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COMPARATIVE EXAMINATION OF PERFORMANCE CHARACTERISTICS OF AN IC ENGINE FUELLED WITH DIESEL OIL AND RAPE METHYL ESTERS

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Summary

Results of comparative examination of the performance characteristics of a compression ignition (CI) engine fuelled with diesel oil and rape methyl esters (RME) have been presented. The engine performance characteristics were assessed from the point of view of energy (effective power and torque of the engine), economy (effective efficiency), and environmental impact (pollutant emission). At the tests, the admixture of summer and winter additives to the rape methyl esters was taken into account. The tests were carried out in the conditions of taking the full-load engine performance vs. engine speed on an AVL Single Cylinder Test Bed provided with a single-cylinder CI research engine AVL 5402, a set of exhaust gas analysers, and instrumentation to control the operation of the whole system. The measurement data were completed and analysed with the use of the AVL PUMA software. In result of the tests carried out, significant differences were found to exist between the engine performance characteristics obtained for the summer and winter versions of vegetable-oil methyl esters. Apart from this, the use of the biofuels under test was found to have a favourable impact on pollutant emission.

Keywords: internal combustion engines, rape methyl esters, pollutant emission, fuel consumption, effective power

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1. Introduction

The search for unconventional fuels, different from the traditional petroleum-derivative fuels (motor spirits and diesel oils), especially for the powering of internal combustion (IC) engines, arises from both ecological and economic reasons. The factors most often mentioned as being important for environmental protection is pollutant emission, which include not only those harmful to human and animal health but also, for the fuels obtained from renewable energy sources, the avoided emission of fossil carbon dioxide in connection with the climate protection programs aimed at a reduction in the emission of this gas [10, 18]. The activities undertaken to pursue both the ecological and economic objectives include the searching for non-fossil fuels, which is also important for the protection of natural resources [10]. An economic and social aspect is the mobilization of the previously neglected communities and areas to provide raw materials suitable for the production of unconventional fuels [10, 18].

Among the unconventional fuels different from the traditional petroleum-derivative fuels, a special role is played by those referred to as "substitute fuels", i.e. the fuels that can be used in mass-produced spark ignition (SI) engines in place of motor spirits and in mass-produced CI engines in place of diesel oils [10]. It is a debatable issue whether substitute fuels are available at all. Normally, engine settings must be more or less radically changed for the use of unconventional fuels to be possible. Obviously, synthetic fuels can be provided with properties close to those of the conventional originals, but the synthetic fuels are now relatively expensive; apart from this, their potential as engine fuels usually cannot be fully utilized when they are modified to offer specific desirable characteristics.

Among the unconventional fuels being most popular at present and comparable with traditional petroleum-derivative fuels, those most closely related to the category of substitute fuels are the ones that are based on esters of biological oils [1, 6–9, 11–24, 26–30].

This article covers tests carried out on the following commercial fuels:

- traditional diesel oil ORLEN VERVA,
- self-contained biofuel B100 with a summer additive, denoted by RME – S (RME – Rape Methyl Ester),
- self-contained biofuel B100 with a winter additive, denoted by RME – W.

The tests were chiefly carried out to assess whether, and to what extent, the biofuels RME – S and RME – W may be considered as fuels substitute for the diesel oil.

The examination of the properties of CI engines fuelled with biological oil esters has a long tradition. The idea of using fuels of biological origin, in its essence, is by no means new. Just the opposite, the first fuels used by humans were of biological origin. The first documented evidences of the use of fire by humans date back to 300000 years ago and they were found at Zhoukoudian in China, where *Homo Erectus Pekinensis* (Peking Man) used wood as a fuel [25].

The idea of using fuels of biological origin for the powering of engines is very old, too. Fuels of biological origin, such as alcohols, vegetable oils, and biogas, were used to power even the first IC engines. In historical terms, the first documented report of using fuels of biological origin for the powering of compression ignition engines has been included in the patent description by Rudolf Christian Karl Diesel of 1892, where the inventor wrote that although the use of vegetable oil as a fuel was at that time an issue of insignificant importance but it was possible that fuels of that kind would gain importance over the course of the years, as it was then in the case of coal- and petroleum-derivative fuels [28].

