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Dagna ZAKRZEWSKA
Zdzisław CHŁOPEK
Krystian SZCZEPAŃSKI

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The criteria for qualifying fuels as a replacement fuels for internal combustion engines

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The article presents the classification of motor fuels into conventional and unconventional. The concept of replacement fuels is formalized as fuels that can replace conventional petroleum fuels for spark ignition and self-ignition engines without any structural or regulatory changes. The criteria for qualification of unconventional fuels as replacement fuels are presented. This article also introduces the results of empirical research conducted on a single-cylinder research engine powered by diesel fuel and rapeseed methyl esters (RME) in the summer version and winter versions. The engine was tested, and the combustion phenomenon in the cylinder was analyzed. Very similar engine properties were observed for diesel fuel and rapeseed methyl esters in the summer version, while greater differences were found for rapeseed methyl esters with winter additives. In light of the empirical research and the physicochemical properties of the fuels, it is concluded that RME warrants consideration as a replacement fuel for engines with self-ignition, especially in the case of biofuel in the summer version.

Key words: *replacement fuels, substitute fuels, emission of pollution, unconventional fuels, rapeseed methyl esters (RME)*

1. Introduction

In today's era, the use of fuels in internal combustion engines has emerged as a pressing global concern. The widespread utilization of energy sources poses a substantial environmental threat, impacting human health and accelerating the depletion of fossil resources essential for energy production. This situation markedly fuels socio-political tensions, driven by disparities in resource accessibility.

As a result, within the energy-related economy, there is currently a significant interest to explore broader avenues for obtaining accessible energy resources [2, 3, 9, 14, 15, 20–26, 28]. This is primarily driven by environmental protection issues [1, 13, 16–19, 29, 30] and the energy security of states and state structures, ultimately impacting the quality of human life. Therefore, this constitutes a global issue for sustainable civilizational development.

2. Classification of motor fuels and formalization of the concept of replacement fuels

Energy carriers encompass various substances, phenomena, objects, or devices utilized to meet civilization's energy demands [12]. Among these, fuels play a pivotal role by facilitating energy acquisition through combustion. This process involves an exothermic oxidation-reduction reaction, swiftly releasing heat that emits electromagnetic radiation within the visible frequency range – an intensity delineated as the threshold of luminescence. In this context, fuel operates as the reducing agent in the combustion reaction, interacting with an oxidizer, chiefly oxygen from the ambient air (though certain heat engines, like rocket engines, might utilize alternative oxidizing agents).

Due to the widespread use, engine fuels can be categorized in the following manner [12]:

- conventional
- unconventional.

Typically, conventional motor fuels refer to those specifically designed for standard adaptation by manufacturers of internal combustion engines. These fuels primarily stem from crude oil processing and predominantly include motor gasoline and diesel fuels. Unconventional fuels constitute an array of alternative options utilized to drive internal combustion engines, expanding beyond the traditional hydrocarbon-based choices (e.g., natural gas-based fuels [3, 26] and gas derived from petroleum [22]) and others derived from petroleum processing and other mineral resources encompass a spectrum of materials, including those derived from the refinement of biological raw materials (e.g., fuels based on biological oils – B20 and B100 – for self-ignition engines [10, 11, 15, 19, 20], ethanol-based fuels: E95 – for self-ignition engines [13, 14, 21] and E85 for flex-fuel spark-ignition engines [13, 30], and so-called biogas-based biomethane [26]), as well as synthetic fuels [24, 25].

Replacement fuels are unconventional fuels that can be used instead of conventional fuels: motor gasoline for engines with spark-ignition and diesel fuel for engines with self-ignition without structural or regulatory changes to the engines [12].

Several fundamental criteria evaluate unconventional fuels based on their compliance with substitute fuel conditions. These criteria can generally be classified as follows [12]:

- criteria derived from assessing the physicochemical properties guiding the selection of fuels for engine running
- criteria derived from assessing the processes within internal combustion engines fueled by the considered fuels
- criteria derived from assessing the performance characteristics of internal combustion engines fueled by the considered fuels.

