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EXAMINATION OF THE COMBUSTION PROCESS IN A COMPRESSION IGNITION ENGINE FUELLED WITH DIESEL OIL AND RAPE METHYL ESTERS

BADANIA PROCESU SPALANIA W SILNIKU O ZAPŁONIE SAMOCZYNNYM ZASILANYM OLEJEM NAPĘDOWYM I ESTRAMI METYLOWYMI OLEJU RZEPAKOWEGO

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Summary

Results of an examination of the combustion process in a compression ignition (CI) engine fuelled with diesel oil and rape methyl esters (RME) with admixtures of summer and winter additives have been presented. The examination was undertaken to assess whether rape ethyl esters may be legitimately recognized, from the point of view of the properties of the combustion process, as substitute fuels for diesel oil. The tests were carried out in the conditions of taking the full-load engine performance vs. speed curve on an AVL Single Cylinder Test Bed provided with a single-cylinder CI research engine AVL

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5402. The full-load torque and effective efficiency curves were taken and the maximum values of the indicated pressure and the corresponding crank angle values were determined. The extreme values of the derivative of the indicated pressure with respect to the crank angle were established as well. To plot the curves that would visualize variations in the quantities characterizing the combustion process, the CONCERTO data processing platform was used. The maximum values of the air-fuel mixture temperature were measured, with finding out the corresponding crank angle values. The characteristics determined for diesel oil and rape methyl esters with an admixture of summer additives were found to be very similar to each other, while for the winter biofuel version, the characteristics were markedly different.

Keywords: internal combustion engines, rape methyl ester, combustion process

Streszczenie

W artykule przedstawiono wyniki badań procesu spalania w silniku o zapłonie samoczynnym zasilanego olejem napędowym i estrami metylowymi oleju rzepakowego z dodatkami letnim i zimowym. Celem badań była ocena, czy ze względu na właściwości procesu spalania jest uzasadnione traktowanie estrów metylowych oleju rzepakowego jako paliw zastępczych w stosunku do oleju napędowego. Badania przeprowadzano w warunkach zewnętrznej charakterystyki prędkościowej na stanowisku badawczym AVL Single Cylinder Test Bed z jednocylindrowym silnikiem badawczym o zapłonie samoczynnym AVL 5402. Wyznaczono charakterystykę zewnętrzną momentu obrotowego i sprawności ogólnej. Zbadano wartości maksymalne ciśnienia indykowanego i kąty obrotu wału korbowego odpowiadające tym wartościom. Wyznaczono wartości ekstremalne pochodnej ciśnienia indykowanego względem kąta obrotu wału korbowego. Do wyznaczenia przebiegu wielkości charakteryzujących proces spalania wykorzystano oprogramowanie CONCERTO. Zbadano wartości maksymalne temperatury czynnika, wyznaczono także kąty obrotu wału korbowego odpowiadające tym wartościom. Stwierdzono duże podobieństwo wyznaczonych charakterystyk[5] dla oleju napędowego i estrów oleju rzepakowego z dodatkiem letnim, natomiast wyraźnie różnią się charakterystyki zimowej wersji biopaliwa.

Słowa klucze: silniki spalinowe, estry metylowe oleju rzepakowego, proces spalania

1. Introduction

Fuels based on esters of biological oils are commonly considered as substitutes for diesel oils when used for the powering of compression ignition (CI) engines [8, 9, 11-13, 16-21, 23-26].

It is expected that the substitutes for petroleum-derivative fuels should have such properties that engines might be powered with the substitutes and traditional fuels alternately with no additional engine design changes or readjustments [13]. There are several primary criteria of assessment of the unconventional fuels for conformity with the requirements that should be met by substitute fuels. In general, the criteria may be divided into three categories, where the following data are taken as a basis:

[5] Pod pojęciem „charakterystyka" autorzy rozumieją nie tylko zależności, jak jest to zazwyczaj powszechnie stosowane, ale i wartości – w tym wypadku są to charakterystyki zerowymiarowe (inaczej: punktowe). Takie stosowanie nazwy „charakterystyka" jest zgodne ze źródłosłowem rozpatrywanego terminu: podstawowym Znaczeniem tego terminu jest – zgodnie ze Słownikiem Języka Polskiego – „opis cech charakteryzujących kogoś lub coś".

- physicochemical characteristics of the fuels under test in respect of the usability of a fuel for engine powering;
- performance characteristics of internal combustion (IC) engines powered with the fuels under test;
- assessment of the processes that take place in IC engines powered with the fuels under test.

The criteria based on the evaluation of physicochemical characteristics of fuels include, above all: elementary composition and, related to it, calorific value and stoichiometric point of a fuel [7-9, 13, 25]. Other important parameters include fuel viscosity and other quantities that characterize the tribological properties of a fuel, such as propensity for having an impact on engine component and operation materials [7, 8, 18, 25]. For organizational reasons, the stability of fuel properties is another matter of significant importance [7-9, 15].

Among the criteria based on the evaluation of IC engine performance characteristics, those considered most important are engine operational characteristics, especially if they are related to energy output (effective power, engine torque) and economy of operation (effective efficiency and other fuel consumption characteristics) [11, 12, 16-21, 23-26]. Considerable importance is also attached to the ecological criteria, characterizing e.g. pollutant and noise emissions or fuel biodegradability [1, 11, 12, 16-21, 23-26]. The criteria based on the evaluation of IC engine performance characteristics should also include engine durability and reliability parameters and requirements related to engine operation and maintenance [7, 8, 25].

