# WATER-CARBOHYDRON EMULSIONS OBTAINED BY CAVITATION USED FOR THE FUELLING OF DIESEL ENGINES

**LECH J. SITNIK[1], MACIEJ K. DWORACZYŃSKI[2], PIOTR HALLER[3]**

Wrocław University of Technology

## Summary

The recent development of internal combustion engines goes towards the meeting of increasingly stringent requirements imposed to reduce toxic exhaust emissions and fuel consumption and thus to strive for carbon dioxide abatement and against depletion of global natural resources.

The research on engines fuelled by water-carbohydron emulsions has already a long tradition. So far, tests were based on emulsions obtained in chemical reactions. In this paper, similar analysis results have been presented, but the water-fuel emulsions used for the tests were obtained with making use of the cavitation effect.

At the Wrocław University of Technology, Department of Motor Vehicles and Internal Combustion Engines, a unique cavitator was developed, which was then used to producewater-carbohydron emulsions of mineral and synthetic diesel fuel. Both of these fuels as well as their water emulsions with 20% water content by volume were used for tests. Maximum engine power and torque vs. crankshaft speed curves were determined for a selected engine. Based on them, the ESC (European Stationary Cycle) test conditions were determined and the engine was tested on an engine dynamometer in accordance with the predetermined ESC test conditions. During the tests, engine emission and fuel consumption levels were measured under close scrutiny. The use of emulsions was found to result in a reduction in the consumption of diesel fuel.

**Keywords:** cavitation, emulsions, IC engines, fuel consumption, emissions

## 1. Introduction

The work was undertaken to evaluate the fuel consumption and exhaust emissions of a compression-ignition (CI) engine powered with water emulsions of hydrocarbon fuels.

The work described here was done as a preliminary study, which was also aimed at verifying whether this direction of work may be considered promising.

[1] Wrocław University of Technology, Department of Motor Vehicles and Internal Combustion Engines, 164 Braci Gierymskich Street, 51-640 Wrocław, Poland, e-mail: lech.sitnik@pwr.wroc.pl, ph.+48 71 347 79 18

[2] Wrocław University of Technology, Department of Motor Vehicles and Internal Combustion Engines, 164 Braci Gierymskich Street, 51-640 Wrocław, Poland, e-mail: maciej.dworaczynski@pwr.wroc.pl, ph. +48 71 347 79 18

[3] Wrocław University of Technology, Department of Motor Vehicles and Internal Combustion Engines, 164 Braci Gierymskich Street, 51-640 Wrocław, Poland, e-mail: piotr.haller@pwr.wroc.pl, ph.+48 71 347 79 18

Water-in-oil diesel fuel emulsions may be obtained chemically, by adding detergents (supportive substances) [1, 3, 4, 5, 6, 7, 8, 9], or in result of physical processes, e.g. with makinguse of the cavitation effect. In the work presented, water-carbohydron emulsions were obtained by employing the latter method.

Two diesel fueltypes were used for the tests: mineral diesel oil (MON) and synthetic diesel oil (SON). Moreover, water emulsions (20% v/v) of these fuels, i.e. water emulsions of mineral and synthetic diesel oils (EMON and ESON, respectively), were also used.

The emulsions were produced with the use of a prototype cavitator of special design.

**Fig. 1. Provisional facilityfor making the emulsion of diesel oil + water**

The emulsion-making system included two tanks of 20 l and 10 l capacity with valves. The tanks were filled with the liquids necessary for making the emulsion, i.e. diesel oil and water. A pump provided in the system forced the liquids from the system tanks via a gravitational column to an electric mixer, from where the liquids returned to the tanks in a closed cycle. The mixer comprised two electric motors arranged opposite each other and appropriately spaced. The motors, together with a specially designed housing, formed two chambers, i.e. a preliminary chamber to receive the liquids and a chamber where the liquids were mixed together. The motor rotors provided with discs rotated in opposite directions, thanks to which the mixture was set in two rotary motions in opposite directions;in consequence, both liquids were perfectly mixed together. Additionally, the spindles were specially shaped in result of which the cavitation effect was produced behind them. The cavitation is a relatively complex phenomenon caused by a drop in the pressure of the flowing liquid to a level close to the boiling pressure, in result of which vapour-gas bubbles are generated and afterwards implode when entering a higher pressurezone.The cavitation occurs when pressure drops, i.e. at higher liquid flow velocities.