3. Research methodology

The objective of the study was to evaluate the extent to which it is justified to consider bio-origin fuels – rapeseed methyl esters (RME) as replacement fuels regarding diesel fuel.

The empirical research methodology encompassed studies conducted on the AVL 5402, a single-cylinder research engine with self-ignition capabilities. The study utilized the AVL Single Cylinder Test Bed [5–7] and relied on AVL PUMA [6] and AVL Concerto [4] software for data recording and analysis.

The empirical research was carried out at the Department of Vehicles and Automotive Engines of the Vehicle and Machine Exploitation Institute at the Faculty of Mechanical Engineering of the Kazimierz Pułaski University of Technology and Humanities in Radom. The research was conducted by Skrzek from the Department of Vehicles and Automotive Engines at the Vehicle and Machine Exploitation Institute of the Faculty of Mechanical Engineering at the Kazimierz Pułaski University of Technology and Humanities, along with engineers Jagiełło and Juwa – graduates supervised by Chłopek from the Faculty of Automotive and Construction Machinery Engineering at the Warsaw University of Technology [10]. The development of the empirical research program involved the researchers and Chłopek and Zakrzewska the Institute of Environmental Protection – National Research Institute [10, 11].

The apparatus used for the research complies with the requirements of the following regulations: 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.

The fundamental data of the AVL 5402 engine are provided in Table 1.

Table 1. Basic information on the AVL 5402 engine

Number of cylinders	1
Cylinder diameter	85.01 mm
Piston stroke	90.00 mm
Displacement	511.00 cm^3
Combustion system	Self-ignition
Timing	Four-valve
Compression ratio	17.0–17.5
Engine power system	Direct injection, single injector, tray system (Common Rail)
Maximum net power, non-supercharged	6 kW
Maximum net power, supercharged	16 kW
Rated speed	4200 min^{-1}
Injection pressure	180 MPa

The AVL 5402 engine, thanks to the use of special head gaskets, allows for the adjustment of compression ratio. Special openings in the cylinder head enable the introduction of cameras into the combustion chamber and observing the combustion process of the mixture. The engine is equipped with an exhaust gas recirculation system and sensors allowing, among other things, the measurement of pressure in the combustion chamber and exhaust gas temperatures. Thanks to the installed injection equipment and accompanying software, it is possible to modify the engine's fuel supply algorithm. The research utilized a two-phase fuel injection.

The research program entailed the engine operating statically across a range of engine speeds (from 1200 rpm to 3600 rpm) at intervals of 400 rpm. Primary measurements encompassed diverse parameters:

- engine speed
- torque
- mass fuel consumption rate
- mass air consumption rate
- carbon monoxide (CO) volumetric concentration
- hydrocarbons (HC) volumetric concentration
- nitrogen oxides (NO_x) volumetric concentration
- particulate matter (PM) mass concentration
- indicated pressure recorded in the crankshaft rotation angle
- exhaust gas temperature.

The engine was fueled with:

- classic diesel fuel – ORLEN VERVA
- biofuel B100 with an additional summer blend, designated as RME-S
- biofuel B100 with an additional winter blend designated as RME-W.

Table 2 presents a comparison of the basic physicochemical properties of the tested fuels.

Table 2. Physical and chemical characteristics of fuels

Characteristics	Unit	Fuels		
		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	LC	55.6	57.3	57.3
Kinematic viscosity at 40°C	mm^2/s	2.87	4.50	4.49
Elemental composition of the fuel:				
carbon content mass of the fuel, mass fraction	% m/m	0.837	0.772	0.772
hydrogen content of fuel, mass fraction	% m/m	0.149	0.120	0.120
oxygen content of fuel, mass fraction	% m/m	0.014	0.108	0.108
sulfur content of fuel, mass fraction	ppm	7.5	3.0	3.0
Cold filter plugging point (CFPP)	deg C	–28	–15	–20
Flash point	deg C	65	101	101

In Figure 1 to 6, a comparison of the basic properties of fuels is presented:

- elemental composition of fuels: 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 40°C – ν
- temperature of cold fuel filter plugging – t_b.

