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Study on co-combustion of diesel fuel with oxygenated alcohols in a compression ignition dual-fuel engine

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ABSTRACT

Alcohol fuels offer opportunities to reduce the use of fossil fuels in CI engines and to increase percentage of biofuels in the transport and energy sectors, where combustion engines are often used. This study presents experimental examinations of a stationary single-cylinder compression ignition dual-fuel engine based on co-combustion of diesel fuel with alcohols. The study evaluated the effect of addition of methanol, ethanol, 2-propanol and 1-butanol to diesel fuel on the combustion process, performance and emissions from a research engine. Percentage of the energy supplied in the alcohol fuel was 15, 30, 45, 55 and 70% of total energy supplied with fuel to the engine. The results of the examinations were compared to the examinations for the engine fuelled with pure diesel fuel as a reference. Addition of alcohol to diesel fuel had a positive effect on the level of mean indicated pressure, thermal efficiency and stability of the research engine. The increase in energy percentage of each alcohol to 55% during co-combustion with diesel fuel led to the mean increase in indicated mean effective pressure (IMEP) by 22%, mean increase of indicated thermal efficiency (ITE) by almost 13% and reduction in coefficient of variation COV_{IMEP} by 52%. Of the alcohols analysed in the study, methanol was the most beneficial in terms of high indicated pressure and high efficiency, with maximal values of IMEP = 0.86 MPa and ITE = 35.3% at DM55. Addition and increase in percentage of each alcohol to 55% led to the increase in emissions of nitrogen oxides (by 139% on average), decline of carbon oxide emissions (by 45% on average) and increase in carbon dioxide emissions (by 17% on average). However, it did not lead to significant changes in emissions of hydrocarbons. The highest content of NO_x, CO and CO_2 in engine exhaust were found for co-combustion of diesel fuel with addition of methanol.

1. Introduction

Compression ignition engines have been popular all over the world due to relatively high efficiency and reliability, fuel savings, longer life and high torque [1,2]. A typical fuel for compression-ignition engines is diesel fuel derived from crude oil, with its combustion involving substantial emissions of engine exhaust components such as nitrogen oxides (NO_x), hydrocarbons (THC), carbon oxide (CO), carbon dioxide (CO_2) and particulate matter (PM). It is known that global oil reserves are limited while production of diesel fuel is becoming more expensive. Combustion of fossil fuels, such as petroleum, leads to air pollution, climatic changes and gradual increase in mean global temperature. Most of CO_2 emissions generated all over the world by people are connected with combustion of fossil fuels [3–6]. The contribution of carbon dioxide to the effects of global warming and climate change is commonly known. Therefore, the EU set forth far-reaching objectives to reduce emissions. The European Parliament adopted the Directive 2009/28/EC on promotion of the use of energy from renewable resources. Mandatory targets of 20% were defined for the percentage of energy from renewable sources in total energy consumptions for the countries of the European Union by 2020 [7]. The document also stipulates that the EU member states should increase the share of biofuels in total consumption of gasoline and diesel fuel in transport to at least 10% [8]. Furthermore, more and more urban complexes all over the world are going to impose a ban on vehicles with diesel engines. The ban is expected to reduce air pollution. By 2025, vehicles with conventional diesel engines will have been ousted from the streets of Paris, Athens, Mexico and Madrid [9]. Biofuels can offer an alternative to fossil fuels and be considered a renewable source of energy to be derived from processing of biomass from plants or animal matter, even using microalgae [10–12]. Emissions of toxic components of engine exhaust gas can be reduced by a controlled process of combustion inside the engine cylinder or by external exhaust treatment systems [13–18]. Modern exhaust treatment technologies, including oxidation catalyst,

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Nomenclature

IMEP	indicated mean effective pressure, MPa
HRR	heat release rate, J/deg
ITE	indicated thermal efficiency,%
COV_{IMEP}	coefficient of variation in indicated mean effective pressure,%
STD_{IMEP}	standard deviation of the IMEP, MPa
LHV	lower heating value, MJ/kg
ID	ignition delay, deg
BD	burn duration, deg
V_d	displaced cylinder volume, cm^3
T	temperature, K
Q_e	total heat in the fuel supplied to the engine, J
Q_{cyl}	heat in the fuel supplied to the cylinder, J
Q_{in}	heat in the fuel supplied to the intake manifold, J
p	pressure, bar
n	engine speed, rpm

Abbreviations

NO_x	nitrogen oxides
THC	total hydrocarbons
CO	carbon monoxide
CO_2	carbon dioxide
O_2	oxygen
TDC	top dead centre
SOI	start of injection
MFB	mass fraction burn