**Fig. 2. Electric mixer**

The emulsions produced were homogenous; however, they underwent emulsion breaking with time. For the mineral and synthetic diesel oil, the emulsion breaking took place after about ten minutes and after about seven minutes, respectively.

The physico-chemical properties of the emulsions produced were not examined, but most likely they were not in conformity with the standard specifications applicable to diesel fuel.

The tests were to be carried out with following the ESC test procedure [1, 2]. The ESC test (also referred to as the OICA/ACEA test) was introduced simultaneously with the ETC (European Transient Cycle) and ELR (European Load Response) test procedures. It is used for the evaluation of exhaust emissions of CI engines. In Europe, it has been used since 2000 (Directive 1999/96/EC of 13 December 1999). It consists of 13 modes and has superseded a 13 mode test R 49.

The test is run at selected engine crankshaft speeds and loads. Four crankshaft speed values are set, with one of them being the idle engine speed and the other being selected in a special way;test loads are applied to the engine at the said preselected engine speeds. Actually, the test is carried out in the conditions of engine low-idle speed and three load response characteristics.

Before the test is begun, specific reference points should be located on the maximum engine power vs. crankshaft speed curve. The location of thesepoints has been depicted in Fig. 3.

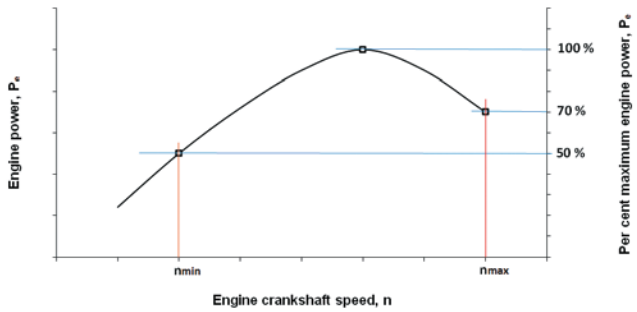


**Fig. 3. Location of the reference points on the maximum engine power vs. crankshaft speed curve, needed to determine the ESC test parameters**

The values of the engine crankshaft speed at which exhaust emissions are measured for appropriate per cent engine load values are defined as follows:

$$n_A = n_{min} + 0{,}25\ (n_{max} - n_{min})$$

$$n_B = n_{min} + 0{,}50\ (n_{max} - n_{min})$$

$$n_C = n_{min} + 0{,}75\ (n_{max} - n_{min})$$

(1)

At each of the above crankshaft speeds, measurements are carried out for four engine loads corresponding to 25%, 50%, 75% and 100% of the engine power output at the specific speed, which has been mapped in Fig. 4 as points representing individual ESC test modes in the per cent engine load / per cent engine speed coordinate system.

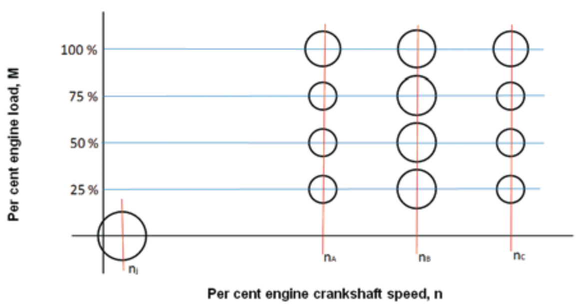


**Fig. 4. Mapping of the points representing individual ESC testmodesintheper cent engine load / per cent engine speed coordinate system**

Apart from the 12 ESC test modes where the engine loads were as previously specified, the test included a mode where the engine was run with its idle speed (at,approximately, zero engine load).

In consideration of the fact that actually the intensity of engine operation is not uniform all over the whole engine load and speed range, weighting factors have been introduced for this non-uniformity to be taken into account at determining the exhaust emission values. The ESC test parameters have been presented in Table 1.

