is a fuel-water emulsion, which has a particularly positive effect on NOx emissions. The article presents tests carried out on a fuel-water emulsion containing from 3% to 15% water and from 1% to 3% emulsifier, aiming to determine the microscopic properties of the developed emulsion. The study focused on the influence of the composition of the tested emulsion, the mixing time of its components and the influence of pumping it through the fuel pump on the size of water droplets of the discrete phase.*
Keywords: fuel-water emulsion, alternative fuels, emulsifier, emulsion fuels, emulsion discrete phase

Streszczenie: *W dobie coraz większej dbałości o klimat na Ziemi prowadzone są liczne badania naukowe poszukujące paliw alternatywnych o ograniczonej emisyjności. Jednym z nich jest emulsja paliwowo-wodna, której zastosowanie szczególnie korzystnie wpływa na emisję NOx. W artykule przedstawiono badania przeprowadzone na emulsji paliwowo -wodnej zawierającej od 3% do 15% wody oraz od 1% do 3% emulgatora, których celem było poznanie właściwości mikroskopowych opracowywanej emulsji. Skupiono się na wpływie składu badanej emulsji, czasu mieszania jej składników oraz przepompowania jej przez pompę paliwa na wielkość kropel wodnej fazy dyskretnej.*
Słowa kluczowe: emulsja paliwowo-wodna, paliwa alternatywne, emulgator, paliwa emulsyjne, faza dyskretna emulsji

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1. Introduction

The impact of the combustion of fuel-water emulsion on operating parameters and exhaust gas emissions from engines is currently the subject of scientific research. This applies to piston units [1,2] and gas turbines [3]. Experiments conducted on a single-cylinder naturally aspirated diesel engine have shown that emulsion fuel with 10% of added water can reduce NOx emissions by 32.5% compared to engine emissions using standard fuel (Diesel). However, adding water to the fuel, in this case, also increased the emission of carbon oxides and unburnt hydrocarbons [4]. On the other hand, replacing the Jet A-1 fuel with a fuel-water emulsion with 12% water added in a miniature gas turbine led to a reduction of NOx emissions by over 35%, a reduction of over 12% of CO emissions and a reduction in the consumption of Jet A-1 [5].

The micro-explosion phenomenon is often considered an important process contributing to the positive effect of adding water to the fuel during combustion [6]. Secondary atomization of emulsion fuel drops is successfully observed in studies on single drops [7-9]. However, the authors [6] emphasize the scarcity of literature on studying this phenomenon in the conditions of a real engine combustion chamber. Moreover, according to the literature, this phenomenon does not occur when the diesel engine is supplied with emulsion fuel [10]. In the review on the combustion of fuel-water emulsion in gas turbines, it was emphasized in the conclusion that there are no experimental studies in the literature examining the effect of the micro-explosion phenomenon on the combustion process in the actual turbine combustion chamber [3].

The intensity of the micro-explosion depends not only on the conditions of the combustion process itself but also on the physical parameters of the emulsion fuel droplets, such as the size of the emulsion fuel droplet, the amount of water contained in it or the size of the discrete phase droplets [11]. Therefore, to study the impact of the micro-explosion phenomenon on the combustion process in a real engine, under certain conditions it would be hypothetically possible to influence the intensity of this phenomenon by changing the size of the discrete phase droplets without changing the shares of individual components in the fuel mixture. Improving the combustion process when the engine would be fed with an emulsion with the size of droplets of the discrete phase causing the maximum force of the micro-explosion in relation to its non-optimal size would be an important premise confirming the positive effect of this phenomenon on the combustion process.

With reference to the above considerations, the authors made efforts to determine the composition of the emulsion that could be a functional fuel for the gas turbine and to investigate the factors affecting the size of the water droplets of the discrete phase in the fuel-water emulsion.

