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Influence of regulating parameters on noise emitted by diesel engine powered with blends of diesel oil and ethyl tert-butyl ether

Abstract: The article will present results of research into assessment of noise emissions from AD3.152 engine powered with diesel fuel and its blends including between 10 and 40 % (by volume) of ethyl tert-butyl ether (ETBE). An estimate was attempted of how noise emissions of this engine change as dependent on regulation of the tested fuel's injection start angle. The investigations were executed in conditions of load characteristic profile (Mo = 40, 60, 80, 100, and 120 Nm) in respect of three different speeds of shaft crank rotation, i.e. 1200, 1600, and 2000 rpm. In addition, rates of pressure increase in the combustion chamber of AD3.152 engine powered with the tested fuels were determined. This helped to estimate dependences between the noise of the engine under testing and variation in rates of pressure increase in its combustion chamber.

Key words: *sound emission, alternative fuels, diesel fuel blends*

Wpływ parametrów regulacyjnych na hałas silnika wysokoprężnego zasilanego mieszaninami oleju napędowego z eterem etylo-tert butylowym

Streszczenie: W artykule zostaną zaprezentowane wyniki badań z zakresu oceny emisji hałasu silnika AD3.152 zasilanego olejem napędowym oraz jego mieszaninami z eterem etylo-tert butylowym w ilości od 10 do 40 % (objętościowo). Starano się ocenić jak zmienia się emisja hałasu tego silnika w zależności od regulacji kąta wyprzedzenia wtrysku testowanego paliwa. Badania wykonano w warunkach charakterystyki obciążeniowej (Mo = 40, 60, 80, 100 i 120 Nm) i dla trzech różnych prędkości obrotowych wału korbowego tj. 1200, 1600 i 2000 obr/min. Ponadto wyznaczono prędkości narastania ciśnienia w komorze spalania silnika AD3.152 zasilanego testowanymi paliwami. Pozwoliło to ocenić zależności występujące pomiędzy hałasem badanego silnika i zmianami prędkości narastania ciśnienia w jego komorze spalania.

Słowa kluczowe: *emisja dźwięku, paliwa alternatywne, mieszaniny oleju napędowego*

1. Introduction

Search for alternative fuels to be used in internal-combustion engines has been conducted in a range of scientific centres for years now. It primarily concerns possible applications of vegetable oils and their esters and has led, in most European countries, to industrial-scale manufacture and distribution of biofuels containing blends of diesel oil and vegetable oil esters. Increasingly stringent standards of toxic exhaust gas emissions and the instable situation of the oil fuel market drive the search for new types of diesel engine fuels. A line of this research involves testing heavy oil additions to produce fuel blends of beneficial properties [1]. Such additions modify fractional composition and thereby affect physico-chemical properties of fuel (viscosity, density, lubricity, cetane number, lower heating value, etc.). This contributes to changes of the combustion process and results, among other things, in sound emission levels different than where pure diesel oil is applied.

The article presents results of testing impact of regulation parameters on sound emission of the internal combustion engine AD3.152 powered with ON diesel oil and its blends with ethyl tert-butyl ether (EETB). The testing occurred in conditions of load characteristic profile for three values of fuel's injection start angle α_{dpt} and three shaft crank rotations. Both pressure fluctuations in the combustion chamber and sound power Lw(A) emitted by the given engine were recorded at each measurement point.

2. Methods and materials

Research was carried out in an engine laboratory of Technical University of Radom. The laboratory is equipped with AD3.152 diesel engine and a measurement system of high-speed parameters such as: in-cylinder pressure, needle lift, and pressure in the delivery pipe. Technical specifications of the measurement system of high speed parameters for IC engines are described in [2].

2.1. Test stand

The view of the tested engine connected to a water type brake /2/ is presented in Fig. 1. Measurements of engine noise were carried out with the use of advanced Brüel & Kjaer 2595 model sound level meter /3/ connected to a B&K model 2595 microphone /4/. The analysis of sound parameters employed specialist software, code BZ7205, implemented in the analyzer's memory card. In-cylinder pressure variations: in-cylinder pressure, needle lift, and pressure in the delivery pipe were recorded by means of Keithely KPCI3110 data acquisition board inserted in a PC work station /5/. The engine load, coolant temperature, and crankshaft rotational speed were controlled by a dynamometer system /11/ [3].

