THE EFFECT OF TEMPERATURE ON THE PROPERTIES OF FUEL-WATER EMULSION APPLIED FOR FEEDING MARINE COMBUSTION ENGINES

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Abstract

Delivering water to cylinders is a means of restricting the emergence of nitrogen oxides in the combustion process in SI engines. In consequence of feeding the engine with fuel-water emulsion with simultaneous decrease of nitrogen oxides in the exhaust gases, there occur changes in the concentrations of: carbon oxide, hydrocarbons, solid particles, and also changes in the basic indexes of engine work. The values of these changes depend in large degree on the assumed method of producing emulsion. Depending on the method applied there exists a definite set of control parameters characteristic for each method, whose values of particular parameters determine the properties of emulsion produced. One of these parameters is the temperature of, essential insomuch as it can be controlled in a simple way.

The work presents the results of research on the effect of temperature of fuel-water emulsion produced in a helicoidal agitator on its properties, essential from the point of view of NO_x emission load in the exhaust gases.

Keywords: *marine diesel engine, emission of toxic compounds, fuel-water emulsion*

1. Introduction

One of the factors determining the further development of combustion engines, marine ones included, are the ever sharpened criteria of toxic compounds emission. A way of ensuring fulfilment of the ever more strict requirements is the constant improvement of the combustion process in the whole range of the engine's work, not excluding non-stationary states and the transitory states connected with them.

An ever more frequently applied method of actively influencing the combustion process is supplying water to the cylinders, aimed at decreasing the maximum values of combustion temperature in the cylinder. A method of supplying water to the cylinders is the injection of fuel-water emulsion by a standard but more efficient injector [3,9].

In the author's opinion, the application of fuel-water emulsion ensures the largest effect of NO_x emission, with simultaneous complete control of combustion process in the cylinder. This is due to the fact, among other things, that the injected water contained in the emulsion is supplied directly to the flame zone in the cylinder, i.e. the area where the nitrogen oxides are directly produced [1,9].

The selection of composition and methods of producing fuel-water emulsion remains an essential topic. In the case of selecting the composition of fuel-water emulsion for a particular engine (with definite features of utilization process), what becomes essential is such selection of emulsion that with the required toxic compounds emission level the engine's operational parameters should possibly be affected as little as possible [4,5,6,7].

An equally important problem is obtaining significant emulsion stability, which is small by nature. Attempts are made to improve this condition by applying various methods of its production. Depending on the method applied there is a set of control parameters characteristic for each method, determining the properties of emulsion produced [4,5]. The physical state of emulsion already produced is not without significance either, among which temperature is a very essential factor, conditioning the degree of emulsion comminution, but simultaneously affecting the unfavourable process of secondary emulsion.

2. Properties of fuel-water emulsion

As mentioned before, fuel-water emulsion is characterised by small stability, which is a result of considerable differences in the chemical construction of water and hydrocarbons. Oil-related fuels, propulsion fuels included, evince limited ability to mix with water. The solubility of water in fuels of this type depends mainly on their fractional composition (particularly the content of aromatic hydrocarbons) and temperature. It is assumed that the amount of water dissolved in hydrocarbons of $20^{o}C$ temperature does not exceed 582 ppm. With the increase of temperature there increases the solubility of water in hydrocarbons, particularly aromatic ones. After passing the solubility threshold, when the diameter of water droplets reaches the value of 0.1 μm, fuel-water emulsion forms a typical two-phase system. From the balance of various influences in both phases there results the value of free energy of phase distribution surface, that is interfacial tension. The surface tension of fractions and kerosene products depends on their molar mass, hydrocarbon composition and the presence of surface-active compounds.

The formation of water emulsion in kerosene fuel consists in the comminution of water with total area A_1 to small droplets with area A_2, i.e. $A_2 > A_1$ [8]. Thus, the increment of total area of dispersed phase is equal to

$$\Delta A = A_2 - A_1 \qquad (1)$$

Assuming that the value of interfacial tension coefficient in the system remains constant, the thermodynamic condition of emulsion formation can be written down as

$$\Delta G^{tw} = \sigma_{HW} \cdot \Delta A - T \cdot \Delta S \qquad (2)$$

where:

ΔG^{tw} – change of thermodynamic potential of emulsion formation,
σ_{HW} – interfacial tension coefficient at the water – hydrocarbon phase boundary,
ΔS – change of system entropy.