2. Subject and methodology of research

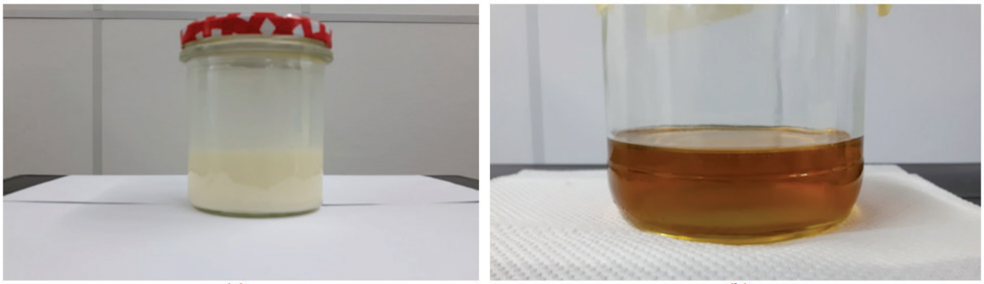
Jet A-1 kerosene, produced by the Polish refinery Orlen, was selected as the base fuel, the continuous phase of the two-phase water-in-oil fuel-in-oil emulsion. Before starting the emulsion production, the fuel was enriched with AeroShell Turbine Oil 500 in the proportion of 95:5 (by mass) to adapt the fuel for combustion in miniature gas turbines with an open-bearing lubrication system. The emulsifier used as an addition to the emulsion was a mixture of four surfactants and demineralized water (Table 1).

Table 1

Composition of the surfactant expressed by mass

Surfactant Ingredients	Procentage
Rokwin 80	50.00
Rokanol RZ4P11	25.00
Rokanol DB3	22.50
Rokafenol N8	1.67
Water	0.83

All emulsion samples were prepared according to the same scheme. In the first stage, an emulsifier was added to the mixture of Jet A-1 with oil, followed by a 5-minute mixing with a 550 W electric stirrer. After that, water was added to the laboratory vessel, and it was mixed for a predetermined time. Radwag Wlc 2/a2 balance was used to measure the amount of individual components of the fuel-water emulsion. The fuel-water emulsion obtained by this method was an opaque milky liquid (Fig. 1a). The emulsifier used for its production is an oily dark brown liquid (Fig. 1b).



(a) (b)

Fig. 1. Fuel-water emulsion (a) and surfactant (b)

The experiment was divided into several main stages. In the first stage, the effect of the amount of surfactant on the size of water droplets in the emulsion was checked. An emulsion with an emulsifier content of 1%, 2% and 3% of the total fuel mixture weight was tested. The starting point for the research was the content of 2% since it is the most typical amount used in research on combustion in reciprocating engines [1]. The emulsion with three different contents of emulsifier contained from 3% to 15% of demineralized water. Each sample of the prepared mixture had a mass of 300 g. After adding water, the second stage lasted 5 minutes.

For the fuel-water emulsion, which included an emulsifier of 3% and water in the amount of 9% of the total mass, the influence of the mixing time of water with other ingredients on the size of discrete phase droplets was studied. The mixing time was changed from 2.5 min to 12.5 min. Other parameters of the experiment were identical to those described earlier.

The next part of the research aimed to determine the effect of pumping the fuel-water emulsion by the AERIOS 7 fuel gear pump, used to power miniature GTM gas turbines, on the size of water droplets in the emulsion. For this case, two emulsions were prepared, one containing 6% water and the other containing 12% water. Both emulsions contained 2% of the emulsifier, and in the second stage, they were mixed for 5 minutes. In this part of the experiment, 1500g of the fuel-water emulsion was prepared. The fuel pump used in the experiment is voltage-controlled. To reflect the revolutions of the fuel pump corresponding to the engine load from idling to maximum load, the influence of the mass flow rate of the pumped liquid on the voltage at the pump clamps was determined. Then, the mass flow rate of the pump was converted into a volumetric flow rate, taking into account the change in the composition of the pumped mixture. On this basis, the voltages at the fuel pump clamps corresponding to the fuel flow of the gas turbine operating at 40, 60, 80, 100 and 120 kRPM were selected. The fuel flow rates corresponding to individual operating points were adopted in accordance with previous studies [12] and increased by the volume of added water and surfactant. This was done because it was assumed that using the emulsion as fuel would not significantly change the flow rates of the base fuel, as was the case during the tests on the J79-GE-10 jet engine [13].