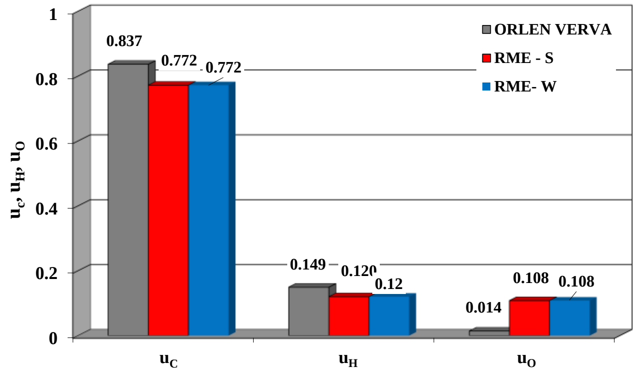

Fig. 1. Composition of the fuels in terms of elemental content: mass fraction of carbon – u_C, hydrogen – u_H and oxygen – u_O

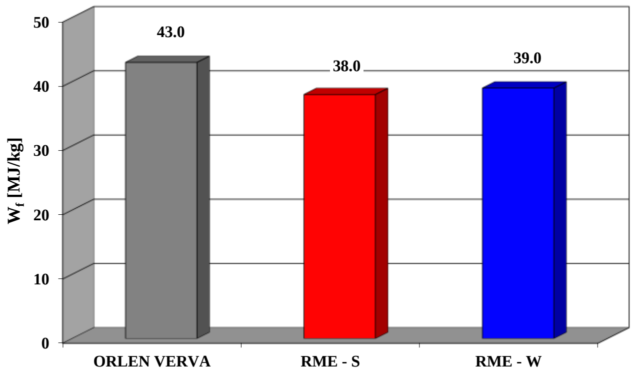

Fig. 2. Calorific values of the fuels tested – W_f

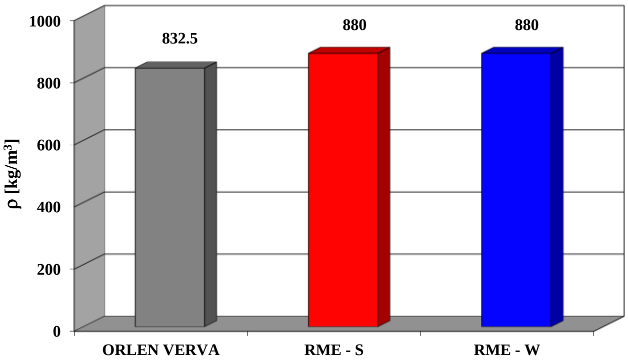

Fig. 3. Density of the fuels tested – ρ

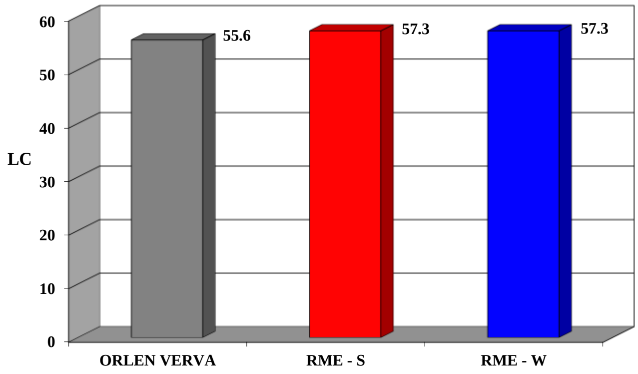

Fig. 4. Cetane number of the fuels tested – LC

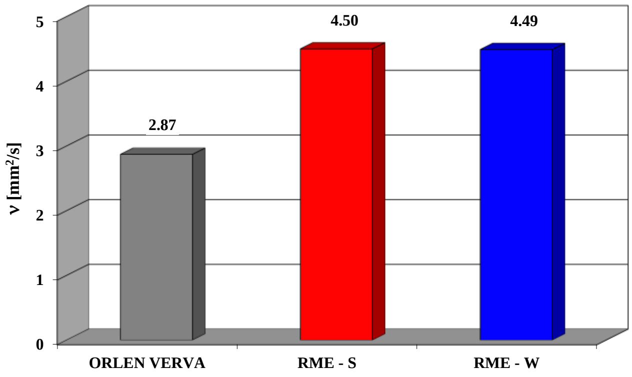

Fig. 5. Kinematic viscosity of the fuels tested at 40°C – ν

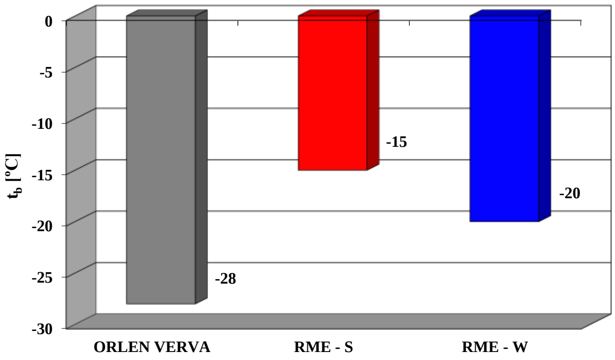

Fig. 6. Temperature of cold fuel filter plugging of the fuels tested – t_b

RME biofuels have a significantly higher mass fraction of oxygen – nearly ten times higher than the content found in diesel fuel, consequently, the calorific value of RME is over 10% less than that of diesel fuel. The density of RME surpasses that of diesel fuel by approximately 6%. However, RME has a higher tendency for auto-ignition – a cetane number greater by about 1.7. The kinematic viscosity of RME fuels at 40°C is much higher compared to diesel fuel – the relative difference is almost 