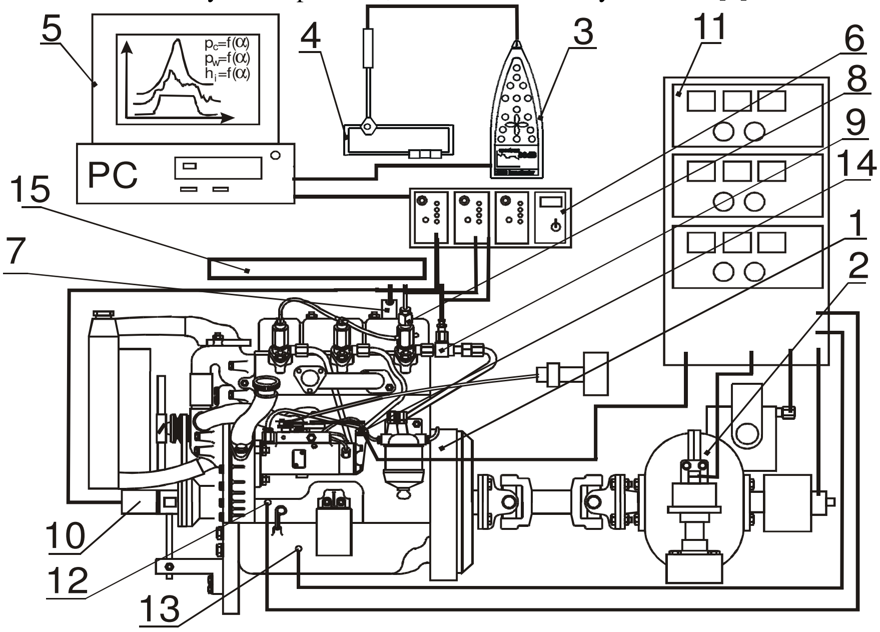

Fig. 1. View of the test stand: 1 – AD3.152 engine, 2 – engine brake, 3 – sound analyser, 4 – B&K model 2595 microphone, 5 – PC with a measurement card, 6 – signals amplifier, 7 – in-cylinder pressure transducer (AVL QC34D), 8 – needle lift sensor (CL80), 9 – fuel pressure sensor (AVL QL61D), 10 – engine crankshaft encoder, 11 – dynamometer control system, 12 – engine temperature sensor, 13 –oil temperature sensor, 14 – fuel temperature sensor, 15 – measurement surface.

Rys. 1. Widok stanowiska pomiarowego: 1 – silnik AD3.152, 2 – hamulec silnikowy, 3 – analizator dźwięku, 4 – mikrofon pomiarowy (B&K, typ 3595), 5 – komputer z kartą pomiarową, 6 – wzmacniacz sygnału, 7 – czujnik ciśnienia w komorze spalania (AVL QC34D), 8 – czujnik wzniosu iglicy (CL80), 9 – czujnik ciśnienia paliwa w przewodzie wtryskowym (AVL QL61D), 10 – nadajnik kąta obrotu wału korbowego, 11 – system kontroli hamulca, 12 – czujnik temperatury czynnika chłodzącego silnik, 13 – czujnik temperatury oleju, 14 – czujnik temperatury paliwa, 15 – powierzchnia pomiarowa.

Engine testing was performed on an in-line 3-cylinder 2.5-liter diesel engine (AD3.152) with a peak torque of 165 Nm at about 1200 rpm and a peak power of 34.6 kW. Selected technical specifications of the tested engine are presented in Table 1. The engine's oscillating parameters were measured as time-dependent. A 10 kHz low-pass filter and signal sampling frequency of 100 kHz were applied. High-frequency measurement noise was removed by wavelet shrinkage method. Necessary calculations were carried out with MathCAD ver. 14 software featuring a 'Wavelet Extension Pack'.

Table. 1. Technical specification of AD3.152 diesel engine.
Tabela. 1. Specyfikacja techniczna silnika AD3.152.

No	Parameter	Value
1.	Cylinder number and arrangement	3, in line
2.	Cylinder diameter	91.44 mm
3.	Piston stroke	127 mm
4.	Engine capacity	2502 cm^3
5.	Compression value	16.5
6.	Maximum power	34.6 kW
7.	Maximum torque	165.4 Nm
8.	Crankshaft speed at idle run	750 rpm
9.	Fuel injection system	Lucas - CAV type DPA

2.2. Measurements of engine noise emissions

Acoustic measurements were carried out with Brüel & Kjaer 2260 sound analyzer connected to 3595 microphone (Fig. 2). It is a two-microphone probe for measuring sound intensity. The application of a two-microphone technique provides information on both the instantaneous pressure and pressure gradient in the sound field. The microphones are separated by a fixed distance in the sound field, and the microphone signals are fed to a sound intensity processor which calculates the sound intensity. The sound intensity is calculated as average sound pressure of the unit time multiplied by particle velocity (calculated from the measured pressure gradient). Such a system measures the component of the sound intensity along the probe axis and also indicates the direction of energy flow [4, 5].

Fig. 2. View of Brüel & Kjaer 2260 sound analyser with measurement microphones and calibrator.
Rys. 2. Widok analizatora 2260 firmy Brüel & Kjaer z mikrofonami pomiarowymi i kalibratorem
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The analyzer is equipped with BZ7205 software dedicated to measuring sound intensity and calculating sound power. The sound level meter allows real-time 1/1- and 1/3-octave frequency analysis and broadband statistical distributions.

Area of the measurement surface equals 0.48 m^2 and is located directly above the tested engine head. The sound power measurements were carried out according to ISO 9614-2:1996 "*Acoustics. Determination of sound power levels of noise sources using sound intensity. Measurement by scanning*". The measurement period is approximately 10 seconds. The tested surface was scanned twice in such a short time. This method of sound emission measurements can be utilised in conditions of near field of noise source (where the distance from the measurement microphone to the source of sound is less than three times the size of a tested item), which obtains in most engine-testing laboratories.