All fuel-water emulsions were photographed by a Delta Optical MET 200TRF microscope equipped with a 10x eyepiece and a 40x objective. Microscopic images were taken with the DLT Cam PRO 10MP camera. Emulsions prepared in the manner described above were photographed as soon as possible after their preparation or pumping by a fuel pump with pre-planned voltage on its clamps. An additional series of photos of the fuel-water emulsion with 1% to 3% of emulsifier and 3% to 15% of water was also taken about 24 hours after its preparation. The second stage of mixing these emulsions lasted 5 minutes. An exemplary photo of the fuel-water emulsion taken during the tests is shown in Fig.2.

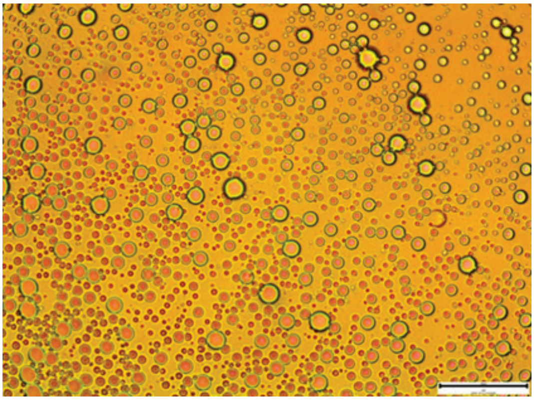


Fig. 2. Fuel-water emulsion with 9% water content and 1% emulsifier addition. Photo scale bar corresponds to 50 μm [14]

After taking a series of photos, the size of the water droplets was measured using Fiji ImageJ software. Based on the measured droplet diameters d_i, Sauter mean diameter (SMD) was calculated according to the formula (1). Before starting this procedure, calibration was performed using a calibration glass with an elementary scale of 0.01mm. All the photos used to analyze the size of water droplets have been made public in the Zenodo database [14], and a detailed description of this catalogue of photos and an explanation of the markings found in it can be found in [15].

$$\mathrm{SMD} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \tag{1}$$

3. Results

In the case of a fuel-water emulsion, photographed immediately after preparation, containing at least 2% surfactant in its composition, there is no strong relationship between the amount of water in the emulsion in the range of 3%-15% and the SMD of water droplets constituting the discrete phase of the emulsion (Fig. 3). In the case of a reduced emulsifier content in the emulsion to 1%, a clear minimum of the SMD of the droplets is observed between 9% and 12% of the water content in the emulsion. Increasing the amount of surfactant in the emulsion reduces the SMD of the water droplets. In addition, there is a clear reduction in the SMD of the water droplets in the emulsions photographed about 24 hours after preparation (Fig. 3 denoted 1 day). In the case of the emulsion containing 1% of the emulsifier, the dependence of the SMD of the droplets on the water content in the emulsion decreased. The most resistant emulsion to changes in the SMD of water droplets over time is the emulsion containing 3% surfactant.