60%. There are notable variations in the cold filter plugging point temperatures, particularly in the properties of RME biofuels, notably the summer variant – RME-S, which demonstrates considerably inferior characteristics.

4. The results of empirical research

Figures 7 to 13 present the results of empirical research and their analyses.

Figures 7 to 9 show external speed characteristics of fundamental parameters characterizing the engine's properties:

- energetic parameters: torque – M_e and effective power – N_e
- economic parameters related to fuel consumption: general efficiency – η_e.

Because of the lower calorific value in bio-based fuels, the engine's torque and effective power are lower when fueled by RME compared to diesel fuel. Yet, the variance in the summer fuel is minor, attributable to the engine's overall higher efficiency when running on RME-S compared to RME-W fuel.

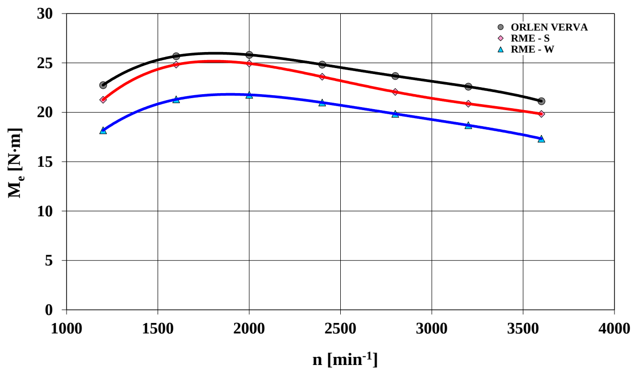

Fig. 7. External speed characteristic of the torque – M_e; n – engine speed

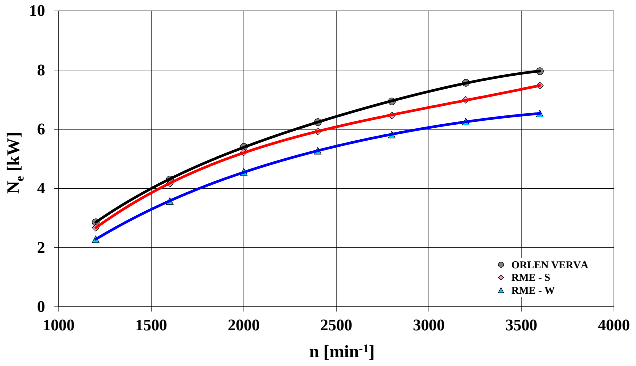

Fig. 8. External speed characteristic of the effective engine power – N_e; n – engine speed