The literature related to the use of vegetable oil esters for the fuelling of CI engines deals with, above all, the following:

- ecological properties of the engines in terms of pollutant emission [1, 6–24, 26–30],
- energy characteristics of the engines in terms of effective power and torque [1, 6–24, 26–30],
- economic properties of the engines in terms of specific brake fuel consumption, effective efficiency [1, 6–24, 26–30] and, for vehicles, operational fuel consumption [7–9, 28],
- operational properties of the engines in terms of engine reliability, wear of engine components and, above all, engine startability at low temperatures [28],
- properties of the process of combustion of biological oil esters in CI engines [1, 11, 12, 14, 17, 20, 22, 23, 26],
- methods of the production of engine fuels from biological oils of various origins [28].

The properties of IC engines powered with biofuels are the subject matter of, *inter alia*, monographs [22, 28] and doctoral dissertations [14, 20, 23]. Thorough works have been devoted to the powering of engines with both self-contained fuels [1, 6–24, 26–29] and mixtures of biological oil esters with diesel oil [1, 7–9, 11, 14, 15, 19–24, 26–30]. Some of the works have been dedicated to the results of investigations on the process of biofuel combustion in engines [1, 11, 12, 14, 16, 20, 22, 23, 26].

In most cases, the conclusions appearing in the literature reports may be summarized as follows:

1. The use of vegetable oil esters as engine fuels brings about small reductions in carbon monoxide and hydrocarbon emission and a big reduction in the emission of particulate matter [1, 6–24, 26–30]. Simultaneously, many of the publications inform about an increase in the emission of nitrogen oxides, with significant differences in this field being reported: this growth ranged from 10% to 30%.
2. The fuelling of automotive CI engines with rape methyl esters results in an increase in the operational fuel consumption and the relative growth is about 10% [7–9].
3. The use of vegetable oil esters involves some operational problems, in particular a growth of bacterial flora in engine fuelling systems [28] and deterioration in engine startability at low temperatures, chiefly due to high viscosity of vegetable oil esters under cold conditions [28].
4. Vegetable oil esters have been found to have an aggressive chemical impact on some materials, both metallic and, in particular, non-metallic, used in IC engines, especially in their fuelling systems [28].

5. The research on the combustion process in cylinders of IC engines has chiefly highlighted differences in the autoignition delay time and in the pressure growth rate in the case of biofuels being used [1, 11, 12, 14, 16, 20, 22, 23, 26]. Usually, a trend is observed towards a reduction in the autoignition delay time and in the pressure growth rate for biofuels compared with diesel oil [1, 11, 12, 14, 16, 20, 22, 23, 26].

2. Empirical engine tests

The comparative examination of performance characteristics of an IC engine fuelled with diesel oil and rape methyl esters was carried out at the University of Technology and Humanities in Radom, Faculty of Mechanical Engineering, Institute of Operation and Maintenance of Machines and Vehicles, Department of Automotive Vehicles and Engines, within the student's graduation work carried out by Sebastian Jagiełło and Sebastian Juwa under the supervision of Prof. Zdzisław Chłopek, PhD. Eng.

The tests were carried out on an AVL Single Cylinder Test Bed [5] provided with a single-cylinder CI research engine AVL 5402 [3], a set of exhaust gas analysers, and instrumentation to control the operation of the whole system. The measurement data were completed and analysed with the use of the AVL PUMA software [4].

The basic technical characteristics of the AVL 5402 engine have been given in the table below.

Table. Basic technical characteristics of the AVL 5402 engine

Number of cylinders	1
Bore	85.01 mm
Stroke	90.00 mm
Displacement	511.00 cm^3
Combustion type	Compression ignition
Valve system	4 valves
Compression ratio	17.0 ÷ 17.5
Fuelling system	Direct injection, single injector, Common Rail system
Maximum effective power, without supercharging	6 kW
Maximum effective power, with supercharging	16 kW
Rated engine speed	4200 min^{-1}
Injection pressure	180 MPa

Thanks to the use of special cylinder head gaskets, the compression ratio of the AVL 5402 engine could be changed. Special openings in the cylinder head made it possible to insert cameras into the combustion chamber and to observe the air-fuel mixture combustion process. The engine was provided with an exhaust gas recirculation (EGR) system and sensors making it possible to measure, *inter alia*, the internal pressure in the combustion chamber and the temperature of exhaust gases. Special fuel injection equipment with associated software provided a possibility of modifying the engine fuelling algorithm.

