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Particulate matter emission from diesel engine fuelled with blends of diesel oil and ethyl tert-butyl ether

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The article presents the results of research on particulate matter (PM) emission from ADCR diesel engine fuelled with blends of diesel oil and ethyl tert-butyl ether (ETBE). Measurements were done in conditions of 13-phase, stationary ECE R49 test. Results show, that PM emission was reduced with the use of all tested ETBE/diesel blends with respect to those of the neat diesel fuel. In case of tested engine fuelled with mixture ETBE20 its PM emission was decreased by a half when compared to diesel oil.

1. Introduction

The main fuel for diesel engines is oil obtained from petroleum based sources. Its combustion process is not perfect still. For this reason toxic exhaust emission from diesel engine is a crucial problem, which can be partially solved for example using catalytic converters and particulate matter filters commonly known as DPF - Diesel Particle Filter [1]. The evolution of environmental requirements had been caused, that DPF are present in most modern vehicles equipped with diesel engines.

Since many years a number of different oxygenates have been considered as components for diesel fuel. The most important were plant oils and fatty acid methyl esters (FAME), whose physicochemical properties are similar to those of regular diesel oil. Other group of oxygenates providing potential to reduce particulate emissions in compression-ignition engines include different alcohols, ethers and carbonates. Ethanol is the most popular alcohol, which can be used in blend with diesel oil for diesel engine fuelling [2, 3]. A lot of publications confirm the effect of significant reduction in PM emission when engine was running with ethanol/diesel blends [4÷8]. Such mixtures are stable in higher temperatures only. In temperatures below about 30ºC their miscibility decrease and phase separation can be observed [3]. This phenomenon can be strongly limited with the use of special emulsifiers. One of them is FAME. Its small addition prevents phase separation of ethanol/diesel oil mixture.

Most of ethers are significantly less polar than alcohols. Therefore, ethers provide better miscibility with petroleum based diesel oil than alcohols. It should be noted that ETBE is considered a renewable compound, since the raw material used for its production – ethanol – derives from biomass. For this reason ETBE can be environment friendly fuel for internal combustion engines.

Of the ethers, potentially suitable for diesel engines in neat form are: DME (dimethyl ether), (DEE) diethyl ether, DMM (dimethoxy methane) and glycol ethers (monoglyme, diglyme). Properties of such ethers and their application to combustion engines are described in reference [9].

2. Methods and materials

Researches were carried out in collaboration of Technical University of Radom and ITE Radom, where PCA (Polish Centre for Accreditation) certificated engine laboratory is located. The laboratory is equipped with ADCR Andoria-MOT diesel engine and PIERBURG PTP 2000 gravimetric system with dilution micro tunnel for PM emission measurements.

2.1. Test stand

The main elements of laboratory test stand are ADCR engine and system of PM measurements. View of tested engine connected to engine brake presents Fig. 1. Engine parameters (load, crankshaft rotational speed etc.) were controlled directly by PIERBURG PTP 2000 system.