As the increment of interfacial surface and the value of interfacial tension and entropy change are positive values, and also

$$\sigma_{HW} \cdot \Delta A > -T \cdot \Delta S, \qquad (3)$$

so

$$\Delta G^{tw} > 0 \qquad (4)$$

This signifies that emulsion formation does not occur spontaneously, but requires energy supply from outside the system.

In the presence of certain surface-active compounds (emulsifiers), interfacial tension is reduced. An emulsifier in the two-phase system decreases the energy required for water comminution, initiates the formation of a boundary layer around the new water droplets and eventually increases the stability (durability) of emulsion.

Emulsifying water in the fuel takes place in two stages: comminution of water droplets and emulsion stabilisation. In general, water comminution takes place by deformation of the droplets to unstable cylinders with such size that they disintegrate spontaneously. The stabilisation of emulsion takes place in result of formation on water droplet surface of an adsorptive-solvate layer by a surface-active compound (surfactant).

In the descriptions of patents and specialist literature a very large number of surfactants are mentioned, which are suggested as water emulsifiers in propulsion oil. This signifies lack of uniform recipes for additives efficiently influencing the formation and stabilisation of the system. It should also be underlined that engine propulsion oils are similar as to composition and properties, independently of location and method of production. Emulsifiers evince rather low effectiveness, which is testified by the amounts added to obtain fairly stable emulsions (for example 2 – 3 % for emulsion with 10 % water content). Even larger amounts of surfactants are added for the formation of microemulsion (0.5 to 2 parts for each part of water added to the fuel).

To sum up, with regard to combustion in the cylinder the most important features of fuel-water emulsion are viscosity, dispersion degree and stability.

Viscosity affects energetic inputs attendant on mixing and transporting emulsified fuel, first of all the quality of emulsion dispersion in the engine’s combustion chamber. Emulsion viscosity depends mainly on water content, the system’s dispersion degree, temperature and the properties of the emulsifier. Water content up to 20 % of total emulsion volume slightly exceeds viscosity of the emulsion in relation to fuel viscosity. With water content of 40 % and more viscosity rapidly increases up to the gel stage and subsequently the system’s inversion.

From stability point of view, combustion in particular, dispersion degree and homogeneity of water emulsion in the fuel are very important. The maximal diameter of water particles should not exceed the droplet diameter of emulsion sprayed. Water dispersion degree depends then on the spraying quality of emulsion in the cylinder. On this condition the droplets of emulsion sprayed consist of water surrounded by a layer of hydrocarbons and emulsifier. It is assumed that the diameter of water droplets should not exceed 10 μm, and their main part should be contained in the range of 2 – 3 μm. If the emulsion contains water droplets larger than the diameter of droplets formed in result of spraying by the injector, there comes direct contact in the cylinder of water with the combustion chamber walls, and consequently to deterioration of combustion conditions.

One of emulsion stability aspects is its resistance to low and high temperatures. Emulsions with high water contact are particularly sensitive. Exceeding the limit values of temperature causes inversion of phases or the disintegration of emulsion into separate components of fuel and water.

The emulsion’s high resistance to the effects of heightened temperature is enhanced by high fuel viscosity and high degree of water dispersion. Resistance to the effects of lowered temperature is obtained by the addition of small amounts of aliphatic alcohols.

As mentioned before, the formation of emulsions does not take place spontaneously, but requires energy supply from outside the system. The most effective means of emulsifying water in fuels for engines with self-ignition is introducing it beneath the surface of propulsion oil. For the production of emulsion rotational devices are used: disc dispersants, mixers, ultrasonic, cavitational, injector devices, helicoidal agitators etc.

In the case of helicoidal agitator the properties of obtained fuel-water emulsion depend on the agitators setting parameters [10]. These are: rotational speed of the rotor, slot height in the agitator and efficiency understood as total stream of fuel and water mass flowing through the agitator.

3. Research on the effect of temperature of fuel-water emulsion production on its properties

The purpose of the experiment was to find the dependence of the effect of input values, i.e. rotational speed of the rotor – E and the fuel-water emulsion temperature – T on changes in output parameters. Elements of the output values set are: number of droplets, size of droplets (understood as their diameter) and dispersion degree.