The research facility AVL Single Cylinder Test Bed was equipped with a water-cooled eddy-current dynamometer AVL DP80 to apply external load to the research engine and an electric motor to start and drive, if necessary, the research engine, as well as pumps and heat exchangers to circulate the cooling liquid and to maintain the temperature of system components at the required level.

The test program included engine operation in static states in the conditions of taking the full-load engine performance vs. engine speed, with the engine speed being changed within the range of (1200 ÷ 3600) min^{-1} in 400 min^{-1} intervals. During the tests, primarily the following quantities were measured:

- engine speed – n,
- engine torque – M_e,
- mass consumption intensity of fuel – G_f,
- mass consumption intensity of air – G_a,
- carbon monoxide concentration in exhaust gases – c_{CO},
- hydrocarbon concentration in exhaust gases – c_{HC},
- nitrogen oxides concentration in exhaust gasses – c_{NOx},
- particulate matter concentration in exhaust gases – c_{PM},
- indicated pressure – p_g recorded in the domain of crankshaft rotation angle – α,
- exhaust gas temperature – T_{ex}.

The measuring apparatus used for the tests was in conformity with the requirements of the following normative documents: Directive 1999/96/EC of the European Parliament and of the Council of 13 December 1999, Regulation (EC) No. 715/2007 of the European Parliament and of the Council of 20 June 2007, and Commission Regulation (EC) No. 692/2008 of 18 July 2008.

In this article, the authors limited themselves to presenting only the results related to the energy, economic, and ecological properties of the engine, without showing the results of an analysis of the combustion process (because of the limited publication size).

Figures 1–6 show comparisons of the following basic characteristics of the fuels:

- elementary composition, i.e. mass content of carbon – u_C, hydrogen – u_H, and oxygen – u_O,
- calorific value – W_f,
- density – ρ,
- cetane number – LC,
- kinematic viscosity at a temperature of 40 °C – ν,
- cold filter plugging point – t_b.

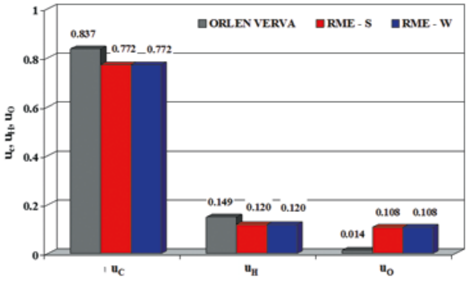

Fig. 1. Elementary composition of the fuels, i.e. mass content of carbon – u_C, hydrogen – u_H, and oxygen – u_O