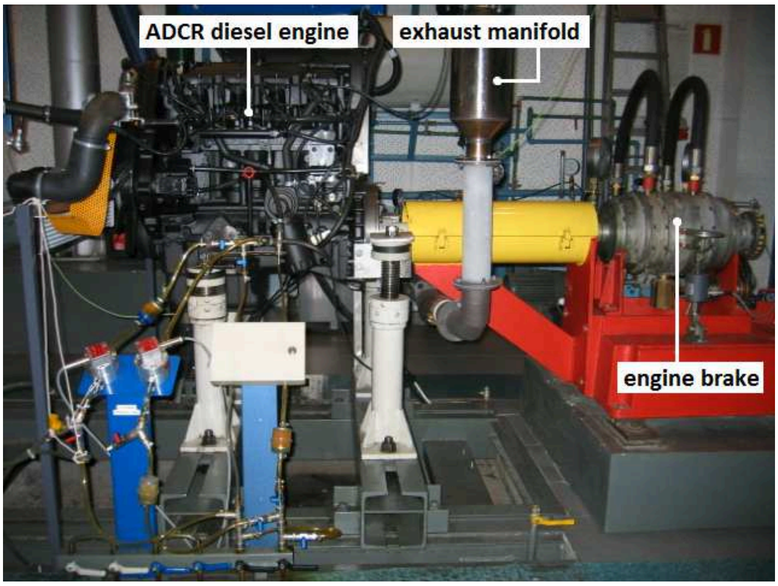

Fig. 1. View of ADCR diesel engine tested at ITE Radom laboratory.
Rys. 1. Widok silnika ADCR badanego w laboratorium ITE Radom.

Selected technical specifications of ADCR Andoria-MOT diesel engine are presented in Table 1. Engine was equipped with Common Rail fuel injection system developed by BOSCH.

Table. 1. Technical specification of ADCR Andoria-MOT diesel engine.
Tabela 1. Specyfikacja techniczna silnika ADCR Andoria-MOT.

No	Parameter	Value
1.	Cylinders number and arrangement	4, in-line
2.	Cylinder diameter	94 mm
3.	Piston stroke	95 mm
4.	Engine capacity	2636 cm^3
5.	Compression value	17,5
6.	Maximum power	85 kW at 3700 rpm
7.	Maximum torque	250 Nm at 2000 rpm
8.	Crankshaft speed at idle run	750 rpm
9.	Brake specific fuel consumption	210 g/kWh
10.	Fuel injection system	Common Rail
11.	Environment requirements	EURO4

2.2. Properties of tested fuels

Tested diesel oil and ETBE were get directly from PKN ORLEN S.A., which is the most important producer of these fuels in Poland. Properties of diesel oil were checked in chemical laboratories which have accreditation of PCA. Results of these researches confirm high quality of tested diesel oil which properties meet the requirements of PN-EN 590/2006 standard. Selected, physico - chemical properties of tested diesel oil and ETBE are presented in Table 2.

Table 2. Selected physico-chemical properties of tested base fuels.
Tabela 2. Wybrane własności fizykochemiczne badanych paliw bazowych.

Parameter	Value	
	Diesel oil	ETBE
Density at 20 °C [kg/m^3]	834	752
Density at 15 °C [kg/m^3]	839	750
Kinematic viscosity at 40 °C [mm/s^2]	2,79	-
Kinematic viscosity at 20 °C [mm/s^2]	-	1,5
Lubricity at 25°C [μm]*	222,1	-
Surface tension [mN/m]	25,9	20,6
Ignition temperature [°C]	72	-25
Elementary content: kg C/kg kg H/kg kg O/kg	0,86 0,14 -	0,705 0,138 0,157

*diesel oil lubricity measured at 25 ºC can not be higher than 380 μm [10]

ETBE can be blended with diesel oil and used in unmodified diesel engines. Tested ether versus ethanol is miscible in diesel oil over a wide range of temperatures and water content. For this reason it was possible to prepare stable fuel blends of diesel oil with ETBE. Table 3 shows the properties of the blends at different ratios of diesel and ETBE.

Table 3. Selected physico-chemical properties of tested fuel blends.
Tabela 3. Wybrane własności fizykochemiczne badanych mieszanin paliwowych.

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

The addition of ETBE to diesel fuel changed some physicochemical properties of the tested blends.

Density of all of the tested blends was slightly lower (up to about 4%) in comparison to neat diesel oil. It is recognized that lower density leads to lower flow resistance of fuel oil, resulting in lower viscosity. It can be observed that the kinematic viscosity of the blends decreased with an increase of the volume percentage of ETBE in the blends. This is attributed to the fact that tested ether has significant low viscosity and as such will lower the density of the mixture. Lower viscosity and surface tension should affect better fuel spray atomization and in result lower toxic gases emission.