2.3 Properties of tested fuels

Diesel oil and its blends with ethyl tert-butyl ether were used. Selected physico-chemical properties of these fuels are illustrated in table 2. ETBE (etyl tert-butyl ether) is considered a semi-renewable compound produced from ethanol and isobutene. In Poland, ETBE is used as an oxygenated compound in the formulation of gasolines. One of the most important properties of ETBE is its high value of octane number (about 119). For this reason, the ether can be used as an excellent anti-knock additive to gasoline. In the case of diesel engines, cetane number is a more important property of fuel. As illustrated by Table 2, the increasing addition of ETBE to diesel oil causes a significant decrease of cetane number value. It affects the first phase of fuel combustion process (longer ignition delay). The ignition delay in diesel engines has an important, indirect effect on higher engine noise. In case of too long ignition delay, the rate of fuel burning can be too rapid, resulting in engine knock that decreases efficiency while increasing engine noise and wear.

The addition of ETBE to diesel fuel affects other physicochemical properties of the tested blends as well. The increasing addition of ETBE in diesel oil leads to a proportional decrease of: density, viscosity, surface tension, and heating value. For this reason, injection and combustion processes of such fuel blends are different than of neat diesel oil. Results of these investigations will be presented in further publications.

Table 2. Selected physico-chemical properties of tested fuel blends.
Tabela 2. Wybrane właściwości fizykochemiczne badanych mieszanin paliwowych.

Parameters	Values				
	DF	ETBE10	ETBE 20	ETBE 30	ETBE 40
ETBE content in diesel oil, [%, by vol.]	0	10	20	30	40
Density at 15 °C, [kg/m^3]	839	831	821	814	804
Kinematic viscosity at 40 °C, [mm/s^2]	2,79	2,24	1,79	1,47	1,21
Lubricity at 25°C , [µm]	222,1	254	244,5	267,1	256,1
Surface tension, [mN/m]	25,9	24,6	23,3	22,1	21,2
Lower heating value, [MJ/kg]	42,8	42,1	41,1	40,8	40,0
Cetane number, [-]	51,2	46	42,7	38,4	31,4

*diesel oil lubricity measured at 25 ºC cannot be higher than 380 µm [1]

2.4 Testing conditions

All the testing was performed under steady-state conditions for engine partial loads and selected crankshaft rotational speeds and angles of beginning of fuel injection. Detailed conditions of engine researches are presented in Table 3.

Table. 3. Testing conditions of AD3.152 diesel engine fuelled with blends of ETBE and diesel oil.
Tabela. 3. Warunki badań silnika AD3.152 zasilanego mieszaninami EETB z olejem napędowym.

Parameters	Values		
Crankshaft rotational speed, n [rpm]	1200	1600	2000
Angle of beginning of fuel injection, α_{dpt} [ºCA]	12; 17 and 22 before TDC		
Engine torque, M_o [Nm]	40; 60; 80; 100 and 120		

Regulation of the dynamic angle of beginning of fuel injection was tested when the engine, powered with diesel oil, was running idle. A graphic interpretation of α_{dpt} is presented in Fig. 3.

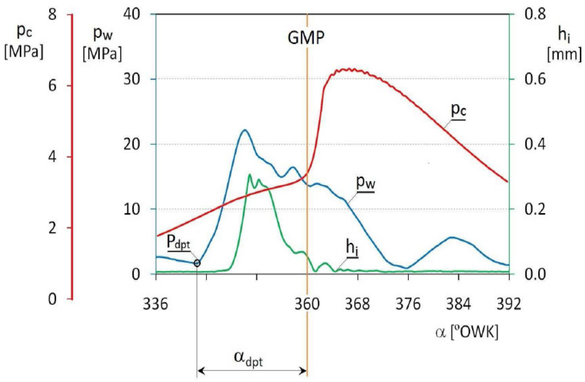

Fig. 3. Graphic interpretation of α_{dpt} angle: GMP – top dead center (TDC), α [ºOWK] - angle position of engine crankshaft (ºCA), p_w – pressure variations in the delivery pipe, p_c – pressure variations in the combustion chamber, h_i – fuel injector needle lift.
Rys. 3. Interpretacja graficzna kąta dynamicznego początku tłoczenia paliwa α_{dpt}: GMP – górne martwe położenie tłoka, α [ºOWK] – położenie kątowe wału korbowego, p_w – przebieg ciśnienia w przewodzie wtryskowym paliwa, p_c – przebiegi ciśnienia w komorze spalania, h_i – wznios iglicy rozpylacza.

According to Table 3, all the measurements were executed in conditions of load characteristic profile for three rotational speeds of the crankshaft: 1200, 1600, and 2000 rpm and in respect of selected load values, i.e. 40, 60, 80, 100, and 120 Nm. Regulation of α_{dpt} was varied under these conditions of the speed and engine load. This helped to determine the effect of variations of this angle on the engine's acoustic parameters and the rate of pressure increment in the combustion chamber.

