



# The effect of ethanol–diesel–biodiesel blends on combustion, performance and emissions of a direct injection diesel engine



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## ABSTRACT

The article presents the test results of a four-stroke, four-cylinder, naturally aspirated, DI 60 kW diesel engine operating on diesel fuel (DF) and its 5 vol% (E5), 10 vol% (E10), and 15 vol% (E15) blends with anhydrous (99.8%) ethanol (E). An additional ethanol–diesel–biodiesel blend E15B was prepared by adding the 15 vol% of ethanol and 5 vol% of biodiesel (B) to diesel fuel (80 vol%). The purpose of the research was to examine the influence of the ethanol and RME addition to diesel fuel on start of injection, autoignition delay, combustion and maximum heat release rate, engine performance efficiency and emissions of the exhaust when operating over a wide range of loads and speeds. The test results were analysed and compared with a base diesel engine running at the same air–fuel ratios of  $\lambda = 5.5$ , 3.0 and 1.5 corresponding to light, medium and high loads. The same air–fuel ratios predict that the energy content delivered per each engine cycle will be almost the same for various ethanol–diesel–biodiesel blends that eliminate some side effects and improve analyses of the test results.

A new approach revealed an important role of the fuel bound oxygen, which reflects changes of the autoignition delay more predictably than the cetane number does. The influence of the fuel oxygen on maximum heat release rate, maximum combustion pressure, NO<sub>x</sub>, CO emissions and smoke opacity of the exhaust is highly dependent on the air–fuel ratio and engine speed. Fuelled with blend E15B the diesel engine develops the brake thermal efficiency of 0.362, i.e. the same as a straight diesel running on slightly richer air–fuel mixture  $\lambda = 1.5$  at rated 2200 rpm speed. Adding of the ethanol to diesel fuel reduces the NO<sub>x</sub> and the HC emissions for richer combustible mixtures whereas the influence of a higher ethanol mass content on CO emissions and smoke opacity depends on the air–fuel ratio and engine speed.

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## 1. Introduction

One of the biggest challenges of the 21st century is the rapidly growing automotive industry with increasing demand of mineral oil products such as petroleum and commercial diesel fuel. To produce enough diesel fuel technically is feasible but every next barrel of crude oil is getting farther, deeper and harder with a higher extraction, production, and delivery price. The fossil fuel basins have been depleted over the past two industrialisation centuries and enormous amount of heat loss energy and harmful engine emissions were released into the atmosphere. As a number of passenger cars and heavy-duty trucks on the market increases along with power plants and home furnaces, the greater than before fuel consumption and air pollution by the greenhouse carbon dioxide become an ever-increasing problem. High urban population and urbanisation have changed the lifestyle of peoples', contributed

to climate changes, quickened ice caps melting, endangered survival of unique sea creatures and wild animals too.

The EU Directive 2009/28/EC approved a target of a 20% share of renewable biofuels in overall transport petrol and diesel consumption by 2020 to be introduced in a cost-effective way. The principal reasons for using of biofuels are to lower greenhouse gas emissions, increase farm income, promote rural development and diversification, create a new dynamics in a global agricultural market, increase energy independence and reduce consumer reliance on imported fossil fuels.

Alcohol-based fuels have been important energy sources since the 1800s. As early as 1894, France and Germany were using ethanol in internal combustion engines [1]. The first investigations on the use of ethanol in diesel engines were carried out in South Africa in the 1970s and continued in Germany and the USA during the 1980s [2]. There is a commitment of the USA government to increase bioenergy threefold in 10 years, which has added impetus to the search for variable biofuels [3]. Between 2000 and 2010 ethanol production increased from 16.9 to 72.0 billion litres while biodiesel grew from 0.8 to 14.7 billion litres [4]. After 2020, 2nd-generation bioethanol could become a much more significant

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## Nomenclature

$\varphi$	crank angle, degree	SOI	start of injection, CADs
$\varphi_i$	autoignition delay period, degree	SOC	start of combustion, CADs
$\tau_i$	autoignition delay time, s	$HRR_{max}$	maximum heat release rate, kJ/(m <sup>3</sup> ·deg)
$\lambda$	air–fuel ratio by mass	$AHRR_{max}$	crank angle corresponding to maximum heat release rate, CADs
$p$	gas pressure in the cylinder, bar	AI 50	crank angle corresponding to 50% heat release, CADs
$t$	temperature, °C	AI 90	crank angle corresponding to 90% heat release, CADs
<i>Abbreviations</i>			
E	ethanol	$p_{max}$	maximum pressure in the cylinder, MPa
B	biodiesel, E15B – RME additive	$A\varphi_{max}$	crank angle corresponding to maximum pressure in the cylinder, CADs
CN	cetane number	$(dp/d\varphi)_{max}$	maximum pressure gradients in the cylinder, bar/°CA
RME	rapeseed oil methyl ester	bmep	brake mean effective pressure, MPa
E5	5 vol% ethanol/95 vol% diesel fuel	bsfc	brake specific fuel consumption, g/kW h
E10	10 vol% ethanol/90 vol% diesel fuel	bte	brake thermal efficiency
E15	15 vol% ethanol/85 vol% diesel fuel	NO	nitric oxide, ppm
E15B	15 vol% ethanol/80 vol% diesel fuel/5 vol% rapeseed oil methyl ester	NO <sub>2</sub>	nitrogen dioxide, ppm
O <sub>2</sub>	fuel oxygen mass content, wt%	NO <sub>x</sub>	total nitrogen oxides, ppm
TDC	top dead center	CO	carbon monoxide, ppm
ATDC	after top dead center	CO <sub>2</sub>	carbon dioxide, vol%
BTDC	before top dead center	HC	unburned hydrocarbons, ppm
CAD	crank angle degree		