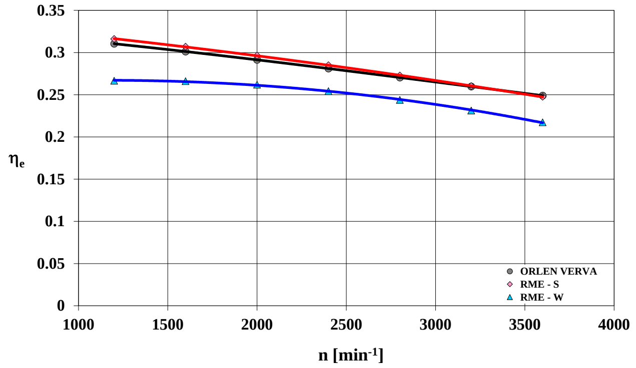

Fig. 9. External speed characteristic of the general efficiency – η_e; n – engine speed

Figures 10 and 11 depict the relative change δ in the average emissions value across the speed domain per unit.

The use of bio-origin fuels results in a relative decrease of approximately 30% in the mean value within the speed domain of the engine for CO and PM emissions. For HC and NO_x, the comparative variance is around 10%, wherein for RME-S fuel, there is a decrease in unit emissions, while for RME-W fuel, there is an increase.

Cylinder pressure indication data recording involved capturing 20 cycles of indicated pressure in each test point within the crankshaft rotation domain. A set of 20 recorded indicated pressure profiles at each measurement point is considered as a realization set of the stochastic process of indicated pressure at that point. The recordings were made with a resolution of 1 deg[1] of crankshaft rotation and within the range (–30–90) degrees for the top dead center position of the piston corresponding to combustion, with a resolution of 0.1 deg. To reduce the influence of high-frequency noise in the signals, a second-order Savitzky-Golay filter was applied for signal processing [8, 27].

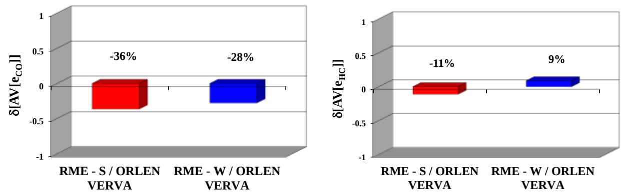

Fig. 10. The relative change – δ of the a mean value in the engine speed domain – AV of emissions: CO – e_{CO} and HC – e_{HC}

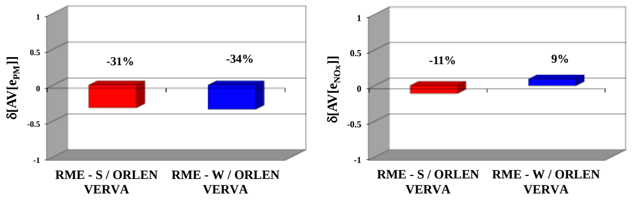

Fig. 11. The relative change – δ of the mean value in the engine speed domain – AV of emissions: NO_x – e_{NOx} and PM – e_{PM}

The engine was indicated. Each registered pressure trace was treated as a realization of a stochastic process. Figures 12 and 13 display a contrast between the indicated pressure and its derivative concerning the crankshaft rotation angle for the analyzed fuels at the point of maximum torque operation.

There is a clear resemblance between the indicator diagrams for diesel fuel and rapeseed methyl esters with summer additives, while the indicated pressure for rapeseed methyl esters with winter additives is lower. There's a distinct variance observed in the derivative of indicated pressure concerning the crankshaft rotation angle.