Diesel fuel should reduce wear of fuel pump and injectors. For this reason, lubricity is an important fuel property, which was tested according to PN-EN ISO 12156-1:2006 standard. Addition of ETBE in diesel oil decreases lubricity of all tested blends. It should be noted, that diesel fuel lubricity measured with the use of HFRR (High Frequency Reciprocating Rig) method at temperature 25 ºC can not be higher than 380 μm [10]. In case of all tested blends the values of lubricity were below this limit.

Lower and higher heating values are one of the most important fuel properties. Table 3 shows that the lower heating value of all blends was found to be lower than that of neat diesel oil. Maximum difference equals 5% and it was found between diesel oil and mixture ETBE40.

The cetane number (CN) of all tested blends was determined using one-cylinder fuel research engine (Waukesha) meets the requirements of PN-EN ISO 5165/2003 standard. It was observed that increasing the concentration of ETBE additive in diesel oil reduces the cetane number of the blends. ETBE itself has very low CN (about 8) and it affects in lower CN value of all tested blends. For this reason, ignition delay period of fuels with higher ETBE content should be longer in time. It should affects on higher values of in-cylinder pressure rise and intensity of diesel knock phenomenon.

2.3. Conditions of engine research

Research has been done in conditions of static 13-mode (ECE R49) test cycle. Period of each test modes equal 6 minutes. So long period was required for engine thermal stabilization and sampling of exhaust gases. These gases have to be preliminary conditioned and then PM can be separated at surface of special filter. Difference of its mass measured at beginning and the end of research allows to calculate total PM emission from engine fuelled with tested blends. An ADCR engine was tested on a matrix of four speeds and six loads with four different fuel blends: ETBE10, ETBE20, ETBE30 and ETBE40 and the baseline diesel oil. Engine work conditions according to ECE R49 test are presented in Table 4.

Table 4. Conditions of ECE R49 test.
Tabela 4. Warunki realizacji testu ECE R49.

Mode Number	Engine crankshaft rotational speed	Engine load, [%]	Weighting factors
1.	Idle run	-	0,25/3
2.	Crankshaft rotational speed at engine maximum torque	10	0,08
3.		25	0,08
4.		50	0,08
5.		75	0,08
6.		100	0,25
7.	Idle run	-	0,25/3
8.	Crankshaft rotational speed at engine maximum power	100	0,10
9.		75	0,02
10.		50	0,02
11.		25	0,02
12.		10	0,02
13.	Idle run	-	0,25/3

Engine work conditions and measurement procedure were automatically controlled by PIERBURG PTP 2000 system.

3. Results

Measurements which were carried out in conditions of 13-mode test show, that PM emission from ADCR engine fuelled with regular (baseline) diesel oil equals 0,33 g/kWh (Fig. 2). It was the highest PM emission for all tested fuels. Addition of 10% of ETBE in diesel oil decreases PM emission to value 21 g/kWh. It is about 30% lower emission in comparison to engine operated with neat diesel oil. In case of ETBE20 particulate matter emission was at lower level i.e. 0,17 g/kWh.