The main processes that take place in IC engines and chiefly determine the engine performance characteristics are those related to the fuel feeding to the engine and to the fuel combustion in engine cylinders [1, 7, 8, 16, 18, 21, 23].

This publication presents selected results of comparative examination of the process of combustion of diesel oil and rape methyl esters (RME) in a compression ignition engine. The examination was undertaken to assess whether rape ethyl esters may be legitimately recognized, from the point of view of the properties of the combustion process, as substitute fuels for diesel oil.

2. Object and program of tests

The tests were carried out on a single-cylinder CI research engine AVL 5402 [4] fed with the following fuels:

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

The empirical tests were carried out on an AVL Single Cylinder Test Bed [6] provided with a research engine AVL 5402 and control, tell-tale, and measuring instrumentation. The measurement data were recorded and analysed with the use of AVL PUMA [5] and AVL CONCERTO [3] software.

In the AVL 5402 engine, the supercharging pressure and compression ratio could be controlled. A Common Rail system provided in the engine made it possible to modify the engine fuelling algorithm. In the tests, a two-phase fuel injection system was used. Fig. 1 shows an example curve representing the injector opening control voltage as a function of crank angle measured from the top dead centre (TDC), at a point on the full-load power curve corresponding to an engine speed of 1 600 min^{-1}.

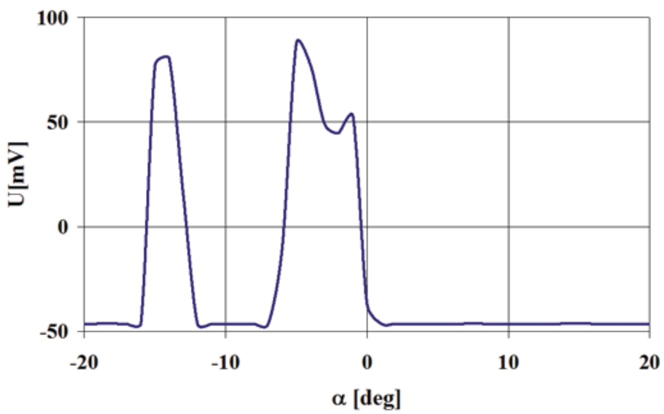

Fig. 1. Injector opening control voltage (U) vs. the crank angle (α) measured from the top dead centre (TDC), at a point on the full-load power curve corresponding to an engine speed of 1 600 min^{-1}

The test program [12] included engine operation in static states in the conditions of taking the full-load engine performance vs. speed curve, with the engine speed being changed within the range from 1 200 min^{-1} to 3 600 min^{-1} in 400 min^{-1} intervals. The quantities measured during the tests included:

- engine speed (n);
- engine torque (M_e);
- fuel consumption rate, by mass (G_f);
- exhaust gas temperature (T_{ex});
- indicated pressure (p_g) recorded in the crank angle (α) domain;

as well as other quantities, not used for the analyses covered herein, e.g. air consumption rate, by mass; concentrations of individual exhaust gas components; and other parameters measured for monitoring and verification purposes.

The measuring apparatus used for the tests [5, 6] 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.

Basic physicochemical characteristics of the fuels under test have been given in the table below.

Table. Basic physicochemical characteristics of the fuels under test

Parameter	Unit of measure	Fuel		
		ORLEN VERVA	RME–S	RME–W
Density	kg/m^3	832.5	880.0	880.0
Calorific value	MJ/kg	43	38	39
Cetane number				
Kinematic viscosity at 40 deg C	mm^2/s	2.87	4.50	4.49
Elementary composition, by mass:				
–carbon		0.837	0.772	0.772
–hydrogen		0.149	0.120	0.120
–oxygen		0.014	0.108	0.108
–sulphur	ppm	7.5	3.0	3.0
Cold filter plugging point (CFPP)	deg C	–28	–15	–20
Flash point	deg C	65	101	101

The density of rape methyl esters (RME) 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 %) and this has a considerable impact on the cold starting properties of an engine.

The mass oxygen content of biofuels is much higher than that of diesel oil, almost by an order of magnitude in the cases under consideration. Sulphur occurred in the fuels under test as a trace component only; nevertheless, the sulphur content of the RME fuels was lower by 60 % than that of diesel oil. Nowadays, however, this parameter has lost a lot of its importance since the time when biofuels were introduced into use.

Significant differences were observed in the values of the cold filter plugging point (CFPP): the biofuels, especially their summer version (RME–S), were definitely inferior to conventional diesel oils in this respect; this translates into worse engine starting properties when the RME fuels are used.

The flash point of the RME fuels exceeds that of diesel oil by more than 30 deg C. In terms of practical engine operation, this may be interpreted as an advantage of such fuels because of their better properties characterizing the safety of the engine fuelling system.

3. Test results

The tests carried out showed that the engine torque (Me) values measured for the RME fuels compared with diesel oil were reduced in the whole range of engine speeds (n), with the relative torque difference values being as follows (see Fig. 2):

- for the RME–S fuel, the torque dropped by about 6 %, on average (varying from 3 % to 8 %);
- for the RME–W fuel, the torque dropped by about 17 %, on average (varying from 12 % to 20 %).

The effective efficiency values determined for the engine powered with the summer biofuel and diesel oil were comparable to each other (with an accuracy of 1 % of the relative difference); for the winter biofuel, the difference in the effective efficiency was clearly visible, i.e. the efficiency for the RME–W fuel was lower by 11 %, on average (varying from 10 % to 14 %), from that of the same engine fuelled with diesel oil.