3. Results

The paper has focused on determining dependences between the maximum rate of pressure increment in the combustion chamber and noise emissions of the engine AD3.152, powered with diesel oil and its EETB blends. Attempts have also been made to assess effects of variations of the dynamic angle of beginning of fuel injection on these dependences

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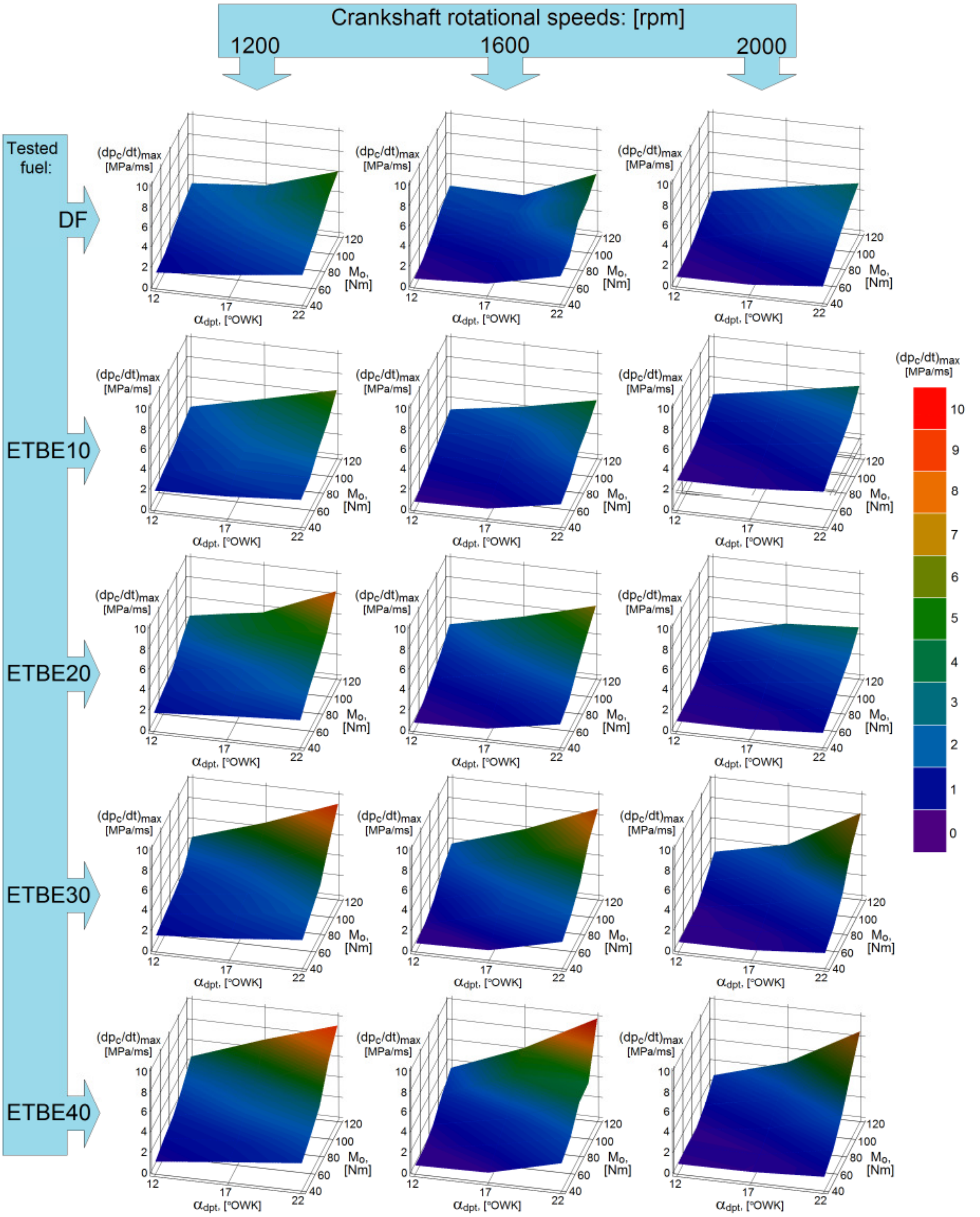


Fig. 4. Maximum rates of pressure increment $(dp/dt)_{max}$ in the combustion chamber of the engine AD3.152 as dependent on the latter's load, rotational speed, dynamic angle of beginning of fuel injection α_{dpt}, and type of tested fuel

Rys. 4. Wartości maksymalnych prędkości przyrostu ciśnienia $(dp/dt)_{max}$ w komorze spalania silnika AD3.152 w zależności od jego obciążenia, prędkości obrotowej, kąta dynamicznego początku tłoczenia paliwa α_{dpt} i rodzaju badanego paliwa

Figure 4 shows calculated maximum rates of pressure increment $(dp/dt)_{max}$ in the combustion chamber of the engine AD3.152 as dependent on the latter's load, rotational speed, dynamic angle of beginning of fuel injection α_{dpt}, and type of tested fuel. It can be noted that as α_{dpt} grows, $(dp/dt)_{max}$ increases markedly. This is especially evident in the case of fuel blends with higher ethyl tert-butyl ether content.