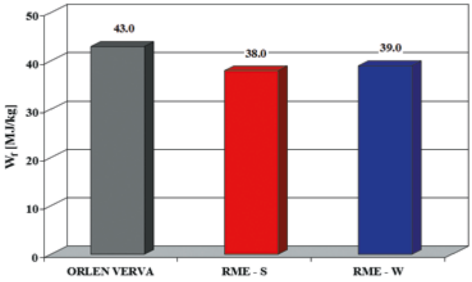

Fig. 2. Calorific value of the fuels – W_f

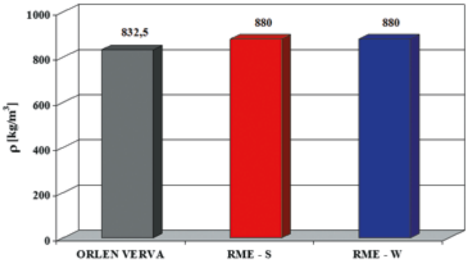

Fig. 3. Density of the fuels – ρ

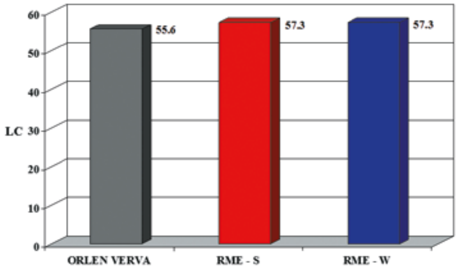

Fig. 4. Cetane number of the fuels – LC

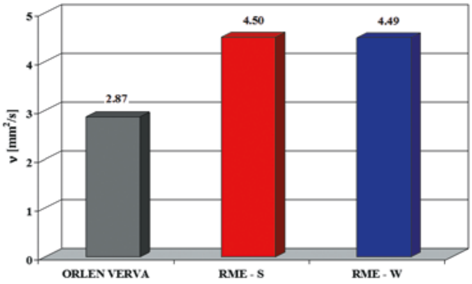

Fig. 5. Kinematic viscosity of the fuels at 40 °C – ν

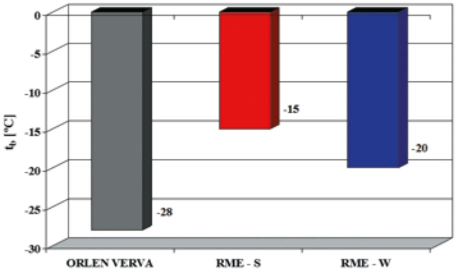

Fig. 6. Cold filter plugging point of the fuels – t_b

The mass content of oxygen in biofuels is much higher than the oxygen content of diesel oil, almost by an order of magnitude; therefore, the calorific value of the RME fuels is lower by over 10% in comparison with that of diesel oil. The density of the RME fuels exceeds that of diesel oil by about 6%; on the other hand, the RME fuels have better autoignition quality: their cetane number is higher by about 1.7. The RME fuels compared with diesel oil show much higher kinematic viscosity at 40 °C (by almost 60%). Significant differences were observed in the values of the cold filter plugging point: the biofuels, especially their summer version (RME – S), are definitely inferior to diesel oil in this respect.

Figures 7–12 shows engine performance vs. engine speed for the following basic quantities:

- energy characteristics, i.e. torque – M_e and effective power – N_e,
- economic characteristics in terms of fuel consumption, i.e. effective efficiency – η_e,
- exhaust gas temperature – T_{ex},
- ecological properties in terms of pollutant emission:
  - concentrations of substances harmful to human and animal health in engine exhaust gases, i.e. volume concentrations of carbon monoxide – c_{CO}, hydrocarbons – c_{HC}, and nitrogen oxides – c_{NOx} and mass concentration of particulate matter – c_{PM},
  - specific brake emission of the pollutants mentioned above, i.e. carbon monoxide – e_{CO}, hydrocarbons – e_{HC}, nitrogen oxides – e_{NOx}, and particulate matter – e_{PM}.

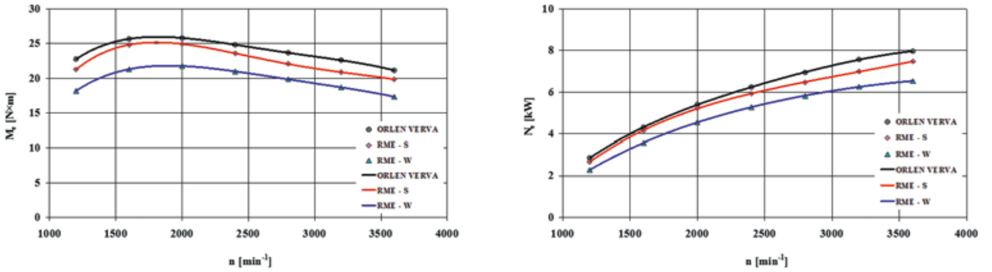

Fig. 7. Engine torque – M_e and effective power – N_e vs. engine speed – n

Due to lower calorific value of biofuels, both the torque and effective power of the engine fed with the RME fuels were lower than the corresponding values obtained for the engine fuelled with diesel oil; however, the difference observed for the summer fuel was quite small, which can be explained by higher effective efficiency of the engine powered with the RME – S fuel in comparison with the same engine powered with the RME – W fuel. The maximum engine torque and effective power values were achieved at engine speed of about 1600 min^{-1} and of 3600 min^{-1}, respectively.