Drawing from the documented indicated pressure profiles and engine-specific details concerning fuel parameters, according to the AVL Concerto algorithm, the following profiles were determined: specific heat release, rate of heat release, and agent temperature – an exemplary graph for ORLEN VERVA fuel for maximum torque operation is shown in Figure 14. The crankshaft rotation angles corresponding to the start of fuel injection, auto-ignition, maximum indicated pressure, and maximum agent temperature are marked on the graphs.

Once more, there was a distinct likeness observed between diesel fuel and rapeseed methyl esters with summer blend, whereas there was a difference in the case of rapeseed methyl esters with winter blend.

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[1] Since the work uses angle differentiation, "deg" rather than "°" is used to denote the degree to avoid the symbol "°" in the denominator of the unit of measurement of derivative with respect to an angle.

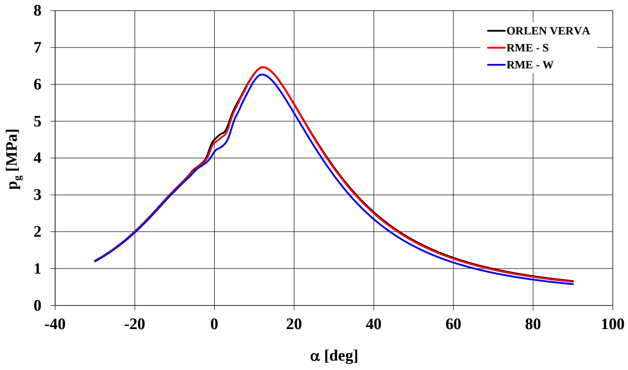

Fig. 12. Indicator diagram – indicated pressure – p_g for the maximum torque

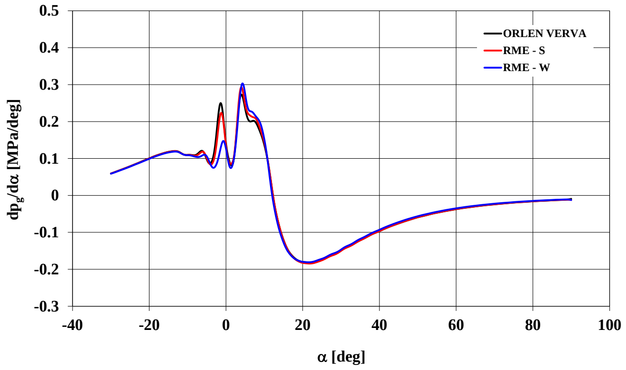

Fig. 13. The derivative of the pressure against the angle of rotation of the crankshaft – $p_g/d\alpha$ for the maximum torque

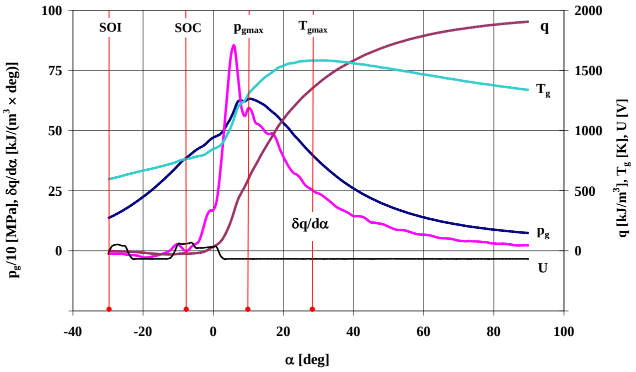

Fig. 14. Indicated pressure – p_g, temperature of the working medium – T_g, unit heat emission rate – δq/dα, unit heat emission – q, injector opening control voltage – U for the maximum torque for the ORLEN VERVA fuel; SOI – fuel injection start angle, SOC – combustion start angle, p_{gmax} – maximum indicated pressure, T_{gmax} – maximum temperature of the working medium

The empirical research yielded the following formulated conclusions:

1. Effective power and torque of the combustion engine are greater for diesel fuel, slightly lower for biofuel in the summer version, and significantly lower for biofuel in the winter version.
2. The utilization of rapeseed methyl esters (RME) led to a noticeable decrease in emissions of CO and PM emissions – by approximately 30%. For HC and NO_x, the relative change was around 10%, whereas for summer fuel, there was a decrease in unit emissions, and for winter fuel, an increase was observed.
3. Similar general efficiency was observed for the combustion engine running on diesel fuel and biofuel with summer blend. However, for biofuel with winter blend, the overall efficiency was noticeably lower.
4. Considering the similarity criteria applied in this study regarding the analyzed combustion processes, a significant resemblance was noted in the assessed characteristics between ORLEN VERVA and RME-fuels.
5. The characteristics determined for RME-W fuel, in most cases, deviate from the analogous characteristics of other fuels, despite the substantial resemblance in the physical and chemical properties of both types of biofuels. This situation primarily arises from the properties of the biofuel with summer blend and biofuel with winter blend used for rapeseed methyl esters.

5. Conclusions

Based on the conducted research and presented considerations, the following conclusions have been formulated:

1. Renewable energy sources are taking on a more significant role in society's development. Special attention is given to the development and practical implementation of unconventional fuels compared to conventional hydrocarbon fuels for internal combustion engines. Primarily, these fuels consist of bio-based fuels resulting from biomass processing.
2. The general principle is the effect of using bio-based fuels, leading to a reduction in carbon monoxide and organic compound emissions. Additionally, for engines with self-ignition, a decrease in particulate matter emissions is observed. Typically, using esters of plant oils in self-ignition engines may lead to increased nitrogen oxide emissions. This can be mitigated by using alcohols and their derivatives.
3. To comprehensively evaluate the effects of employing biofuels on emissions and engine properties, a detailed study of the combustion process via engine indication is required. This study conducted such research for esters of plant oils compared to traditional diesel fuel. The research results confirmed the effectiveness of such studies, particularly the positive ecological effects of using bio-based fuels in terms of emissions.
4. A practical implication drawn from the conducted research is the assertion that bio-based fuel – rapeseed methyl esters – might be regarded as a replacement fuel for diesel fuel [12], especially for rapeseed methyl esters with fuel additive packages for summer use.

Nomenclature

AV	average value
B100	fuel – vegetable oil methyl esters
B20	20% V/V vegetable oil methyl esters blended with diesel fuel

e	specific brake emission
LC	cetane number
M_e	(engine) torque
n	engine speed
N_e	effective (engine) power
p_g	indicated pressure
p_{gmax}	maximum indicated pressure
q	unit heat emission
RME	rapeseed methyl esters
RME-S	rapeseed methyl esters with summer additive
RME-W	rapeseed methyl esters with winter additive
SOC	combustion start angle
SOI	fuel injection start angle
t_b	cold filter plugging point (CFPP)
T_g	temperature of the working medium
T_{gmax}	maximum temperature of the working medium
U	injector opening control voltage
u_C	carbon content mass of the fuel, mass fraction
u_H	hydrogen content mass of the fuel, mass fraction
u_O	oxygen content mass of the fuel, mass fraction
V/V	volume fraction
W_f	calorific value
α	angle of crankshaft rotation
δ	relative change
$\delta q/\delta\alpha$	unit heat release rate
η_e	general efficiency
ν	kinematic viscosity of fuel
ρ	density of fuel

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Dagna Zakrzewska, MSc. – Environmental Protection – National Research Institute, Warsaw, Poland.
e-mail: *dagna.zakrzewska@kobize.pl*

Krystian Szczepański, DSc., DEng. – Professor of IOS-PIB – Institute of Environmental Protection – National Research Institute, Poland.
e-mail: *krystian.szczepanski@ios.edu.pl*

Prof. Zdzisław Chłopek, DSc., DEng. – Institute of Environmental Protection – National Research Institute, Poland.
e-mail: *zdzislaw.chlopek@kobize.pl*