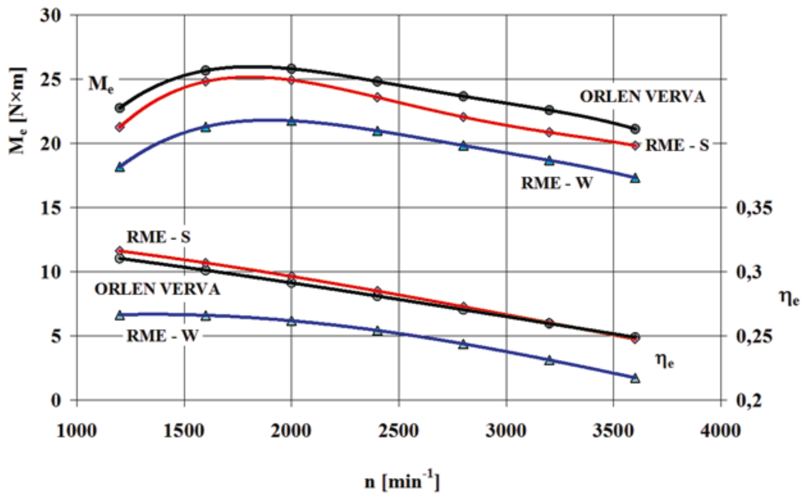

Fig. 2. Engine torque (M_e) and effective efficiency (η_e) vs. engine speed (n)

The maximum engine torque and effective power values occurred at engine speeds of about 1 600 min^{-1} and 3 600 min^{-1}, respectively.

The indicated parameters of engine cylinder operation were determined by recording 20 cycles of the indicated pressure in the engine cylinder in the crank angle domain at every measuring point. A set of 20 curves representing the indicated pressure and recorded at every measuring point is treated as a set of realizations of a stochastic process representing the indicated pressure at specific measuring points. The records were taken with a resolution of 1 deg[6] of the crank angle and with a resolution of 0.1 deg in the crank angle range from –30 deg to 90 deg from the TDC, where the latter range corresponded to the combustion process. To reduce the share of high-frequency noise in the signals analysed, the signals were processed by synchronous averaging [10, 22].

[6] In this study, the operation of differentiation with respect to the crank angle is used. Therefore, the symbol "deg" is used instead of "°" for degrees in order to avoid placing the symbol "°" in the denominator of the symbol of the unit of measure of the derivative taken with respect to the angle.

The processes taking place in the engine cylinder were examined for over the whole crank angle range that covered the combustion process.

Figs. 3 and 4 show a comparison between the indicated pressure and the derivative of the indicated pressure with respect to the crank angle at the working point corresponding to the maximum engine torque. The coarse estimator of the numerical differentiation has been subjected to low-pass filtration for the share of high-frequency noise in the signal to be reduced [14, 15]. The filtration was carried out fivefold with the use of a non-recursive filter [10, 14, 15, 22]:

$$\overline{y_i} = \frac{1}{11}\sum_{j=i-5}^{i+5} y_j$$

where: y – coarse estimator;
$\bar{y}$ – filtered estimator.

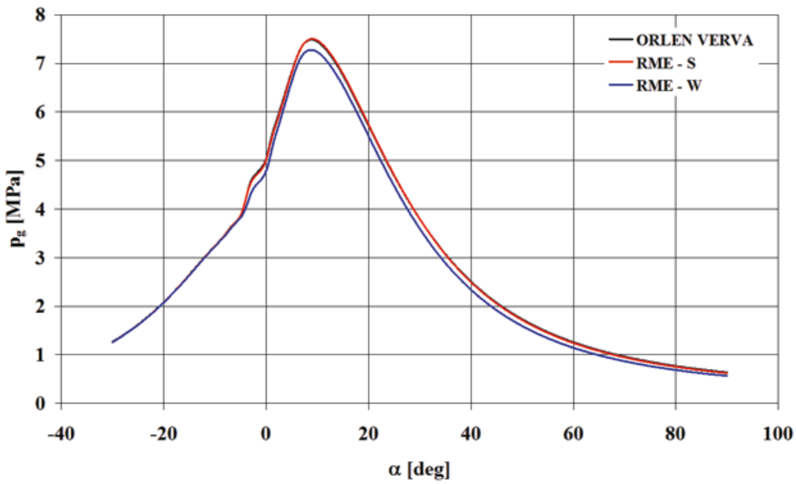

Fig. 3. Indicator diagram: indicated pressure (p_g) for the maximum engine torque (at n = 1 600 min^{-1})

The indicator diagrams for the ORLEN VERVA and RME–S fuels are close to each other. For the RME–W fuel, the indicated pressure is somewhat lower.