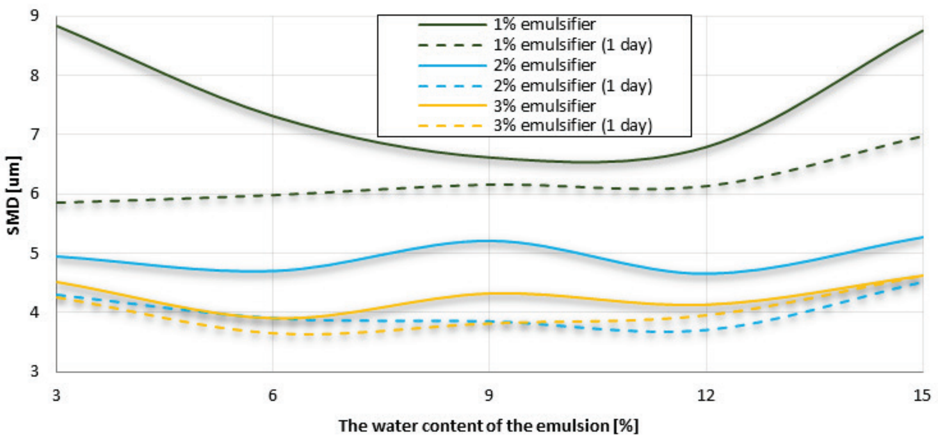


Fig. 3. Dependence of the SMD of water droplets on the water content in the emulsion

The distribution of droplet diameters in emulsions photographed immediately after preparation, with a mixing time of 5 minutes in the second stage, is strongly influenced by the amount of emulsifier contained in the emulsion (Fig. 4 and Fig. 5). In the figures, the vertical axis represents the percentage of water droplets from a given diameter range in their entire population. The horizontal axis represents the droplet diameter value in the interval of 1μm (for example, a diameter of 3μm corresponds to the diameter interval <2;3≥). For an emulsion containing 3% emulsifier, the most common diameters are between 2μm and 4μm (Fig. 4). The exception is an emulsion containing 3% water, in which case a shift in droplet diameters towards smaller values can be observed.

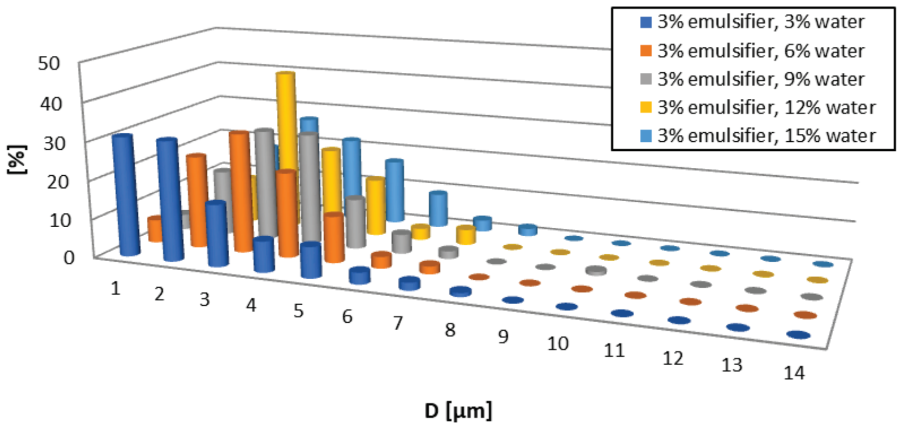


Fig. 4. Distribution of droplet diameter in a fuel-water emulsion containing 3% emulsifier depending on the amount of water

However, in the case of an emulsion containing 1% emulsifier (Fig. 5), a flattening of the droplet size distribution is observed, compared to the previous case (Fig. 4), and a shift in the number of drops with a diameter from a given range towards larger values. This is particularly visible for emulsions containing 12% and 15% water, where an increase in the representation of drops with diameters from 6 µm to 11 µm was observed compared to emulsions with lower water contents.

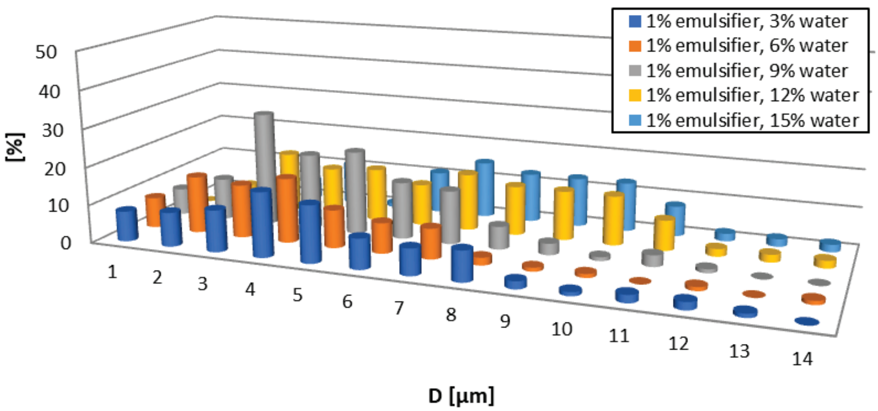


Fig. 5. Distribution of droplet diameter in a fuel-water emulsion containing 1% emulsifier depending on the amount of water