player in a global biofuels market [5]. Anhydrous ethanol has the advantage over methanol because of having higher miscibility with the diesel fuel and of being of renewable nature [6]. Modern technologies and efficient bio-energy conversion are becoming cost-wise competitive with fossil fuels, therefore the biofuel economy based on agricultural production will grow rapidly during the 21st century [7].

The experimental studies on the ethanol using in diesel engines have been carried out by Shropshire and Goering [8], Hansen et al. [9–11], Can et al. [12], Zannis et al. [13], Satge de Caro et al. [14] and other researchers [15–18]. Several methods are used, which are known as alcohol fumigation into the intake air ports [19–21], application of dual injection systems [8], using of alcohol–diesel fuel micro-emulsions [22] and preparation of the alcohol–diesel fuel blends [16,19]. The biggest advantages of the blending are the convenience in application and absence of engine modification, however, in case of using hydrous ethanol (190 proof) with the normal diesel fuel at blending ratios of 5/95 and 10/90 by volume, an emulsifying additive “GE Betz” as co-solvent or isopropanol as a heavy alcohol C<sub>3</sub>H<sub>8</sub>O is recommended in proportion from 1 vol% to 1.5 vol% to improve miscibility of the ethanol–diesel fuel mixture at lower temperatures, satisfy homogeneity and prevent phase separation [12,23].

Ethanol solubility in the diesel fuel depends on the hydrocarbon composition of the diesel fuel, temperature, content of water and wax in the blend and ambient humidity. To improve miscibility, Asfar and Hamed [22] added a stabiliser (isobutanol) of 3.7 vol%, 7 vol% and 13 vol% to tested 5 vol%, 10 vol% and 20 vol% ethanol–diesel fuel blends. The homogeneous mixture of a diesel, biodiesel and ethanol fuels can also be prepared by mixing it with a magnetic stirrer [24] or a mixer can be mounted inside the fuel tank to prevent phase-separation in straight ethanol–diesel fuel blending [25]. To improve blending of the ethanol with the diesel fuel Abu-Qudais et al. [19] used 0.5 vol% of emulsifier that consisted of a styrene–butadiene copolymer and a polyethyleneoxide–polystyrene copolymer. In that research the optimum percentage for ethanol–diesel fuel blends was 15%, which suggested an increase of 3.6% in brake thermal efficiency, 43.3% in CO emissions, 34% in HC and a reduction of 32% in soot mass concentration.

In contrast to the above studies, anhydrous ethanol (200 proof) does not need an emulsifying agent to form a transparent solution in diesel fuel, but these solutions can tolerate only up to 0.5% of water [23]. Other researchers also provided tests with various ethanol–diesel fuel blends without using of any additives [26], except in some cases the ignition improver Hicet 3A (0.16% 2-ethylhexyl nitrate) [9] or cetane improver (0.2% iso-amyl nitrite) [18] were used to increase cetane number, improve autoignition and combustion of oxygenated blends. Satge de Caro et al. [14] determined that adding of the 20 vol% of ethanol to diesel fuel decreased cetane number and led to the longer autoignition delay, increased cyclic irregularity and augmented CO and HC emissions. To avoid phase separation between two fractions the rapeseed oil methyl ester from 5 vol% to 10 vol% [27] or soybean oil methyl ester from 2 vol% to 10 vol% [28], as co-solvents, can be added to ethanol–diesel fuel blends.

Experiments of a four-cylinder, turbocharged, DI diesel engine fuelled with the 10 vol% and the 15 vol% ethanol–diesel fuel blends revealed that the ethanol addition reduces engine power by 12.5% and 20%, the CO, the SO<sub>2</sub> emissions and soot density because of the higher oxygen mass content and lower C/H ratio in ethanol–diesel fuel blends. However, low cetane number and long ignition delay, followed by higher pressures and temperatures inside the cylinder, resulted in slightly higher NO<sub>x</sub> emission at full load within the speed range of 4500–1500 rpm [12]. Similar changes in the CO emission and higher fuel consumption at adequate loads, concentration of unburned hydrocarbons HC and the total NO<sub>x</sub> emissions were obtained when running on various diesel–ethanol-1-butanol microemulsions up to 50% by energy content single-cylinder, DI 7.4 kW diesel engine [16]. The reduced cetane number of emulsified fuel blends increased the autoignition delay and caused a higher maximum pressure and combustion temperature in the cylinder that led to higher NO<sub>x</sub> levels. Experiments with ethanol and rapeseed oil blends showed that the combustion temperature plays an important role in the production of NO<sub>x</sub> [29,30].

Since the boiling temperature of ethanol is about 2.3 times lower than the start of vaporisation of diesel fuel, mixing of diesel fuel with a lighter ethanol may advance the start of fuel vaporisation that, on the one part, accelerates preparation of the air and fuel

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