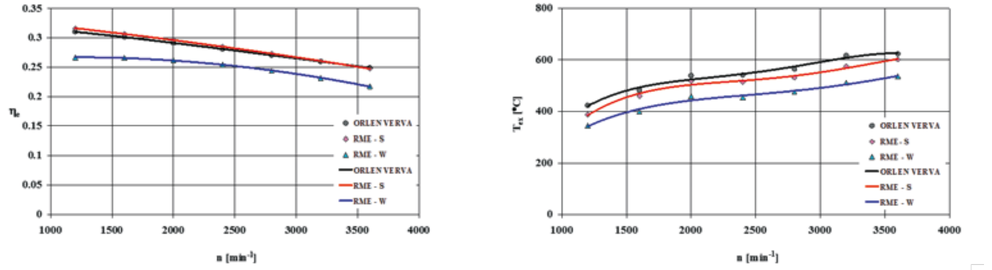

Fig. 8. Effective efficiency – η_e and exhaust gas temperature – T_{ex} vs. engine speed – n

The effective efficiency curves plotted for the engine fed with diesel oil and summer biofuel were close to each other while for the RME – W fuel, the effective efficiency of the engine was markedly lower. The exhaust gas temperature was highest for diesel oil, which was a consequence of higher calorific value of this fuel in comparison with the calorific values of the fuels under test, although the high temperature of combustion of such fuels, conducive to high emission of nitrogen oxides, is usually explained by the molecular proximity of oxygen to carbon and hydrogen, as it is in the case of oil esters [6–9, 13, 14, 17–22, 27, 28, 30].

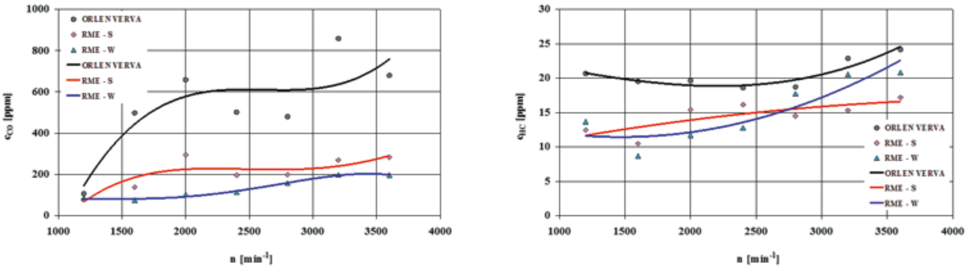

Fig. 9. Volume concentration of carbon monoxide – c_{CO} and hydrocarbons – c_{HC} vs. engine speed – n

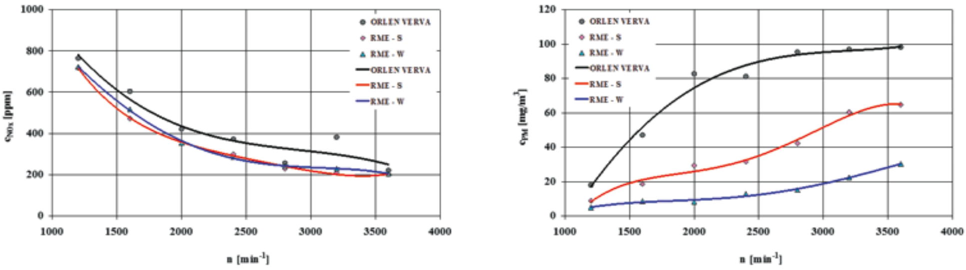

Fig. 10. Volume concentration of nitrogen oxides – c_{NOx} and mass concentration of particulate matter – c_{PM} vs. engine speed – n

The pollutant concentration vs. engine speed show in some cases considerable irregularity; however, a steady trend can be seen that for the biofuels, the concentrations of carbon monoxide and particulate matter were markedly lower, the hydrocarbon concentration was also lower but to a smaller extent, and (which does not confirm many experiment results [6–9, 13, 14, 17–22, 27, 28, 30]) the concentration of nitrogen oxides not only did not increase but even slightly declined.