The size of water droplets in the fuel-water emulsion strongly depends on the time of mixing water with other components of the fuel mixture (Fig. 6). Increasing this time reduces the SMD of water droplets - extending it by 10 minutes reduced the SMD of water drops by 52.2%.

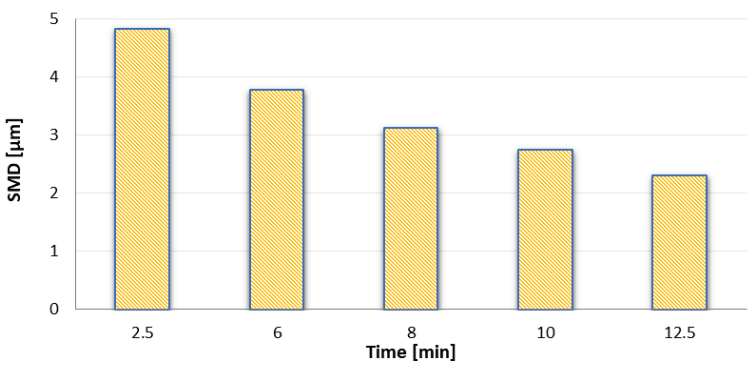


Fig. 6. Influence of time of mixing water with other ingredients of an emulsion containing 9% water and 3% emulsifier on the SMD of water droplets

Pumping the emulsion through the fuel pump does not substantially change the SMD of the emulsion discrete phase droplets (Fig. 7). This indicates that the mixing process in the fuel pump is not intensive enough and/or too short to break up the water droplets trapped in the fuel continuous phase of the emulsion.

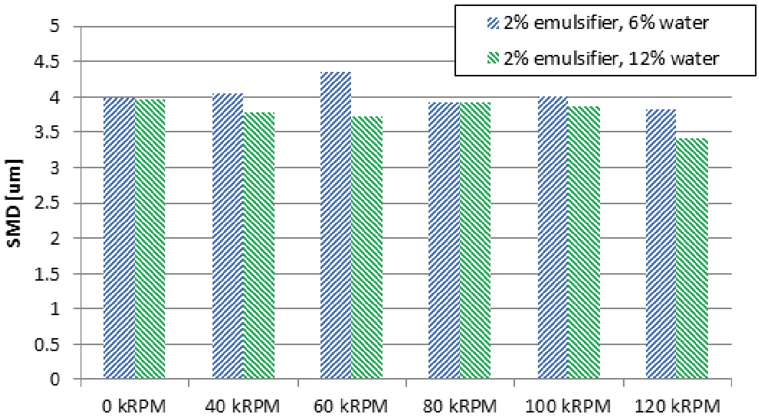


Fig. 7. Dependence of the SMD of water droplets on the simulated rotational speed of the GTM120 gas turbine

4. Discussion

During the study of oil-in-water emulsions [16], a decrease in discrete phase droplets was noted with increasing time and intensity of emulsion mixing. This was consistent with the behaviour of the water-in-oil emulsion subject of this article (Fig. 6). However, the change in size over time in [16] was the most intense until about 3 minutes of mixing, after which the droplet size tended to a certain asymptote. Most likely, the size of the emulsion droplets tested by the authors, after exceeding a certain threshold mixing time, would also be insensitive to its further extension. This issue requires further research. However, it should be taken into account that the extended preparation time of the emulsion makes it less practical as a research fuel.