During the experiment emulsion was produced described with complete plan 3^3, and subsequently microscopic photographs were taken of samples taken during the experiment. Analysis of particular photographs made it possible to obtain a set of water droplets, for which set its amount was determined and a division was made into populations of droplets with various diameters into classes. A comparison of results has been presented in Table 1.

Tab. 1. Comparison of water droplet amounts in particular classes

Number of measurement system	Amount of water droplets in emulsion in particular classes							
	P1	P2	P3	P4	P5	P6	P7	P8
	(…-0.2> [μm]	(0.2 - 0.4> [μm]	(0.4 - 0.6> [μm]	(0.6 - 0.8> [μm]	(0.8 - 1.0> [μm]	(1.0 - 1.2> [μm]	(1.2 - 1.4> [μm]	(1.4-…> [μm]
1	17	11	12	5	0	0	0	0
2	11	8	10	3	6	6	4	0
3	41	10	7	7	5	1	1	7
4	34	13	16	9	3	1	2	2
5	6	18	7	4	3	3	1	1
6	49	22	6	5	3	1	1	13
7	68	57	46	24	7	0	0	0
8	66	36	12	18	24	2	0	0
9	54	26	7	4	2	0	0	18
10	36	21	10	10	4	12	6	5
11	40	38	7	7	2	4	6	6
12	38	24	7	4	2	0	6	10
13	48	27	21	14	7	6	4	3
14	57	49	27	14	12	2	1	2
15	64	44	6	10	4	2	1	14
16	56	41	16	9	3	3	7	12
17	74	37	32	24	14	6	3	1
18	31	27	8	8	9	10	16	17
19	42	28	18	7	6	1	0	0
20	66	58	17	9	4	4	5	7
21	86	61	21	7	3	1	1	9
22	44	67	46	42	12	3	4	6
23	98	44	21	12	8	7	1	0
24	71	51	6	4	2	0	2	9
25	69	46	44	21	11	3	3	4
26	48	40	12	4	6	6	6	8
27	61	14	7	3	1	2	1	15

In connection with the large amount of information contained in the microscopic photographs, decomposition of the research object was performed by creating two models, each research model being characterised by one output value (Fig. 1, 2).

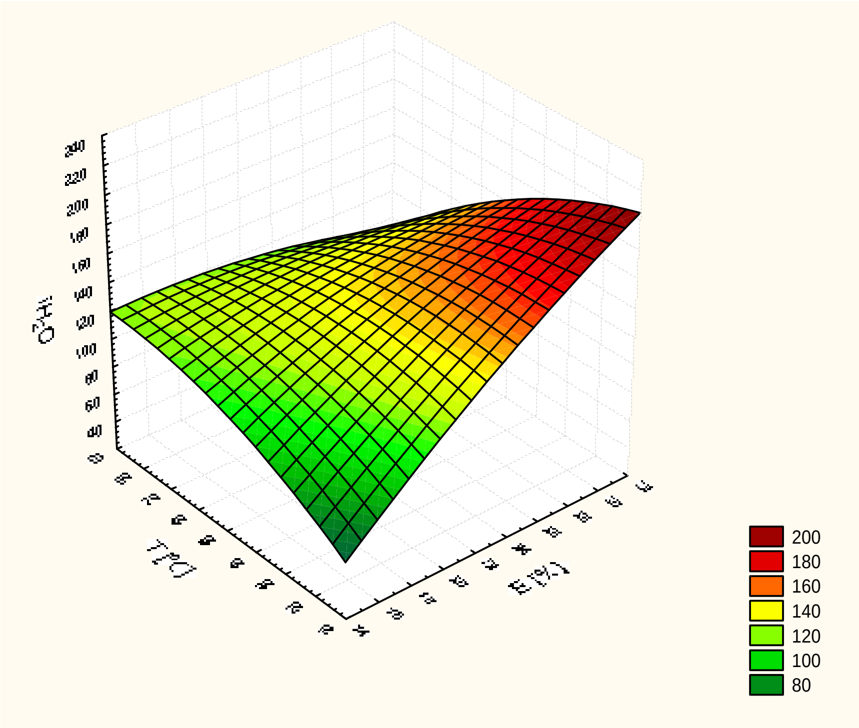

Fig. 1. Dependence between percentage concentration of emulsion, emulsion temperature and the amount of water droplets in area researched, where T- temperature [°C], E- emulsion concentration [%], iH_2O – amount of water droplets in the researched area