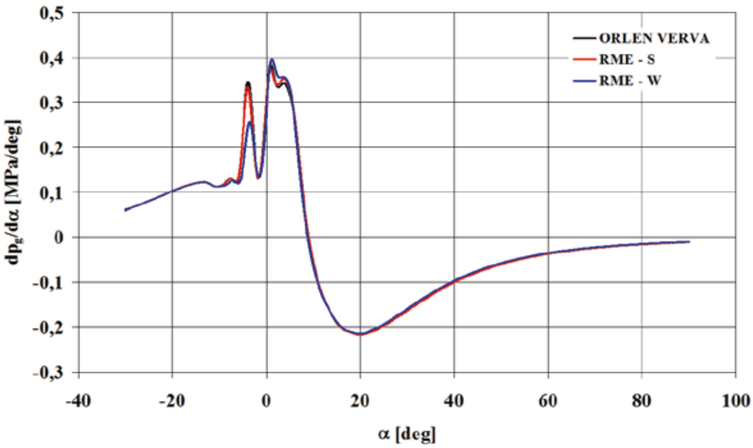

Fig. 4. Derivative of the indicated pressure with respect to the crank angle ($dp_g/d\alpha$) for the maximum engine torque (at n = 1 600 min^{-1})

A close similarity can also be seen between the curves representing the derivative of the indicated pressure with respect to the crank angle for the ORLEN VERVA and RME–S fuels. A considerable difference only appears for the RME–W fuel at the first maximum, where the values of this derivative are lower for the winter biofuel.

The curves in Figs. 5-7 represent values of the maximum indicated pressure as well as maximum and minimum values of the derivative of the indicated pressure with respect to the crank angle as functions of engine speed.

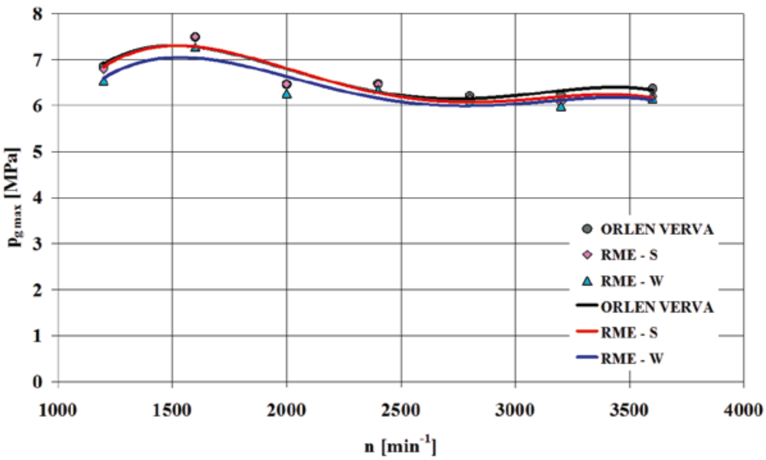

Fig. 5. Maximum indicated pressure (p_{gmax}) vs. engine speed (n)

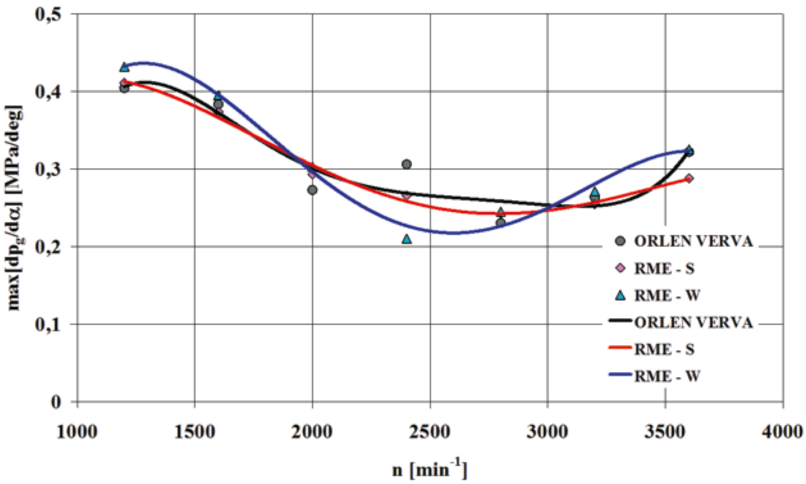

Fig. 6. Maximum values of the derivative of the indicated pressure with respect to the crank angle (max[$dp_g/d\alpha$]) vs. engine speed (n)

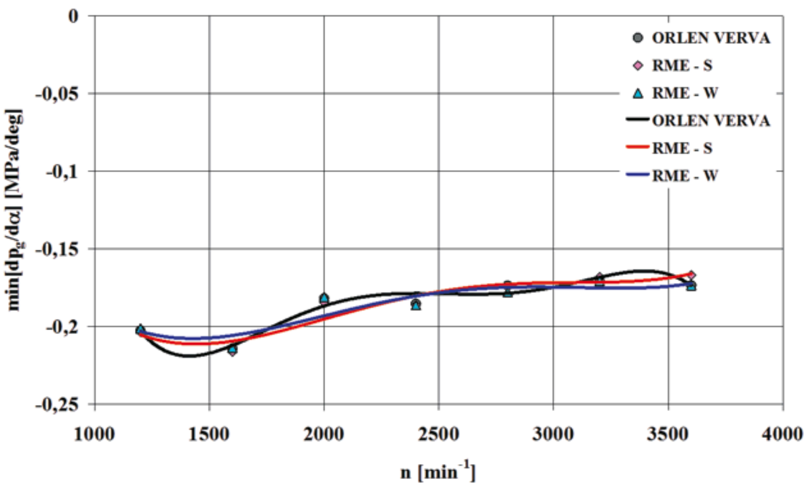

Fig. 7. Minimum values of the derivative of the indicated pressure with respect to the crank angle (min[$dp_g/d\alpha$]) vs. engine speed

The close similarity between the ORLEN VERVA and RME–S fuels can also be noticed when the speed-related characteristic curves are considered.

Figs. 8-10 show values of the maximum indicated pressure as well as maximum and minimum values of the derivative of the indicated pressure with respect to the crank angle, averaged over the engine speed domain.