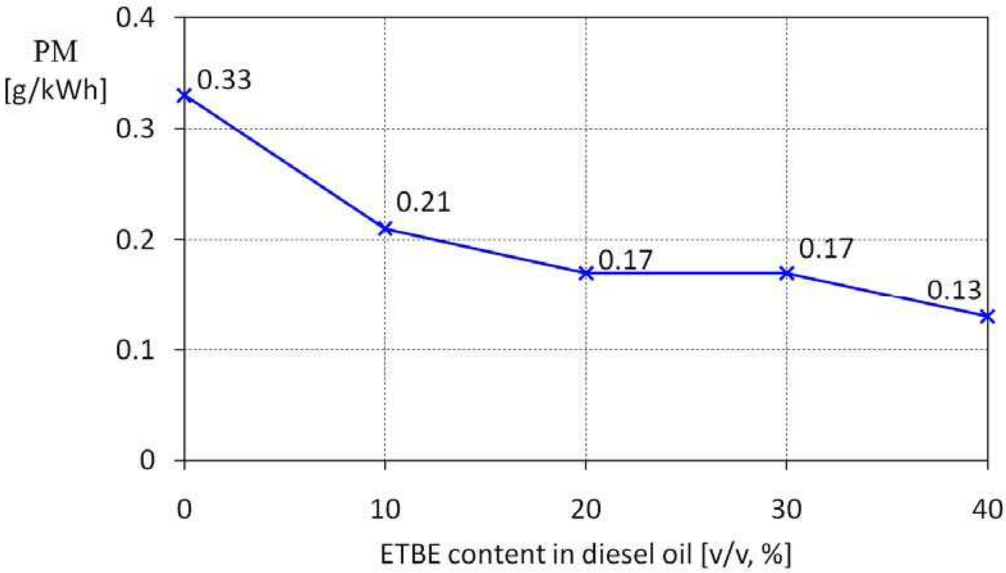

Fig. 2. Influence of ETBE content in neat diesel oil on PM emission of ADCR diesel engine.
Rys. 2. Wpływ zawartości ETBE w oleju napędowym na emisję cząstek stałych z silnika ADCR.

The same value was obtained for fuel blend containing 30% ETBE in diesel oil. The lowest PM emission (0,13 g/kWh) was measured for engine fuelled with ETBE40. In this case particulate emission was about 60% lower in comparison to diesel oil.

4. Conclusions

The main aim of this paper was to describe influence of ETBE addition into diesel oil on particulate emission. The evaluation was carried out using ADCR turbo-charged direct-injection diesel engine.

Presented test results suggest that small addition of ETBE to diesel oil can affect significant decrease of PM emission from modern design diesel engines. In case of tested ADCR diesel engine its PM emission was reduced by 30 and 60 percent for ETBE10 and ETBE40 operation respectively in comparison to engine fuelled with neat diesel oil.

Regular diesel fuel contains hydrocarbon compounds with higher molecular weights, than gasoline. Combustion process of such heavy hydrocarbon chemical structures is more complicated and long-lasting than in case of other light-weight hydrocarbons. For this reason diesel exhaust gases contain more particulates than typical spark – ignition engine. Diesel oil consists mainly of aliphatic hydrocarbons containing up to 28 carbon atoms in chain. Such heavy hydrocarbons have a low H/C mass ratio (about 0,16), which determines the high emission of carbon compounds per unit of energy delivered to the engine. ETBE molecular structure contains 6 carbon atoms and one oxygen atom. For this reason H/C ratio (about 0,20) of ETBE is a higher than average for diesel oil. Combustion process of such simple structures of hydrocarbons like ETBE is ecologically effective, but in case of diesel engine there is a problem of autoignition. The cetane number of the tested fuel blends was adequately reduced with the increase of ETBE content in diesel oil because of the low cetane number of the ETBE. A lower cetane number means an increase in the ignition delay. For this reason diesel engine fuelled with ETBE/diesel blends should works harder with higher values of in-cylinder pressure rise at the beginning of the combustion.

It should be noted, that significant reductions in regulated PM emissions were observed for engine fuelled with ETBE/diesel oil blends without additional modifications directed at emissions lowering. Further reductions in exhaust emissions could be achieved by optimizing of engine fuel injection/combustion systems.

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Emisja cząstek stałych z silnika o zapłonie samoczynnym zasilanego mieszaninami oleju napędowego z eterem etylo-tert-butylowym

S t r e s z c z e n i e

Artykuł przedstawia wyniki badań w zakresie oceny emisji cząstek stałych z silnika ADCR zasilanego mieszaninami oleju napędowego z eterem etylo-tert-butylowym (EETB). Pomiary wykonano w warunkach 13-fazowego testu stacjonarnego ECE R49. Wyniki wskazują, że emisja cząstek stałych była obniżona dla wszystkich badanych mieszanin w porównaniu do tej, którą uzyskano dla oleju napędowego. W przypadku badanego silnika zasilanego mieszaniną ETBE20 jego emisja cząstek stałych była obniżona o połowę w stosunku do zasilania olejem napędowym.