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Research article

Combustion and emission characteristics of DI diesel engine fuelled by ethanol injected into the exhaust manifold

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ABSTRACT

Dual fuel diesel engine operation is an important technique used for combustion control in diesel engines. In this study, ethanol is injected into the exhaust manifold of a single cylinder diesel engine. The exhaust valve opens during the intake stroke, enabling vaporized ethanol to enter the cylinder where it is then ignited by diesel fuel injection. The effects of exhaust gas recirculation (EGR) ratios, ethanol injection timing, and ethanol amount are studied. Furthermore, exhaust and intake manifold injection of ethanol compared under the same conditions. These results reveal that ethanol injection into the exhaust manifold increases the apparent heat release rate (AHRR) at the premixed combustion phase. Additionally, the ignition delay increases with ethanol injection by 0.2° crank angle (CA). The indicated mean effective pressure (IMEP) and total heat released per cycle are increased by 8.2% and 14.2%, while the NO_x and soot concentrations are reduced by 88% and 30%, respectively. When compared with exhaust manifold ethanol injection, intake manifold injection results in higher AHRR in the premixed combustion phase, decreased engine performance, an increase in soot production of approximately 35%, and decrease in NO_x of 13%.

1. Introduction

The development of new combustion strategies meant to increase fuel efficiency and reduce the harmful emissions has been driven by multiple factors, including the depletion of conventional fuels, environmental pollution concerns, and tightening exhaust emission standards. Diesel engines, widely used in transportation, electrical power generators, and pumps, play a crucial role in the energy economy. Of additional interest, diesel engines significantly contribute to air pollution and are commonly considered the primary source of NO_x and soot emissions.

Complicating efforts to improve pollution, there is a tradeoff relationship between soot and NO_x formation in diesel engines, which makes the simultaneous reduction of both difficult. Low-temperature combustion (LTC) strategies have been considered efficient for concomitantly reducing NO_x and soot. As the formation reaction of NO_x has high activation energy, low combustion temperatures are able to reduce NO_x emissions [1]. The long ignition delays in LTC additionally provide enough time for fuel and air to mix thoroughly before the start of combustion. This reduces soot formation by diminishing fuel rich regions. The diesel engine dual fuel operation is one example of a practical application of LTC strategies for combustion control and emission reduction [2].

Unfortunately, advanced engine combustion strategies cannot solve all the problems facing our society at present. The use of alternative fuels is imperative for addressing these concepts. Among alternative fuels, ethanol is one of the most widely investigated for use in combination with diesel fuel. Ethanol is an attractive alternative to conventional fuels, as it can be renewably produced from crops such as sugar cane, beetroot, cassava, and sweet sorghum. This increases energy security while reducing reliance on fossil fuels. Globally, ethanol is considered a carbon neutral fuel as the CO_2 produced during combustion is absorbed again during photosynthesis, reducing greenhouse gases. The presence of oxygen in ethanol's chemical composition can potentially reduce soot emissions in diesel engines.

However, use of ethanol fuels in diesel engines suffers from many obstacles. Mixing ethanol with diesel fuel lowers the heat value of combustion. Therefore, higher volumes of ethanol are required to complete the same work as diesel fuel. Ethanol mixes with diesel fuel only in small percentages, and these mixtures are unstable and separate easily in the presence of small amounts of water [3]. Diesel fuel has greater lubricating qualities than ethanol. Furthermore, ethanol has higher latent heat of vaporization then diesel, so mixing ethanol into the fuel leads to charge cooling and combustion quenching [3]. Diesel engines use high cetane number fuels which easy autoignition and short ignition delay,

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Nomenclature

AHRR	Apparent heat release rate
ATDC	After top dead center
B7	Fuel blend of 7% biodiesel and 93% diesel fuel
BDC	Bottom dead center
bsfc	Brake specific fuel consumption
BTE	Brake thermal efficiency
CA	Crank angle
CO	Carbon monoxide
COV	Coefficient of variance
E85	Fuel blend of 85% ethanol and 15% gasoline
EGR	Exhaust gas recirculation
EGR10	EGR ratio of 10%
EGR25	EGR ratio of 25%
EPA	Environmental protection agency
EVC	Exhaust valve close
EVO	Exhaust valve open
FPGA	Field programmable gate array
HC	Hydrocarbon
HCCI	Homogeneous charge compression ignition
IMEP	Indicated mean effective pressure
ITE	Indicated thermal efficiency
IVC	Intake valve close
IVO	Intake valve open
NO_x	Nitric oxides
OH	Hydroxyl group
PFI	Port fuel injection
PM	Particulate matter
ppm	Parts per million
RCCI	Reactivity controlled compression ignition
SOI	Start of injection
TDC	Top dead center
VVA	Variable valve actuating
LTC	Low-temperature combustion