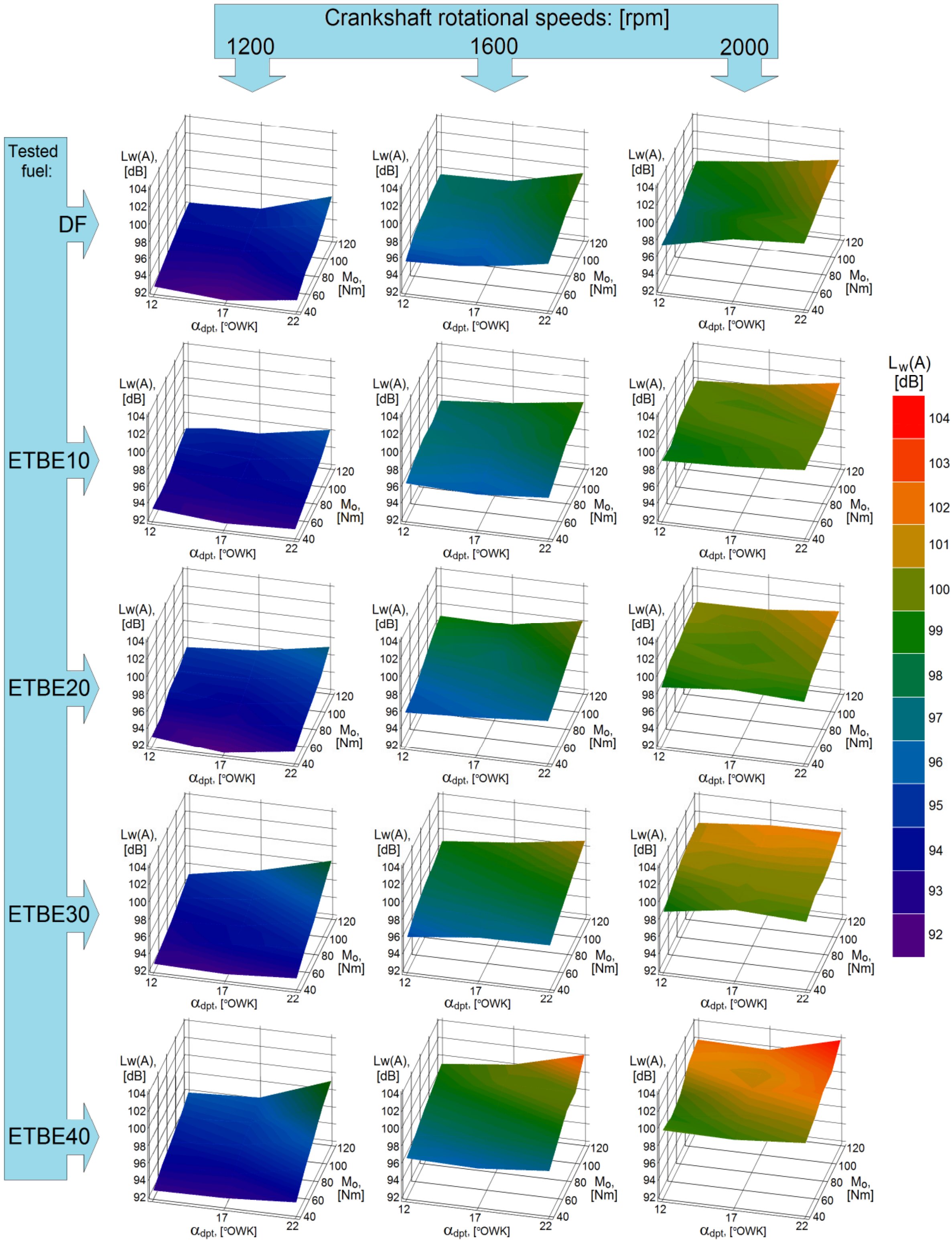


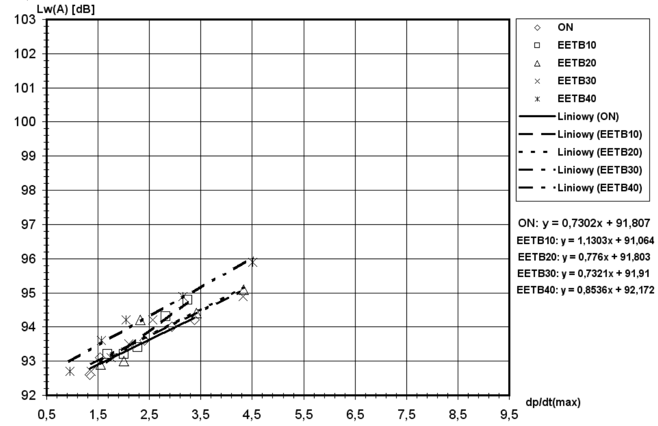
Fig. 5. Value of Lw(A) emitted by AD3.152 as dependent on the engine's load, rotational speed, dynamic angle of beginning of fuel injection $\alpha_{dpt,}$ and type of tested fuel.