**Table 1. ESC test parameters**

| Mode number | Engine speed, n [min$^{-1}$] | Per cent load, M [%] | Weighting factor, u | Mode length [min] |
|---|---|---|---|---|
| 1 | BJ | 0 | 0,15 | 4 |
| 2 | A | 100 | 0,08 | 2 |
| 3 | B | 50 | 0,10 | 2 |
| 4 | B | 75 | 0,10 | 2 |
| 5 | A | 50 | 0,05 | 2 |
| 6 | A | 75 | 0,05 | 2 |
| 7 | A | 25 | 0,05 | 2 |
| 8 | B | 100 | 0,09 | 2 |
| 9 | B | 25 | 0,10 | 2 |
| 10 | C | 100 | 0,08 | 2 |
| 11 | C | 25 | 0,05 | 2 |
| 12 | C | 75 | 0,05 | 2 |
| 13 | C | 50 | 0,05 | 2 |

The total exhaust emission valuesare determined from the equation:

$$E_j=\sum_i E_{jiui} \quad (2)$$

where:

$E_j$ – emission of the j$^{th}$ component of the exhaust gases;
$E_{ji}$ – emission of the j$^{th}$ component of the exhaust gases for the i$^{th}$ mode of the test;
$u_i$ – weighting factor for the i$^{th}$ mode of the test

The engine operates for the prescribed time in each mode of the ESC test, with the engine crankshaft speeds being kept within limits of ± 50 min$^{-1}$ from the specified value and the torque being held as required with an accuracy of ± 2% of the maximum torque.

## 2. Results of bench testing of an engine powered with the fuels under tests

The tests were carried out on a compression-ignition engine MF PERKINS AD3.152UR with a conventional fuel feed system, designed for being fed with mineral diesel oil. During the tests, standard engine settings were maintained.

The tests in the ESC test conditions were carried out on an engine test bed provided with a FROUDE DPX 4 water brake dynamometer. At first, however, the ESC test conditions had to be determined.

Obviously, differences in engine performance, especially in the maximum power and torque vs. speed curves, were expected to result from feeding the test engine with the fuels under testsand with their emulsions. Therefore, the maximum engine performance curves were determined at the first stage of the tests. Based on this, a substitute maximum performance curve was plotted as the lower envelope of all the performance curves determined for the engines fed with the fuels under tests and with their emulsions.

Such an assumption was made because of the necessity that the engine under tests should be subjected to identical load conditions represented by the same point on the engine performance curve regardless of the liquid used for engine fuelling purposes ("fuelling liquid"). The term "fuelling liquid" is used here instead of "fuel" because the emulsions do not meet all the requirements of fuel standard specifications, especially the EN 590 standard.

The results obtained have been illustrated in Fig. 5.

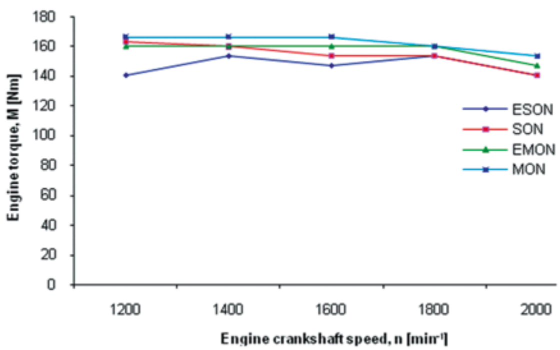


**Fig. 5. Maximum torque vs. speed curves for the engine fuelled with different liquids**

As it can be seen in the graph, the torque vs. speed curve taken for the engine fed with a water emulsion of the synthetic diesel oil was chosen as the substitute maximum performance curve. Based on this curve, the ESC test parameters were determined and maintained at the tests subsequently carried out.