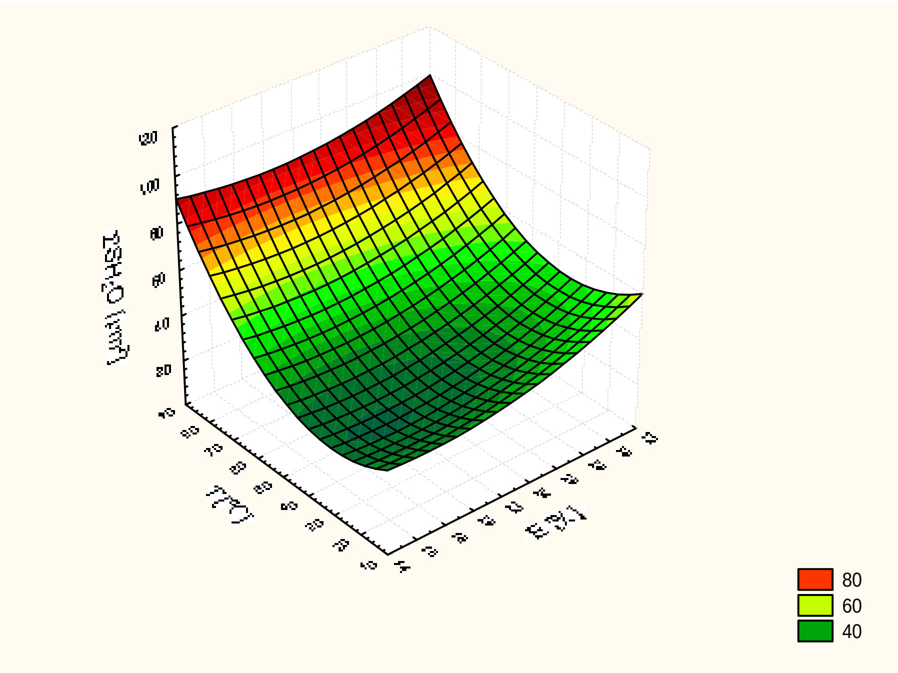

Fig. 2. Dependence between percentage concentration of emulsion, emulsion temperature and the sum of water droplet surfaces in area researched, where T- temperature [°C], E- emulsion concentration [%], ΣSH_2O – summary area of water droplets on researched surface [μm^2]

The first of suggested models presents the dependence of input parameters (rotational speed of agitator rotor – n, percentage concentration of emulsion – E, emulsion temperature – T) for the total amount of water droplets in the photograph (iH_2O) (Fig. 1). The second model, on the other hand, presents relations between input parameters and the sum of areas of all water droplets ($\Sigma S\ H_2O$) (Fig. 2).

During analysis of the experimental material collected, secondary emulsion formation was found in samples of measurement systems of the experiment plan described by the highest temperature. This process manifests itself by the increment of water droplet diameter in the emulsion. Therefore it was determined to examine this problem additionally by making a third model, which presents the relations between input parameters and the sum of droplet areas for classes P5-P8 (Table 1) in the control area.