Rys. 5. Wartości mocy dźwięku Lw(A) emitowanej przez silnik AD3.152 w zależności od jego obciążenia, prędkości obrotowej, kąta dynamicznego początku tłoczenia paliwa α_{dpt} i rodzaju badanego paliwa

Sound power Lw(A) emitted by the engine AD3.152 as dependent on the latter's load, rotational speed, dynamic angle of beginning of fuel injection $\alpha_{dpt,}$ and type of tested fuel is shown in Figure 5. Increasing α_{dpt} raises Lw(A), which is particularly clear where AD.3.152 is fed with fuel blends of higher ethyl tert-butyl ether content and for greater loads. The power of noise emissions is noticeably greater as the engine's rotational speed rises, as well.

Correlations between the calculated maximum rates of pressure increment in the combustion chamber and the measured acoustic emission of the engine were subsequently determined. The point distributions obtained in Figures 6 - 8 suggest that they can be expressed with linear dependences. This also helps to preserve clarity of these illustrations and supports their further interpretations.

a)



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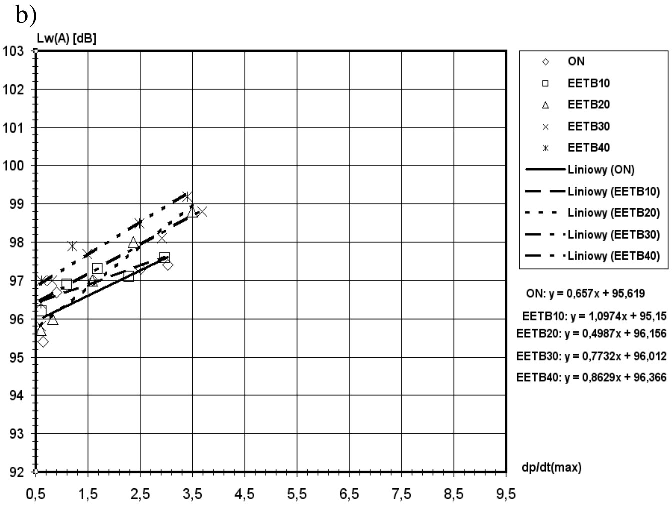

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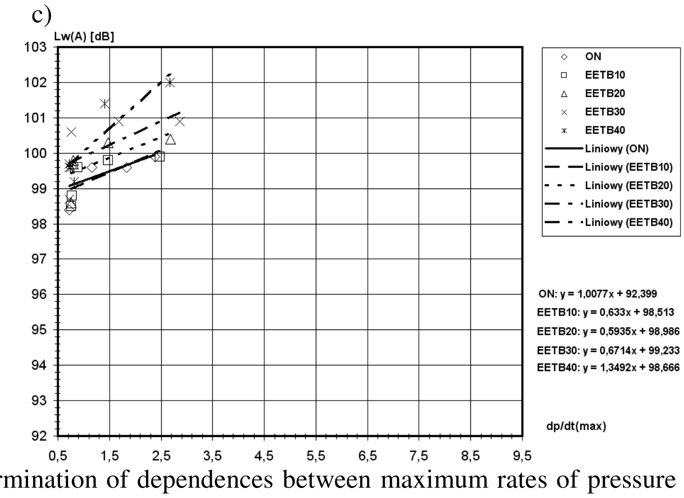
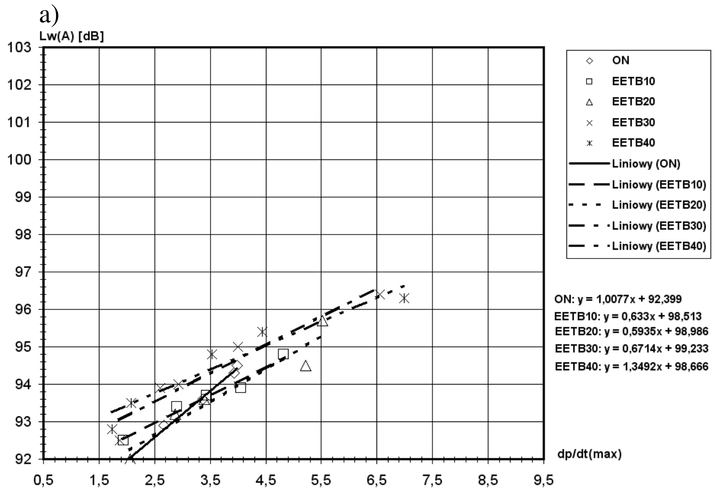


Fig. 6. Attempted determination of dependences between maximum rates of pressure increment in the cylinder $(dp/dt)_{max}$ [MPa/ms] and sound Lw(A) [dB] emitted by the engine AD3.152 powered with diesel oil and its blends with ethyl tert-butyl ether for the dynamic angle of beginning of fuel injection α_{dpt} =12 [ºOWK] and varying loads: a) n=1200 [rpm], b=1600 [rpm], c) n=2000 [rpm]