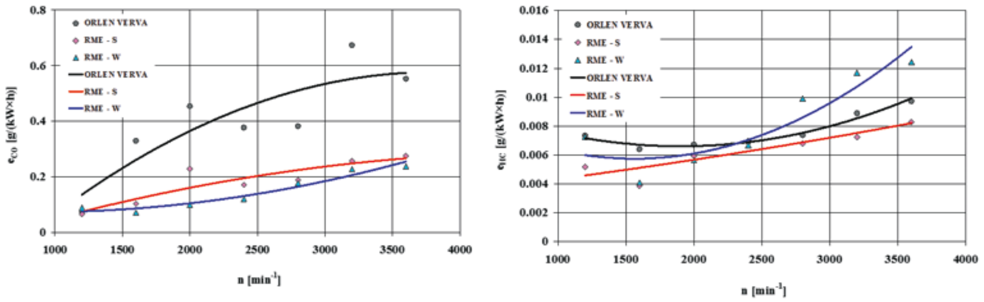

Fig. 11. Specific brake emission of carbon monoxide – e_{CO} and hydrocarbons – e_{HC} vs. engine speed – n

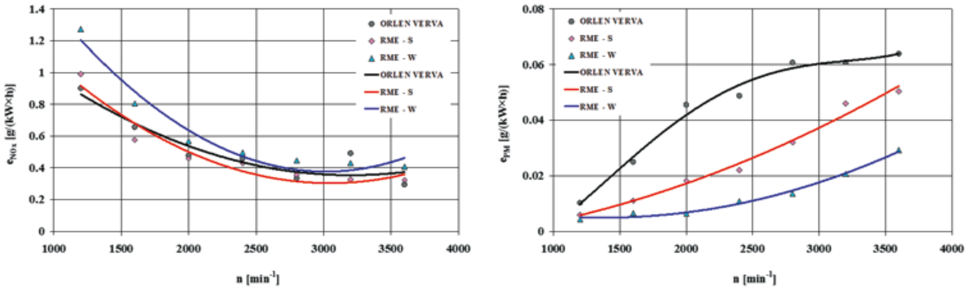

Fig. 12. Specific brake emission of nitrogen oxides – e_{NOx} and particulate matter – e_{PM} vs. engine speed – n

The specific brake emission of carbon monoxide and particulate matter were markedly lower for biofuels. For hydrocarbons and nitrogen oxides, the specific brake emission values were similar for all the fuels under test.

Figures 13 and 14 show the average values of the specific brake pollutant emission for individual fuels under test, determined in the engine speed domain.

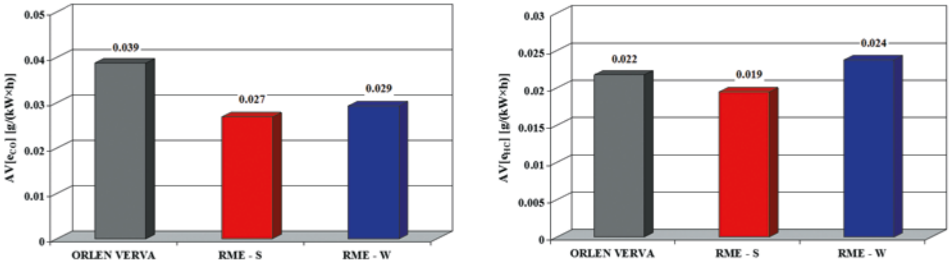

Fig. 13. Average values of the specific brake emission of carbon monoxide – AV[e_{CO}] and hydrocarbons – AV[e_{HC}], determined in the engine speed domain

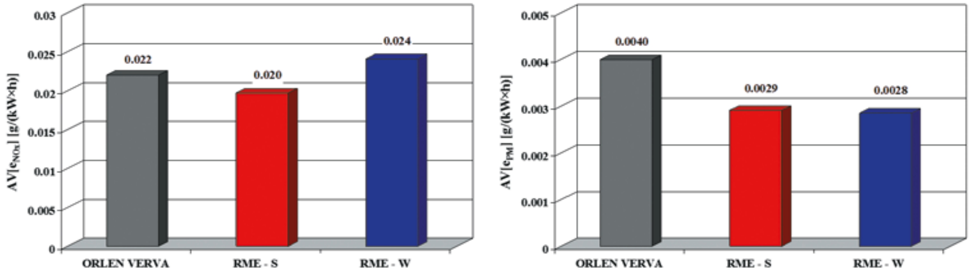

Fig. 14. Average values of the specific brake emission of nitrogen oxides – AV[e_{NOx}] and particulate matter – AV[e_{PM}], determined in the engine speed domain

Similarly to what was previously stated, it was also in the case of the average values of the specific brake pollutant emission for individual fuels under test, determined in the engine speed domain, that the biggest differences were observed for carbon monoxide and particulate matter. For the carbon monoxide and particulate matter emission, the lowest values were recorded in the case of the RME – S and RME – W fuels, respectively.