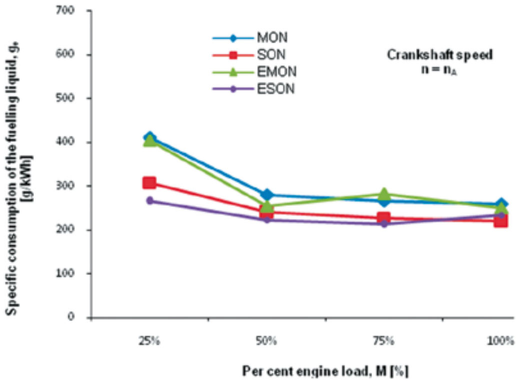


**Fig. 6. Specific consumption of the fuelling liquid vs. per cent engine load at thecrankshaft speed as determined for the A engine load option**

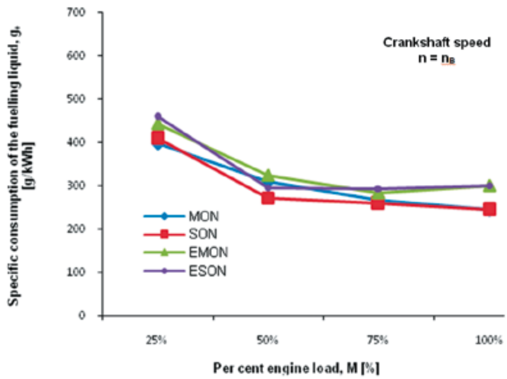


**Fig. 7. Specific consumption of the fuelling liquid vs. per cent engine load atthe crankshaft speed as determined for the B engine load option**

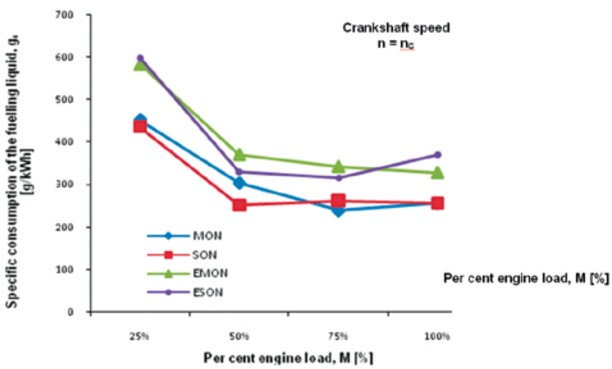


**Fig. 8. Specific consumption of the fuelling liquid vs. per cent engine load at the crankshaft speed as determined for the C engine load option**

According to the data presented, the general nature of changes in the specific consumption of the fuelling liquid remained unaltered. At higher engine loadvalues, greater scatters were observed in the specific consumption of the fuelling liquid. In general terms, the specific consumption of the synthetic diesel oil was lower than that of the mineral diesel oil. The values of specific consumption of water emulsions of diesel oils exceeded those of the non-emulsified diesel fuels, because the total consumption of the fuelling liquid was measured, inclusive of its water content.

**Table 2. A sample set of hydrocarbon emission measurement results and calculated specific consumption of water-fuel emulsion, determined for the engine during the ESC test**

| Mode number | Load option | Engine speed [min$^{-1}$] | Per cent load, M [%] | Engine load, Mr Nm | Weighting factor, u | Mode time [min] | Specific consumptionof the fuelling liquid, $g_e$ g/kWh | $g_e \times u$ g/kWh | HC emission ppm | HC×u ppm |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | Idle | 600 | 0 | 31.96 | 0.15 | 4 | 499.95 | 74.99 | 37.33 | 5.60 |
| 2 | A | 1450 | 100 | 141.91 | 0.08 | 2 | 250.72 | 20.06 | 29.80 | 2.38 |
| 3 | B | 1600 | 50 | 67.76 | 0.1 | 2 | 324.98 | 32.50 | 21.00 | 2.10 |
| 4 | B | 1600 | 75 | 102.28 | 0.1 | 2 | 284.75 | 28.48 | 23.00 | 2.30 |
| 5 | A | 1450 | 50 | 70.96 | 0.05 | 2 | 255.28 | 12.76 | 23.60 | 1.18 |
| 6 | A | 1450 | 75 | 106.75 | 0.05 | 2 | 282.79 | 14.14 | 25.00 | 1.25 |
| 7 | A | 1450 | 25 | 35.16 | 0.05 | 2 | 404.80 | 20.24 | 31.00 | 1.55 |
| 8 | B | 1600 | 100 | 136.16 | 0.09 | 2 | 301.40 | 27.13 | 26.00 | 2.34 |
| 9 | B | 1600 | 25 | 33.88 | 0.1 | 2 | 444.14 | 44.41 | 31.00 | 3.10 |
| 10 | C | 1750 | 100 | 140.00 | 0.08 | 2 | 327.58 | 26.21 | 13.00 | 1.04 |
| 11 | C | 1750 | 25 | 34.52 | 0.05 | 2 | 583.24 | 29.16 | 10.50 | 0.53 |
| 12 | C | 1750 | 75 | 104.84 | 0.05 | 2 | 342.34 | 17.12 | 10.00 | 0.50 |
| 13 | C | 1750 | 50 | 69.68 | 0.05 | 2 | 370.21 | 18.51 | 9.20 | 0.46 |
| | | | | | | | **Total** | **365,70** | | **24,33** |