Rys. 6. Próba wyznaczenia zależności pomiędzy maksymalnymi prędkościami przyrostu ciśnienia w cylindrze $(dp/dt)_{max}$ [MPa/ms] a mocą dźwięku Lw(A) [dB] emitowaną przez silnik AD3.152 zasilanego olejem napędowym i jego mieszaninami z eterem etylo-tert butylowym, dla kąta dynamicznego początku tłoczenia paliwa α_{dpt} =12 [ºOWK] i różnych wartości obciążenia: a) n=1200 [obr/min], b=1600 [obr/min], c) n=2000 [obr/min] a)



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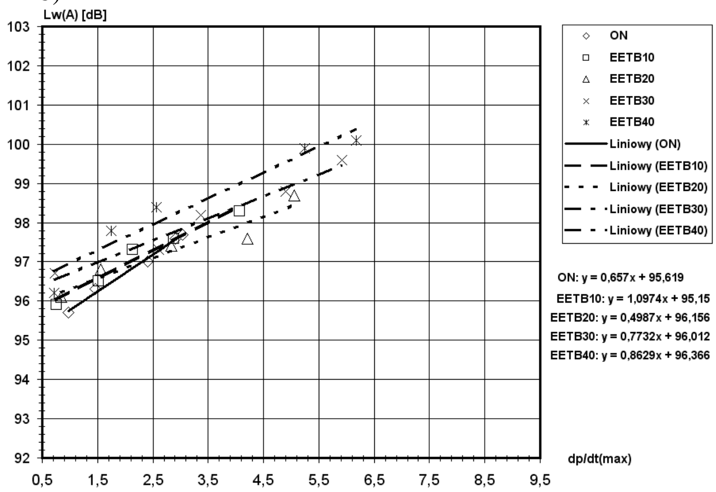

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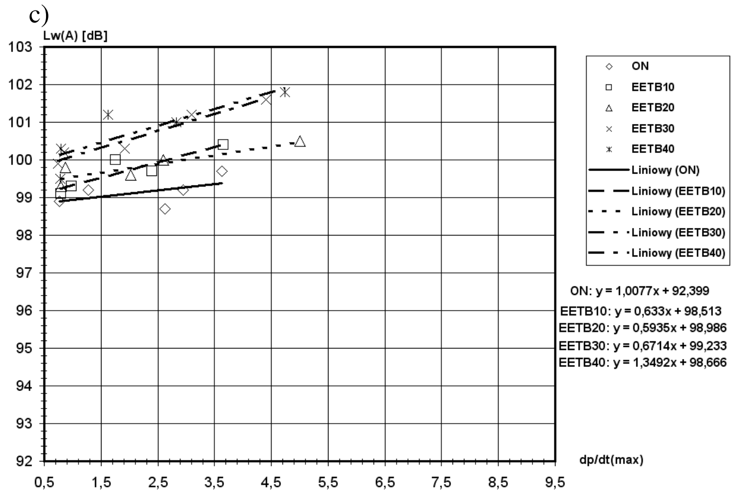
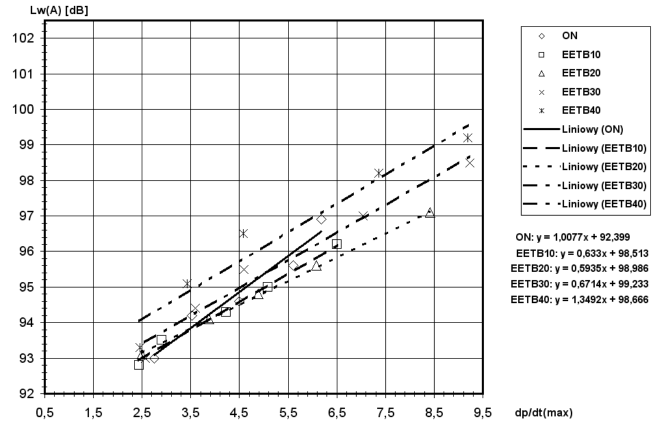


Fig. 7. Attempted determination of dependences between maximum rates of pressure increment in the cylinder $(dp/dt)_{max}$ [MPa/ms] and sound Lw(A) [dB] emitted by the engine AD3.152 powered with diesel oil and its blends with ethyl tert-butyl ether for the dynamic angle of beginning of fuel injection α_{dpt} =17 [ºOWK] and varying loads: a) n=1200 [rpm], b=1600 [rpm], c) n=2000 [rpm]

Rys. 7. Próba wyznaczenia zależności pomiędzy maksymalnymi prędkościami przyrostu ciśnienia w cylindrze $(dp/dt)_{max}$ [MPa/ms] a mocą dźwięku Lw(A) [dB] emitowaną przez silnik AD3.152 zasilanego olejem napędowym i jego mieszaninami z eterem etylo-tert butylowym, dla kąta dynamicznego początku tłoczenia paliwa α_{dpt} =17 [ºOWK] i różnych wartości obciążenia: a) n=1200 [obr/min], b=1600 [obr/min], c) n=2000 [obr/min]

a)