Figures 15 and 16 show relative changes – δ in the average values of the specific brake pollutant emission, determined in the engine speed domain.

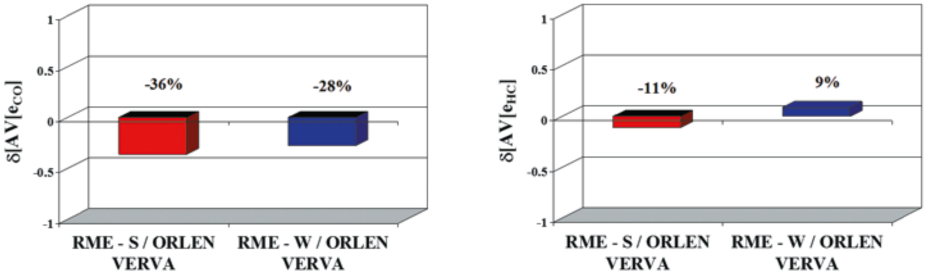

Fig. 15. Relative changes – δ in the average values – AV of the specific brake emission of carbon monoxide – e_{CO} and hydrocarbons – e_{HC}, determined in the engine speed domain

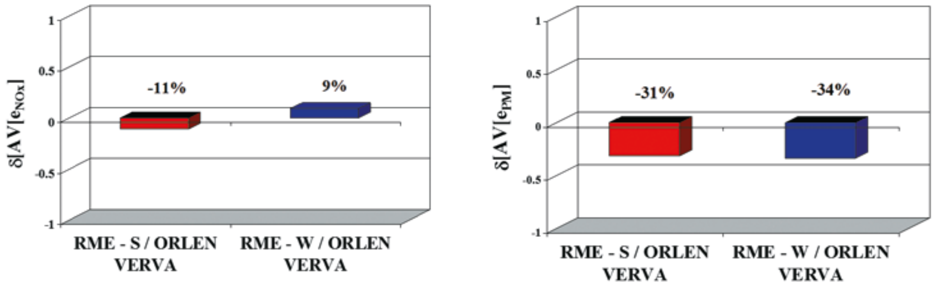

Fig. 16. Relative changes – δ in the average values – AV of the specific brake emission of nitrogen oxides – e_{NOx} and particulate matter – e_{PM}, determined in the engine speed domain

The use of biofuels caused relative reductions in the average values of the specific brake emission of carbon monoxide and particulate matter, determined in the engine speed domain, by about 30%. For hydrocarbons and nitrogen oxides, these relative differences amounted to approximately 10%. For the RME – S fuel, the difference meant a reduction in the specific brake pollutant emission, while for the RME – W fuel, the specific brake pollutant emission increased.

3. Conclusions

The results of the tests carried out make it possible to draw the following conclusions:

1. The highest effective power and output torque of an internal combustion (IC) engine were obtained when the engine was fed with diesel oil. For the summer biofuel, they were somewhat lower; when the winter biofuel was used, the effective power and torque values were considerably reduced.
2. The use of methyl esters of rape oil (RME) resulted in a measurable reduction (by about 30%) in the emission of carbon monoxide and particulate matter. For hydrocarbons and nitrogen oxides, the relative difference was about 10% and meant a reduction in the specific brake emission for the summer (S) biofuel and an increase in the emission for the winter (W) biofuel. The result obtained for the nitrogen oxides emission was ambiguous, the more so that the temperature of exhaust gases was highest for diesel oil, somewhat lower for the RME – S fuel, and much lower for the RME – W fuel.
3. The effective efficiency of the IC engine was found to be at a similar level when the engine was fed with diesel oil and summer biofuel. For winter biofuel, the effective efficiency of the engine was markedly lower.

In general terms, a statement may be made that the relatively small differences in the assessed performance characteristics of the IC engine fuelled with diesel oil and rape methyl esters provide grounds for presenting a cautious opinion that, based on the tests carried out, rape methyl esters with summer and winter additives may be recognized as substitute fuels for diesel oil. To make a more thorough assessment of the usability of rape methyl esters as substitute fuels for diesel oil, investigations should be carried out on the combustion process that takes place in the engine cylinder.

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