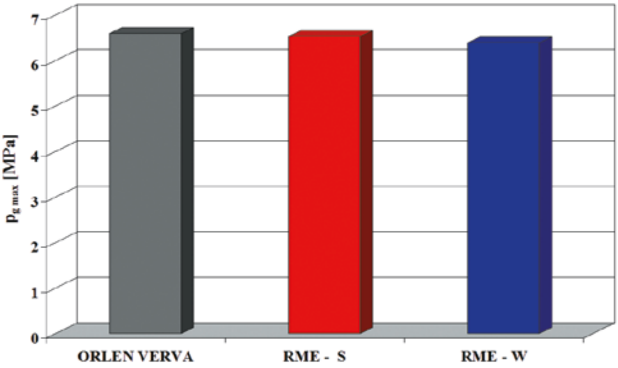

Fig. 8. Values of the maximum indicated pressure (p_{gmax}), averaged over the engine speed domain

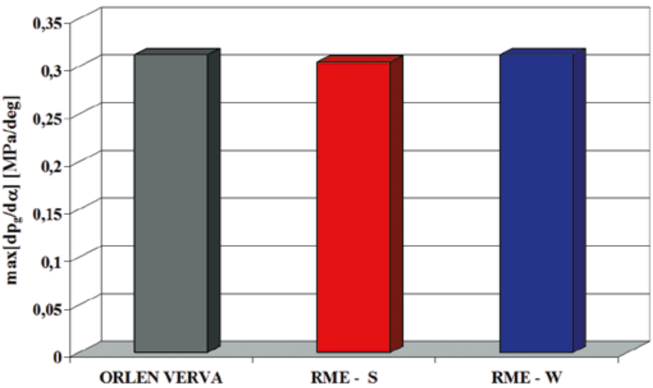

Fig. 9. Maximum values of the derivative of the indicated pressure with respect to the crank angle (max[$dp_g/d\alpha$]), averaged over the engine speed domain

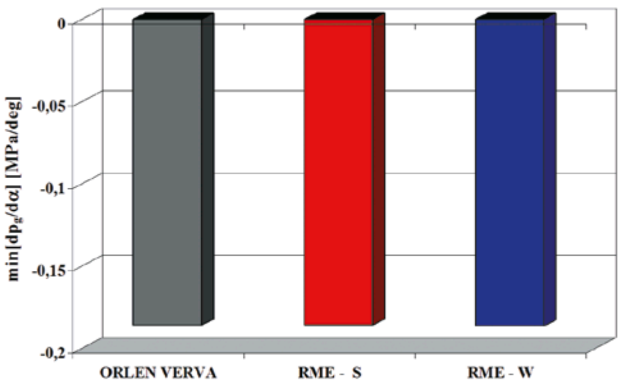

Fig. 10. Minimum values of the derivative of the indicated pressure with respect to the crank angle (min[$dp_g/d\alpha$]), averaged over the engine speed domain

The differences between the values of the quantities under consideration averaged over the engine speed domain are insignificant: the coefficient of variation of the sets of these values does not exceed 2 %.

Based on the indicated pressure curves recorded and the information on the engine and fuel characteristics, curves representing unit heat emission (in relation to cylinder displacement volume), unit heat emission rate, and temperature of the working medium were determined in accordance with the AVL CONCERTO algorithm. The curves representing these parameters for the point corresponding to the maximum engine torque have been presented in Fig. 11, where the values of the crank angle at the start of fuel ignition (SOI), start of combustion (SOC), maximum indicated pressure (p_{gmax}), and maximum temperature of the working medium (T_{gmax}) have been marked.

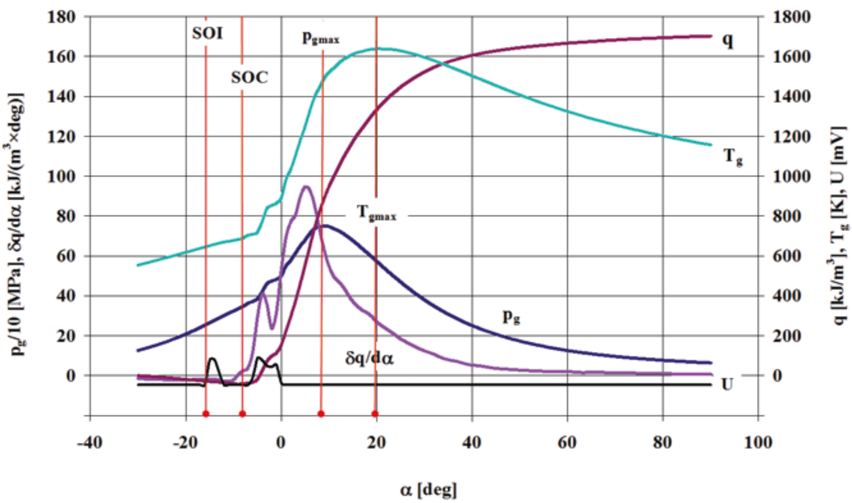

Fig. 11. Indicated pressure (p_g), temperature of the working medium (T_g), unit heat emission rate ($\delta q/d\alpha$, δ is the Pfaffian form), unit heat emission (q), and injector opening control voltage (U) for the maximum engine torque (n = 1 600 min−1) for the ORLEN VERVA fuel: SOI – fuel ignition start angle; SOC – combustion start angle; p_{gmax} – maximum indicated pressure; T_{gmax} – maximum temperature of the working medium

Fig. 12 shows the maximum temperature of the working medium as functions of engine speed.