Greek letters

φ	crank angle, deg
λ	excess air ratio
ρ	density, kg/m^3
δ	error of measurement
Δ	uncertainty of result

diesel particulate filter (DPF) and NO_x reduction catalyst often do not lead to simultaneous reduction in both particulate matter and NO_x. Nowadays, co-combustion of fossil fuels is gaining in popularity, thus reducing emissions of toxic compounds of fuels. Of liquid biofuels, alcohols are being used more and more frequently. The most popular are methyl, ethyl, propyl and butyl alcohols. Although alcohols are not perfect fuels for diesel engines due to their low heating value, high latent heat of vaporization and substantial higher self-ignition temperature compared to diesel fuel, methyl and ethyl alcohols have been attracting much interest as replacement engine fuels compared to conventional ones [19–21]. Alcohols are fuels with substantial oxygen content (for example, half mass fraction of methanol is oxygen). Oxygen contained in fuel is conducive to intensification of the combustion process by increasing the phase of kinetic combustion at the expense of the diffusive phase and leading to the increased heat release rate and improved engine thermal efficiency [22–24]. Alcohols are characterized by a low cetane number, which virtually prevents from their direct use in the compression ignition engines. In recent years, alcohol fuels have been widely used in compression ignition engines with dual-fuel systems for combined combustion of alcohol and diesel [25,26]. Co-combustion can potentially reduce formation of nitrogen oxides which is generated in the premixed part and the post flame region and soot which is generated in the diffusion flame during combustion of diesel fuel [27,28]. Dual fuel combustion in compression ignition engines is ensured in two main ways. With the first method, previously prepared blend of diesel fuel and alcohol is supplied through the injection system to the engine cylinder. The second solution is alcohol fumigation through injection of liquid alcohol to the collector in the area of the inlet value and direct injection of diesel fuel to the cylinder. The first method is easier yet it has several drawbacks. Firstly, mixing lower alcohols with diesel fuel is difficult while the blends are characterized by phase instability and tends to become clouded and stratified. In case of higher alcohols as 1-butanol and 2-propanol with diesel the mixtures are stable. Therefore, stabilizing agents are needed. Secondly, it is impossible to control the content of the blend during engine's operation. With this solution, there is no need for a substantial modification of the engine. With the second method of dual-fuel combustion, with two independent fuel supply systems, additional injector, separate fuel tank, pipes and control components are needed. Despite this drawback, the solution offers several benefits, such as control of the moment of ignition through injection of a diesel fuel dose and accuracy of changes in alcohol-diesel fuel ratio depending on different conditions of engine operation. In this solution, it is usually necessary to modify the injection timing. Recent years have seen intensifying explorations of opportunities to use alcohol-based fuels in compression ignition engines. In paper [28], ethanol dual-fuel combustion was examined experimentally using a heavy duty diesel engine operating at 1200 rpm and IMEP equal to 0.615 MPa. The impact of various ethanol fractions and different diesel injection strategies on combustion, emissions and efficiency were analysed and discussed. Two separate engine calibrations with the highest efficiency and lowest emissions were quantified, complete with effects from EGR, intake air pressure, and injection pressure. Uses split diesel injection technology in dual fuel engine fuelled by ethanol causes higher indicated efficiency compared to diesel-only operation. A split injection strategy adjusted the mixture flammability and promoted in-cylinder reactivity gradients, increasing the fuel conversion efficiency and reducing CO and unburnt THC emissions.

The split diesel injection strategy used in this work allowed for control over combustion phasing without the need for varying the overall fuel reactivity (i.e. ethanol substitution ratio).

With the best emissions, NO_x and soot emissions were reduced by 65% and 29%, respectively. After-treatment requirements, which are generally associated with cost and fuel economy penalties, can be minimised. Combustion efficiency of 98% was achieved at the expense of higher NO_x emissions. In the study [29], experiments and simulations were used to explore the cyclic variability of an ethanol/diesel dual-fuel engine. The experiments were conducted on a light-duty diesel engine fueled with port injection of ethanol and direct injection of diesel. The effects of engine load, ethanol content and diesel injection timing on the cyclic variability were evaluated. In-cylinder pressure traces of 150 consecutive cycles were acquired at each test condition. Consequently, cyclic variations of ignition timing, combustion phasing, accumulated heat release and indicated mean effective pressure (IMEP) were used to quantify the cyclic variability. The experimental results showed that the fluctuations of ignition timing and combustion phasing were very small throughout the premixed ratio sweep for both the light and high loads. However, the cyclic variation of IMEP increased with the increasing ethanol ratio at both load conditions. Furthermore, cyclic variation of IMEP was reduced at the high load. The variations of IMEP and accumulated heat release showed similar trends for the test conditions, indicating that the cyclic variation of IMEP was mainly caused by the variation of accumulated heat release. Wei et al. [30] conducted an experiment on a diesel/methanol dual fuel engine to investigate the effects of single injection and pilot injection strategies on combustion characteristics, regulated and unregulated gaseous emission (included CO, THC, NO_x, CO_2, nitrous oxide, formaldehyde, unburned methanol, 1.3-butadiene, formic acid, benzene and toluene) characteristics at low load condition with four different methanol substitution ratios. Experimental results revealed that the application of pilot injection could improve combustion stability and fuel economy at high methanol