The specific emulsion consumption ($g_e$) and the hydrocarbon emissions (HC) taken in aggregate for individual test modes have been specified in columns 8 and 10 of table 2, respectively. In columns 9 and 11, the respective values multiplied by appropriate weighting factors have been given. In the bottom line of the table, the specific fuel consumption and the hydrocarbon emissions determined for the whole test in accordance with equation (2) have been presented.

Other results of the experiments, processed in accordance with the ESC test procedure, have been summarized in table 3.

Table 3. Results of the experiments carried out in accordance with the ESC test procedure

| Fuelling liquid | CO emission [%] | $CO_2$ emission [%] | HC emission [ppm] | Specific consumption of the fuelling liquid, $g_e$ [g/kWh] |
|---|---|---|---|---|
| MON | 0.032 | 5.190 | 16.150 | 305.19 |
| SON | 0.034 | 6.772 | 9.996 | 288.44 |
| EMON | 0.042 | 7.076 | **24.329** | **365.70** |
| ESON | 0.078 | 6.424 | 32.086 | 323.85 |

The test engine was powered with both diesel fuels (PN EN 590) and their water emulsionscomposed in 20% of water and in 80% of diesel oil in each case. Therefore, a question had to be answered, what the actual diesel oil consumption was when the engine was fuelled with the emulsion. Results of the relevant calculations have been presented in table 4.

Table 4. Comparison of the consumption of various fuelling liquids at the ESC test

| Fuelling liquid | Diesel oil content (v/v) [%] | Water content (v/v) [%] | Specific consumption of the fuelling liquid in relation to the specific consumption of the mineral diesel oil, at the ESC test, by volume [%] | Difference in the specific consumption of the fuelling liquid in relation to the specific consumption of the mineral diesel oil, at the ESC test, by weight [%] |
|---|---|---|---|---|
| MON | 100.00 | 0.00 | 100.00 | 0.00 |
| SON | 100.00 | 0.00 | 94.36 | -5.49 |
| EMON | 80.00 | 20.00 | 116.38 | 19.83 |
| ESON | 80.00 | 20.00 | 110.31 | 6.11 |

The growths and drops, by volume, in the consumption of the fuelling liquids in relation to the consumption of mineral diesel oil have been presented in Fig. 9.

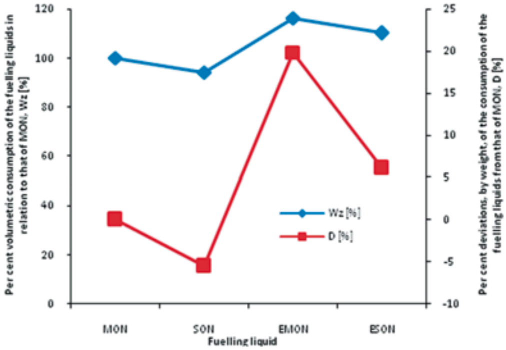


**Fig. 9. Per centvolumetricconsumption of the fuelling liquids in relation to that of the mineral diesel oil (MON) and per cent deviations, by weight, of the consumption of individual fuelling liquids from that of the mineral diesel oil (MON)**

The per cent differences between the consumption of fuel (diesel oil) contained in individual fuelling liquids from that of the mineral diesel oil have been summarized in the table below.