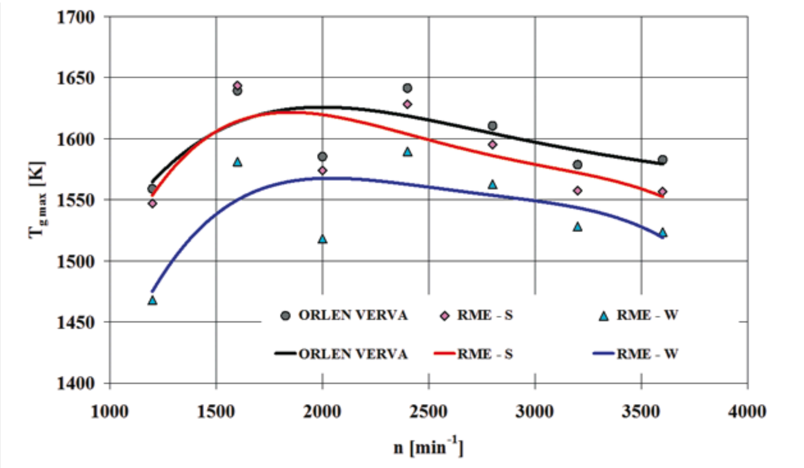

Fig. 12. Maximum temperatures of the working medium (T_{gmax}) vs. engine speed (n)

The curves representing the maximum temperatures of the working medium, plotted for the diesel oil and the summer biofuel are close to each other; for the winter biofuel, the maximum temperatures are lower by about 50 K.

To analyse the curves representing the maximum temperatures of the working medium vs. engine speed, the said curves together with the maximum indicated pressure vs. engine speed curves plotted for individual fuels have been presented in Figs. 13-15.

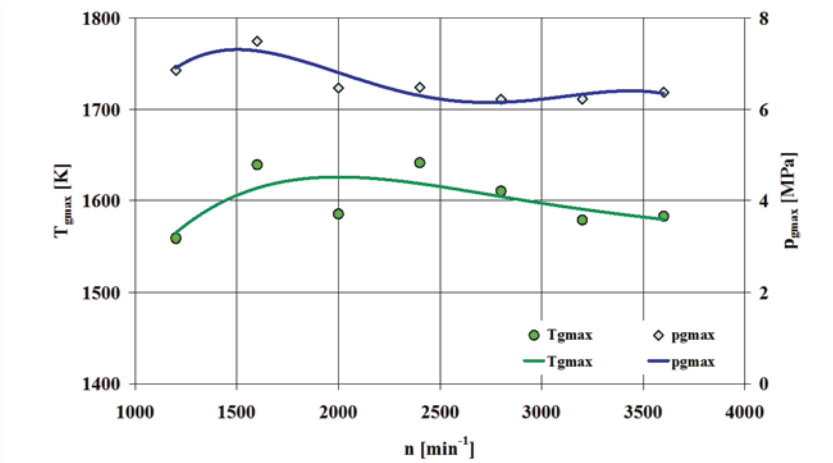

Fig. 13. Maximum temperature of the working medium (T_{gmax}) and maximum indicated pressure (p_{gmax}) vs. engine speed (n) for the ORLEN VERVA fuel

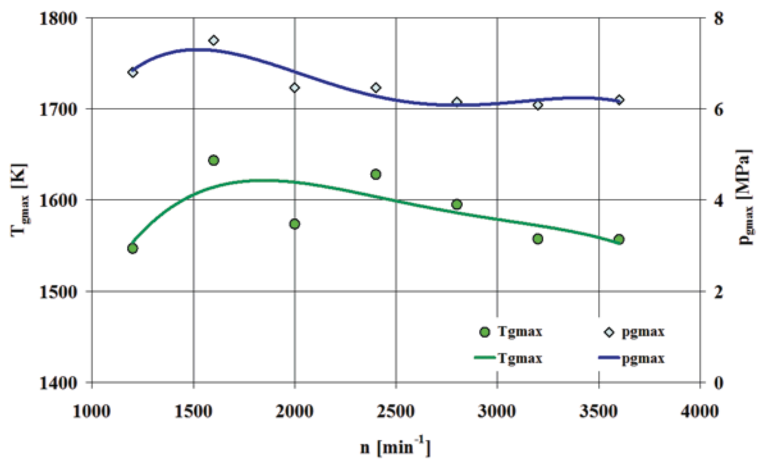

Fig. 14. Maximum temperature of the working medium (T_{gmax}) and maximum indicated pressure (pgmax) vs. engine speed (n) for the RME–S fuel

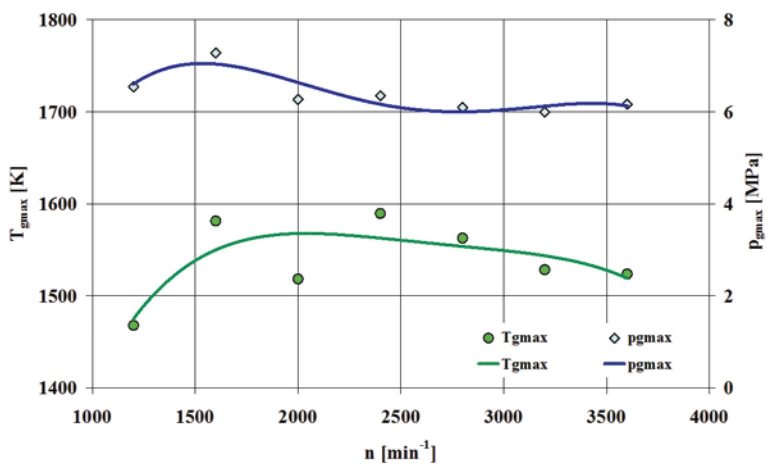

Fig. 15. Maximum temperature of the working medium (T_{gmax}) and maximum indicated pressure (p_{gmax}) vs. engine speed (n) for the RME–W fuel

Fig. 16 shows the correlational interdependence between the maximum indicated pressure (pgmax) and the maximum temperature of the working medium (Tgmax).