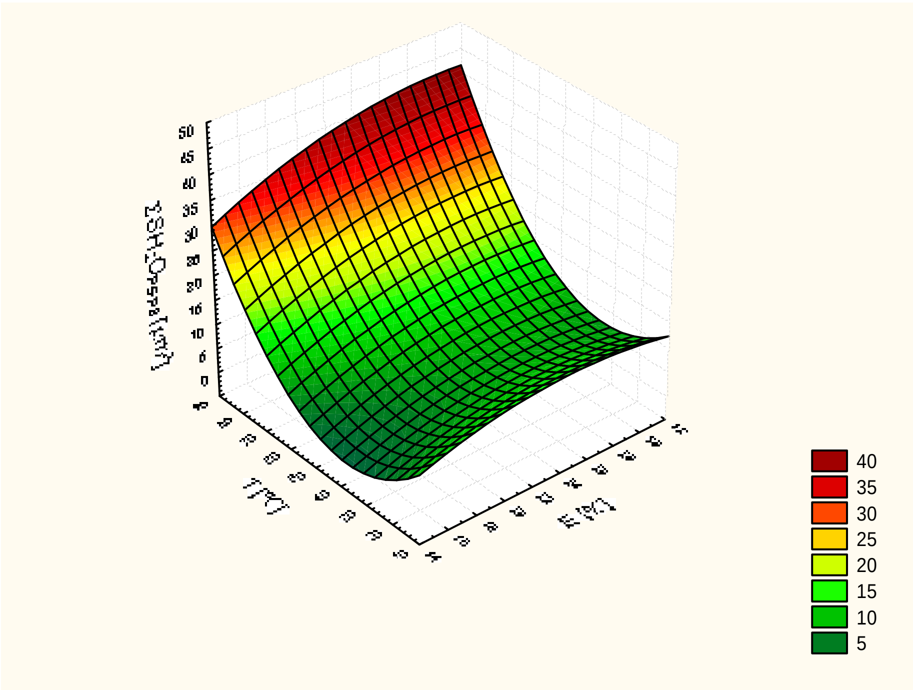

Fig. 3. Dependence between emulsion concentration, its temperature and the sum of droplet areas Σ H_2O classes P5-P8, where: T- temperature, E- emulsion concentration, ΣS H_2O $_{P5-P8}$ – sum of water droplet areas classes P5-P8 [μm.^{2}] acc. to Table 1

Analysis of Figures 1, 2 and 3 confirmed, in accordance with expectations, a significant effect of the temperature of fuel-water emulsion formation on its parameters. Thus, the temperature of fuel-water emulsion directly translates both into water droplets amount and the area occupied by those droplets. The character of changes in the physical properties of fuel-water emulsion is basically similar. Initially, with the increase of temperature the amount of droplets with medium size decreases, and then the amount of droplets with diameter larger than 0.8 μm increases. The most dynamic changes in this process are observed for temperature of 80°C.

This phenomenon is accurately presented in Fig. 4. As can be seen, the amount of droplets increases for classes P1, P2, P6, P7, P8. This proves the merging of droplets with medium size into large drops, as the temperature increases. The phenomenon of secondary emulsion is by all accounts unfavourable, as it decreases the dispersion of water droplets and affects emulsion stability by lowering it. It may also negatively affect the durability of fuel apparatus, and in an extreme case the flushing of oil film off cylinder surface. Yet it is supposed that by proper selection of the means of decreasing surface tension (in this case called Rocanol) this unfavourable phenomenon can be decreased. Undoubtedly, this problem may well constitute a separate research task.

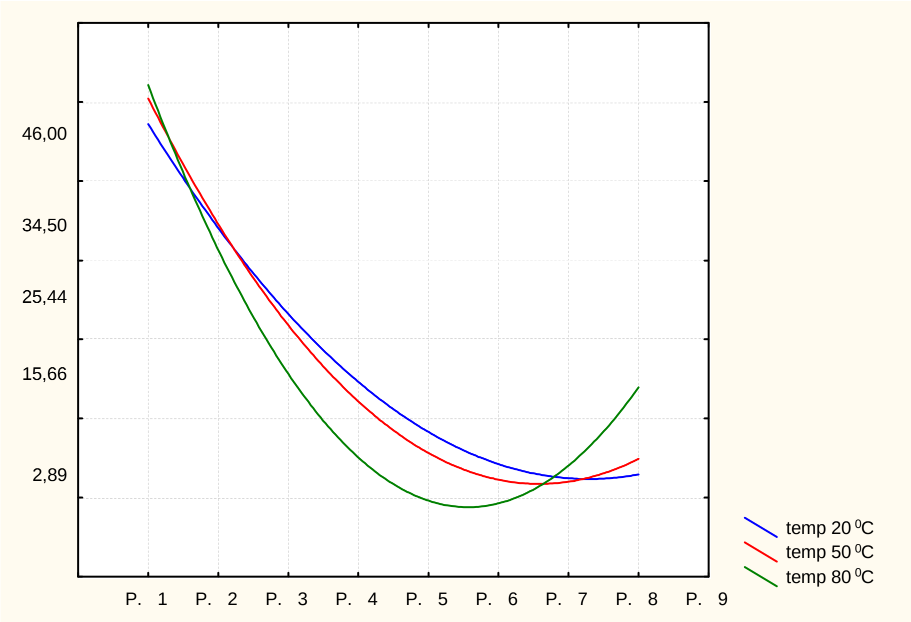

Fig. 4. Amount of droplets of particular class in emulsion depending on its temperature, where: P1-P9 classes of droplet size in accordance with Table 1

Analysing the process of secondary emulsion formation it was observed that the rotational speed of the helicoidal agitator rotor slightly affected this unfavourable phenomenon (Fig. 5).