Table 5. Percent differences between the consumption of fuel (diesel oil) contained in individual fuelling liquids from that of the mineral diesel oil

| **Fuel** | **Difference between the consumption of fuel (diesel oil) contained in individual fuelling liquids from that of the mineral diesel oil** [%] |
|---|---|
| MON | 0.00 |
| SON | -5.64 |
| MON in EMON | -6.90 |
| SON in ESON | -11.75 |

The data provided in table 4 indicate that the fuelling of an engine with the synthetic diesel oil leads to a reduction in the volumetric consumption of such a fuel in comparison with the volumetric consumption of the mineral diesel oil. This is interesting inasmuch as the synthetic diesel fuel is characterized by lower mass density and, at the same time, lower calorific value. This may be explained by better preparation of the air-fuel mixture and, quite evidently, by more complete combustion of the synthetic diesel fuel. This is also evidenced by the $CO_2$ and HC emission measurement results presented in table 2.

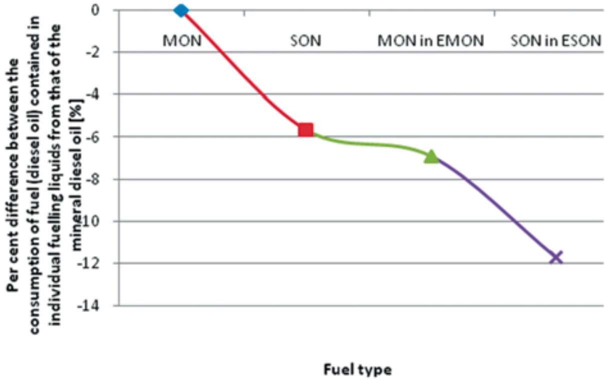


**Fig. 10. Per cent difference between the consumption of fuel (diesel oil) contained in individual fuelling liquids from that of the mineral diesel oil**

The significant reduction in the diesel fuel consumption when this fuel is fed to the engine in the form of a water-fuel emulsion seems to be another interesting thing. The potential reduction by almost 7% and almost 12% in the case of the mineral and synthetic diesel fuel, respectively, seems to be an encouragement to carry out further works in this direction.

Simultaneously, table 2 shows that the fuelling of an engine with water emulsions of diesel oil leads to an increase in toxic exhaust emissions, i.e. carbon monoxide (CO) and hydrocarbons (HC) in this case. If this increase is found considerable, it may be relatively easily reduced by the application of catalytic reactors [1].

## 3. Conclusions

An analysis of the test results has confirmed that the economic and ecological performance of contemporarycompression-ignition (CI) engines may be improved by fuelling such engines withsynthetic diesel oil or with water emulsions of diesel oils.

The maximum performance characteristics of the engine fuelled with the synthetic diesel oil and emulsions of diesel oils differed from each other. The highest torque valueswere achieved when the engine was fuelled with the synthetic diesel oil; on the other hand, the engine developed the lowest torque when it was fed with a water emulsion of this oil.

The fuelling of the engine with the synthetic diesel oil was found to lead to a reduction in the volumetric fuel consumption determined in the ESC test conditions by about 5.6% in comparison with the mineral diesel fuel consumption. The fuelling of the engine with a water emulsion of the synthetic diesel oil led to further reduction in the volumetric fuel consumption by almost 12% v/v in total. Such results should be considered significant.

When a water emulsion of the mineral diesel oil was used to fuel the engine, the volumetric consumption of this oil was reduced by about 7%, which should again be considered a promising result.

The powering of CI engines with water emulsions of diesel oils resulted in changes in toxic exhaust emissions. In general, increased carbon monoxide (CO) and hydrocarbons (HC) emissions were observed.

For the tests described herein, a CI engine made to quite a traditional technology was used. Therefore, it would be advisable now to do similar research work with the use of an engine of the latest generation.

The tests have shown a possibility of fuelling a CI engine for a short time with water emulsions of diesel oils. During the next tests, the issue of the impact of emulsions used as a fuel on the engine durability and reliability should be explored and clarified.

Due to relatively fast breaking of the emulsions under tests (obtained from a physical process with making use of the cavitation effect), the fuels thus prepared should be chiefly used for stationary engines or engines of vehicles of more than 3.5 Mg total mass.

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