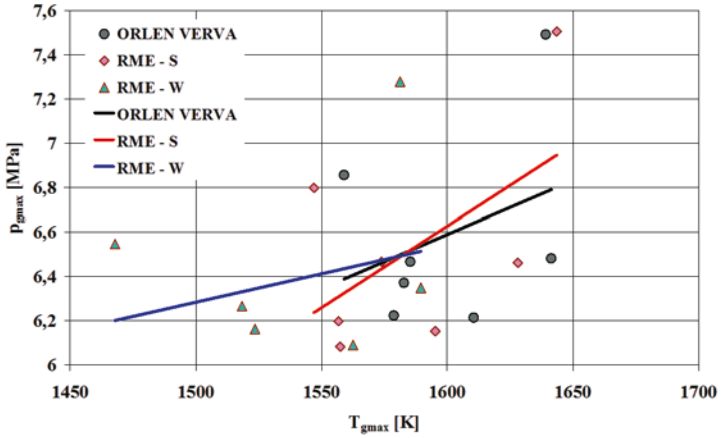

Fig. 16. Correlational interdependence between the maximum indicated pressure (p_{gmax}) and the maximum temperature of the working medium (T_{gmax})

The correlation between the sets under analysis should be assessed as weak. The coefficient of Pearson's linear correlation does not exceed 0.55 and the probability that the hypothesis of absence of linear correlation would not be rejected is higher than 0.19.

The values of the maximum temperature of the working medium, averaged over the engine speed domain, have been presented in Fig. 17.

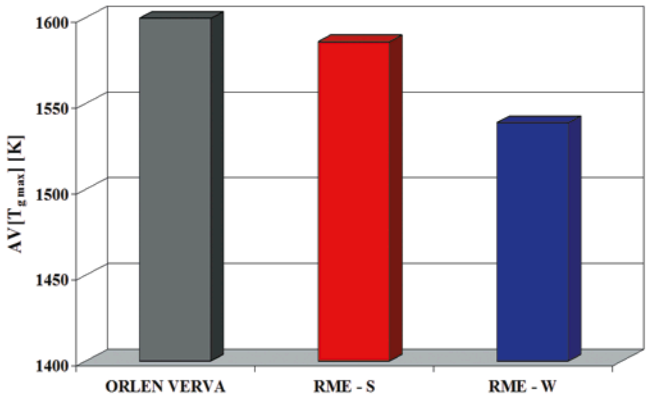

Fig. 17. Maximum temperature of the working medium, averaged over the engine speed domain (AV[T_{gmax}])

The highest maximum temperature of the working medium was observed for the diesel oil. This temperature determined for the rape methyl esters with an admixture of summer additives was considerably higher in comparison with that for the winter biofuel version.

Curves representing the temperatures of the working medium averaged over the crank angle domain vs. engine speed have been presented in Fig. 18.

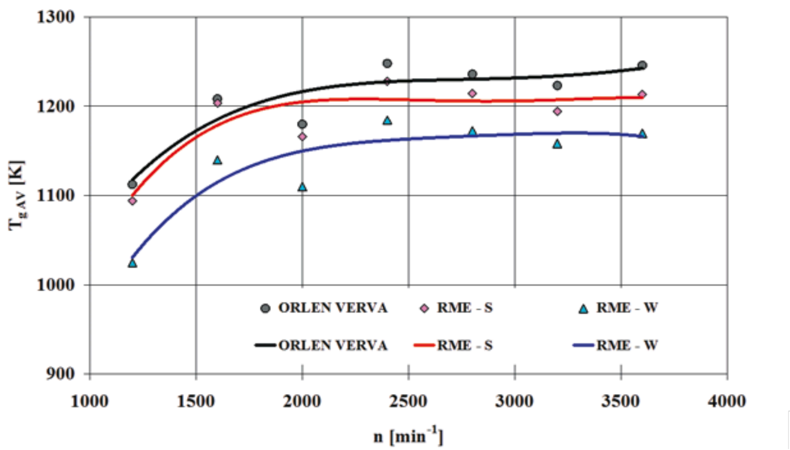

Fig. 18. Temperatures of the working medium averaged over the crank angle domain (T_{gAV}) vs. engine speed (n)

The temperature of the working medium averaged over the crank angle domain also reached the highest values for the ORLEN VERVA fuel. Again, a big difference was observed in these average temperature values between the two biofuel versions. This is confirmed by a significant difference between the average values, taken for individual fuels over the engine speed domain, of the working medium temperature values averaged over the crank angle domain (see Fig. 19).