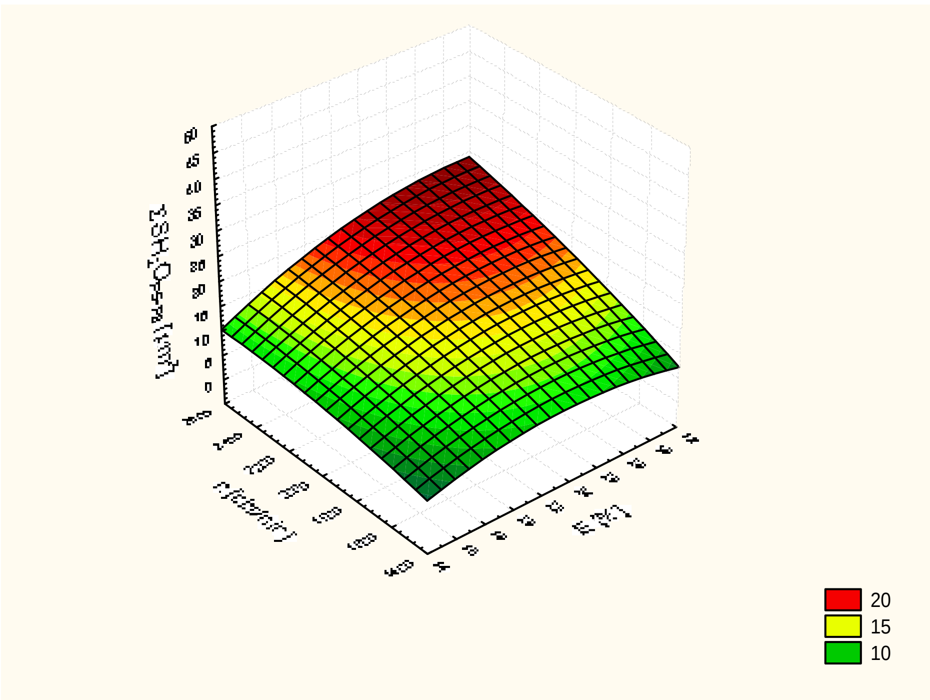

Fig. 5. Dependence between rotational speed of the agitator rotor – n [rpm] and emulsion concentration – E [%] and the sum of droplet areas ΣS $H_2O_{P5\text{-}P8}$ of classes P5-P8 in the area researched [μm.[2]]

Among the agitator setting parameters the rotational speed of the rotor is the decisive factor for water droplet dispersion; meanwhile, the formation of secondary emulsion increases with the increase of emulsion concentration for temperatures above 50°C. Therefore it is not advisable to apply large rotational speeds for the rotor, unlike in the case of emulsion temperatures about 20°C.

4. Résumé

The subject matter presented above does not fully exhaust the subject; it is just an attempt to describe it. An analysis of the effect of temperature of fuel-water emulsion formation – one of the parameters controlling the process of emulsion formation in a helicoidal agitator – on emulsion properties, confirmed the existence of such a parameter set that directly affects its physical properties. They obviously affect the processes in the engine cylinder.

In result of the experiment conducted it was found that with the increase of temperature there increases the amount of droplets of population classes 1, 2, 6, 7, 8 and the area occupied by them. This testifies to the merging of medium-size droplets into large drops with the increase of temperature, which is unfavourable as it decreases emulsion stability.

Further research work on the application of fuel-water emulsion for feeding piston combustion engines should first of all be directed toward its stability. This stability depends mainly on the content of additives decreasing the surface tension of combined liquids. The proper selection of emulsifiers would have an essential effect on maintaining emulsion dispersion, which would directly influence the repeatability of combustion processes in the piston engine cylinder.

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