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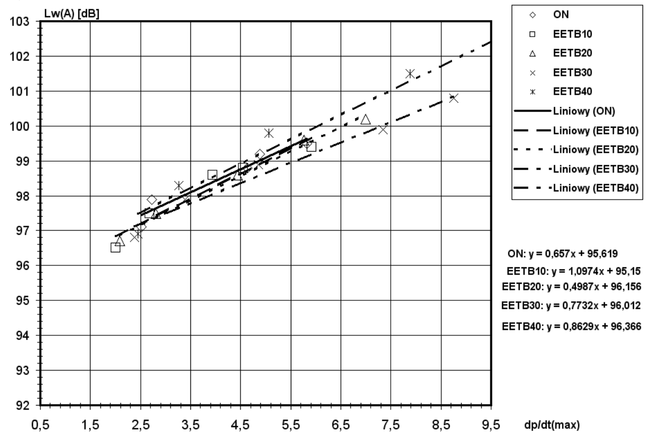

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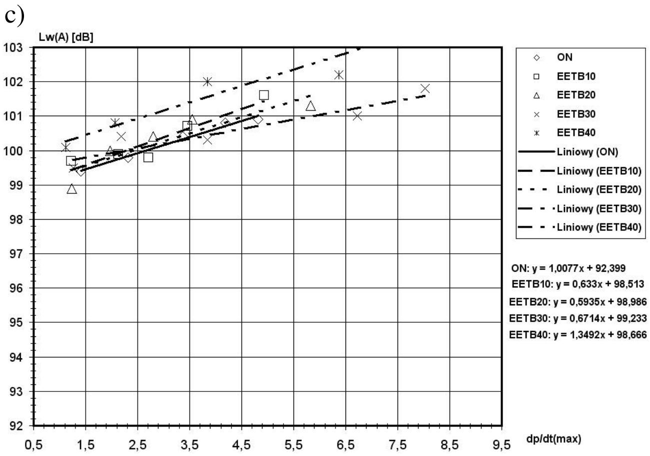

Fig. 8. Attempted determination of dependences between maximum rates of pressure increment in the cylinder $(dp/dt)_{max}$ [MPa/ms] and sound Lw(A) [dB] emitted by the engine AD3.152 powered with diesel oil and its blends with ethyl tert-butyl ether for the dynamic angle of beginning of fuel injection α_{dpt} =22 [ºOWK] and varying loads: a) n=1200 [rpm], b=1600 [rpm], c) n=2000 [rpm]

Rys. 8. Zależności pomiędzy maksymalnymi prędkościami przyrostu ciśnienia w cylindrze $(dp/dt)_{max}$ [MPa/ms] a mocą dźwięku Lw(A) [dB] emitowaną przez silnik AD3.152 zasilanego olejem napędowym i jego mieszaninami z eterem etylo-tert butylowym, dla kąta dynamicznego początku tłoczenia paliwa α_{dpt} =22 [ºOWK] i różnych wartości obciążenia: a) n=1200 [obr/min], b=1600 [obr/min], c) n=2000 [obr/min]

Evaluation of Figures 6 – 8 clearly implies that the increasing maximum rates of pressure increment in the combustion chamber are accompanied by growing noise emissions. This regularity is not varied by changes of fuel types or regulation of α_{dpt}.

4. Conclusion

The process of fuel combustion is a source of noxious emissions of fuel components, subject to extensive research and publications. Ecological treatment of the engine should also consider the issue of its acoustic emissions, however. Therefore, potential use of EETB blended with diesel oil to power compression ignition engines was evaluated with regard to its impact on variations of pressure increment rates in the combustion chamber and on noise emissions. Attempts were then undertaken to define dependences between these two parameters.

The results clearly indicate that increasing the dynamic angle of beginning of fuel injection helps to raise the rate of pressure increment in the combustion chamber. This can be explained by extension of the compressed ignition delay where fuel is too early injected into the combustion chamber. As a result, more fuel accumulates in the chamber and, at a certain point, begins to combust violently, thereby increasing values of $(dp/dt)_{max}$. Delay of the compressed ignition can also be extended under the influence of the fuel's cetane number. EETB is characterised by low values of this number, therefore, its addition to the diesel oil causes the rate of pressure increment in the combustion chamber to accelerate.

Measurements of noise Lw(A) emitted by the tested engine demonstrate that the noise climbs as the volume of EETB and diesel expands. This is particularly marked in respect of higher engine loads and increasing values of α_{dpt}. The maximum variation of noise emissions by the engine powered with a blend of diesel and EETB40 reached approximately 3dB. It should be noted that the human ear receives such a difference as doubling of the noise intensity.

The research was continued to determine dependences between maximum rates of pressure increment in the combustion chamber and the acoustic emission of the engine. Assessment of these dependences produced a distinct correlation: growth of $(dp/dt)_{max}$ is accompanied by greater noise emissions from the engine. This observation obtains for all the fuels tested by the authors of that paper.

Nomenclature/*Skróty i oznaczenia*

ETBE Etyl tert-butyl ether / eter etylo-tert butylowy

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