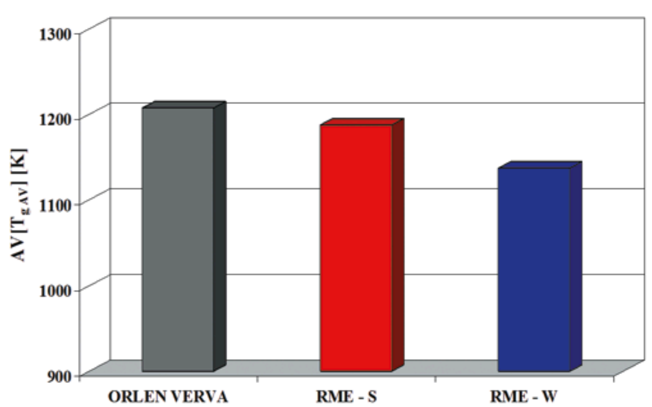

Fig. 19. Average values, taken for individual fuels over the engine speed domain, of the working medium temperature values averaged over the crank angle domain (AV[T_{gAV}])

Like in the previous cases, the average value, taken for individual fuels over the engine speed domain, of the working medium temperature values averaged over the crank angle domain was the highest for the diesel oil and the lowest for the rape methyl esters with an admixture of winter additives.

The curves shown in Figs. 20 and 21 represent the crank angle values corresponding to the maximum indicated pressure and to the maximum temperature of the working medium as functions of engine speed.

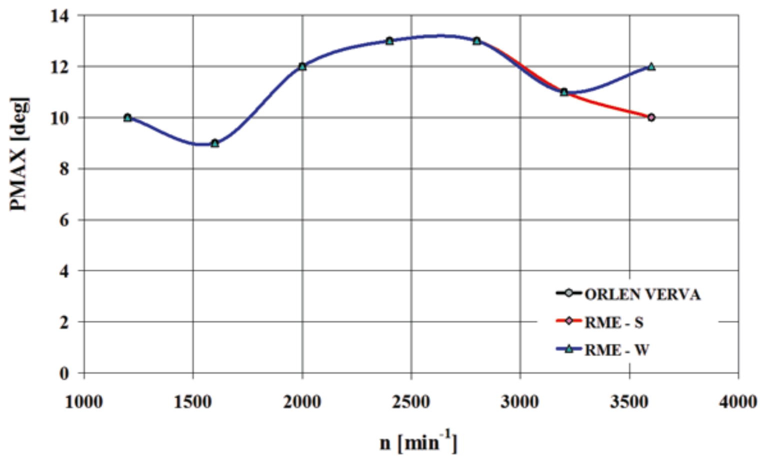

Fig. 20. Crank angle values corresponding to the maximum indicated pressure (PMAX) as functions of engine speed (n)

The crank angle value corresponding to the maximum indicated pressure is rather insusceptible to the engine speed and falls within limits of 9-13 deg. The impact of the fuel type on this angle value is insignificant, too.

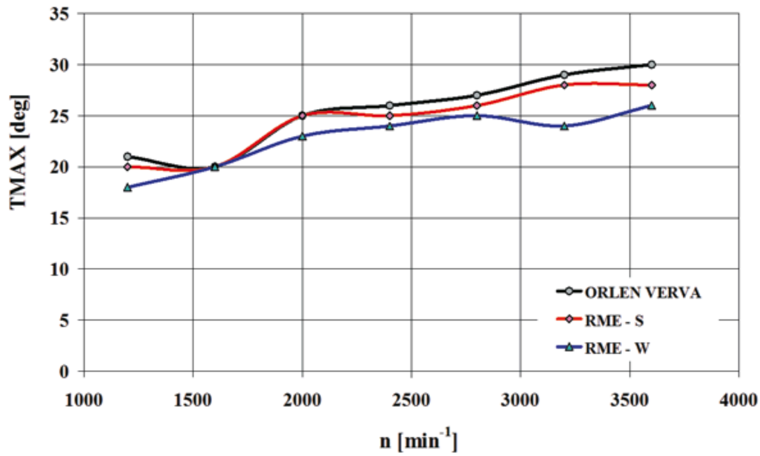

Fig. 21. Crank angle values corresponding to the maximum temperature of the working medium (TMAX) vs. engine speed (n)

The crank angle value corresponding to the maximum temperature of the working medium is an increasing function of engine speed, but the susceptibility of this value to the engine speed is insignificant. The crank angle values at which the temperature of the working medium reached its maximum are the highest, on the average, for the diesel oil and the lowest for the winter biofuel version; however, the differences in these crank angle values are not very big: they are of the order of several degrees.

4. Conclusions

The presented results of empirical tests and of their analysis provide grounds for the formulation of the following conclusions:

1. Based on the similarity criteria adopted in this work for analysing the combustion processes under examination, the ORLEN VERVA and RME–S fuels were found to be quite close to each other in respect of the characteristics evaluated. Such a finding may be deemed true in spite of some relatively big differences in the values of the parameters characterizing the physicochemical properties of these fuels, especially their calorific value and viscosity.

2. Most of the determined characteristics of the RME–W fuel were found to differ from the corresponding characteristics of the other fuels, in spite of a considerable similarity between the physicochemical properties of the two biofuel versions under examination. This is chiefly caused by the properties of the summer and winter additive packages added to the rape methyl esters. As regards details of the differences between the test results, noteworthy are the slightly lower values of the indicated pressure and

temperature observed during the combustion of the RME–W fuel. In general, however, the differences assessed in this item should be deemed as small.

In recapitulation of the deliberations presented herein, a statement may be made, in consideration of the similarity criteria taken into account, that there are grounds for recognizing the fuels under examination, based on rape methyl esters, as meeting the requirements for being accepted as substitute fuels for diesel oil.

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