In [17], where a water-in-diesel emulsion was tested, a significant decrease in the size of discrete phase droplets was observed after increasing the amount of emulsifier in the mixture from 2% to 5%. The emulsifier was Span80 and Tween80 in a 1:1 ratio. This coincides with the results presented in Figure 3. However, in the same study, an increase in droplet size was also observed with increasing emulsion storage time, which is the opposite effect to the results of the presented study (Fig. 3). A decrease in the size of the discrete phase droplets after increasing the emulsifier content in the emulsion was also noted in [18].

The research on the dependence of the SMD of the discrete phase droplets on the amount of water in the emulsion shows that the tested emulsions containing 2% and 3% of the emulsifier did not show such a dependence (Fig. 3). On the other hand, in [19], a decrease in droplet size was noted along with a decrease in the amount of water in the emulsion and an increase in the rotational speed of the stirrer. It should be noted, however, that these experiments tested emulsions containing 10, 20 and 30% water in an emulsion enriched with 1% Tween 80 emulsifier. The difference in the observations may be a much higher amount of water in the emulsion than the emulsion presented in this paper and a relatively small amount of emulsifier.

With reference to the purpose of the article, for further research it is recommended to use a fuel-water emulsion with a surfactant content of 2%. It is the smallest amount of emulsifier tested, which ensures a relatively constant size of discrete phase droplets as a function of water content in the emulsion. This practical approach aims to simplify further research as much as possible. Increasing the amount of emulsifier to 3% reduces the SMD change along with increasing the emulsion storage time (Fig. 3), which is beneficial for using it for scientific research. However, it should be noted that the presence of an emulsifier in the fuel mixture may significantly impact the combustion process and the engine hot section [20, 21]. From this point of view, it is beneficial to minimize its amount in the emulsion or even completely exclude it from the composition.

It was found that the tested fuel pump did not significantly affect the size of water droplets in the emulsion. (Fig. 7). However, it should be noted that changing the fuel pump may cause this effect to cease. Therefore, this issue should be checked individually for the currently used fuel pump model.

Using fuel-water emulsion instead of classic hydrocarbon fuel in engines leads to significant reductions in NOx [2-3]. The effectiveness of NOx emission reduction is influenced by the amount of water in the emulsion and the size of its drops - larger water drops in the emulsion reduce NOx more effectively. However, reducing the droplet size and increasing the water content increases the emulsion viscosity [22]. Changing the viscosity of the liquid changes characteristics of fuel injection into the combustion chamber [23]. Therefore, in order to eliminate changes in the experiment that may affect the measurement results, it is necessary to monitor both the droplet size of the discrete phase of the emulsion fuel and correct the fuel injection characteristics.

In addition, it should be noted that the SMD of the water droplets in the emulsion, observed in the images taken in two different test series, differs by about 0.7 μm (Figs. 3 and 7). This may be due to the difference in the weight of the prepared emulsion in each research series, the time that elapses between the preparation of the emulsifier and its use, or any other factors unknown to the authors. Also, image quality can further contribute to errors in SMD calculations that are difficult to quantify. Therefore, the presented results should be interpreted qualitatively and quantitative conclusions should be approached with caution.

5. Conclusions

Based on the conducted research, literature studies and the presented discussion, the following main conclusions can be formulated:

- increasing the amount of surfactant in the emulsion reduces the SMD of the discrete phase droplets,
- increasing the emulsifier content in the emulsion results in its lower sensitivity to the change of SMD of discrete phase droplets caused by the passage of time from its preparation,
- pumping the emulsion through the fuel pump of the GTM120 miniature gas turbine has a negligible effect on the SMD of the discrete phase droplets - which is important in the context of controlling the parameters of the emulsion supplied to the gas turbine combustion chamber,
- the distribution of water droplet sizes in the emulsion is influenced by both the amount of emulsifier and water contained in it, and the dependence of the water droplet size on the surfactant is greater than on the amount of water in the emulsion,
- the factor that allows for the design of SMD droplets of the discrete phase of the fuel-water emulsion without interfering with its composition is the mixing time of the components.

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