Symbols

N	Number of samples
P	Cylinder pressure [MPa]
Q_{net}	Apparent heat release rate [J/deg]
T	Average gas temperature [K]
V	Cylinder volume [cm^3]
	$V_{displace}$ Cylinder displacement volume [cm^3]

Greek symbols

θ	Crank angle degree
κ	Specific heat ratio

whereas ethanol has a low cetane number, low auto-ignition capability, and associated high knock tendency. Using ethanol in diesel engines is not limited to diesel and ethanol blends. Various techniques such as blending, emulsion, fumigation and fuel injection in the intake manifold have been investigated using ethanol in compression ignition engines [4].

The combustion of ethanol and diesel blends in diesel engines has been investigated over the last few decades [3,5–12]. The ethanol to diesel fuel blend ratios in previous studies have not exceeded 20% volumetrically, as higher values may further reduce soot emission but will also affecting engine performance. This is due to the low heating value of ethanol. An ethanol and diesel fuel blending ratio of 15% by volume has been reported as optimum with regards to performance and emissions [3]. These ethanol and diesel fuel blends increase brake thermal efficiency, CO, and HC emissions while reducing soot and NO_x emissions [3,10]. However, higher specific fuel consumption and decreases in torque, power and brake thermal efficiency have been observed as the percent of ethanol in blends increases. This is a result of the low calorific value of ethanol [5–7]. For in-cylinder analysis, adding ethanol to diesel fuel prolongs ignition delay and reduces combustion duration [11,12]. High ethanol percentages in these blends show higher peak cylinder pressures and higher premixed heat release rates compared to unblended diesel [12]. The effect of injection timing on diesel engine performance was investigated by Murcak et al. [9]. They cited that advancing the injection timing 10° CA for ethanol/diesel mixtures gives better engine performance on power, torque, and bsfc compared to standard injection timing of pure diesel fuel [9]. Multiple studies have investigated changes in combustion resulting from the effects of mixing 5, 10 and 15% by mass anhydrous ethanol with a combination of diesel and biodiesel in a diesel engine [11,13,14]. As the ratio of ethanol increased, cylinder pressure and heat release rate were reduced at lower loads and grew at medium or high loads. The 7% biodiesel (B7) containing 15% of ethanol increased fuel consumption by up to 18%, but reduced CO and NO_x emissions by 8% and 10%, respectively [11]. HC emissions were increased at low loads and reduced at high loads [11].

The stability of ethanol and diesel blends is affected mainly by the temperature and water content of the mixture, showing greatest stability at warm ambient temperatures. However, below approximately 10° C, the two fuels separate. This separation can be prevented by adding an emulsifier or co-solvent [15]. Fumigation, an alternative method of introducing alcohols into diesel engines, improves separation prevention at lower temperatures. In dual fuel operation using fumigation, fuels are introduced to air upstream of the manifold at the intake, where premixing with intake air can occur by way of spraying or carbureting [16–20]. Using the fumigation method, it is possible to increase the percentage of injected alcohol over 20% [16].

In-cylinder analysis shows fumigating ethanol results in higher peak pressures, higher heat release rates in the premixed combustion phase, and longer ignition delays at medium or high engine loads [18]. For low engine loads, the heat release rate remains similar between evaluations of ethanol fumigation and pure diesel fuel. The observed longer ignition delay is a result of ethanol's low cetane number and poor autoignition properties. As a consequence of these longer ignition delays, the amount of fuel burned in the premixed phase increases while fuel burned in the diffusion phase decreases. The combustion duration is shortened at medium and high engine loads [18].

When compared to pure diesel combustion, alcohol fumigation also exhibits a higher coefficient of variation of indicated mean effective pressure (COV_{imep}) and reduced maximum in-cylinder temperature [19]. The decrease in cylinder temperature results from ethanol's high latent heat of vaporization [19]. For engine performance parameters, the brake specific fuel consumption increased by 7–12%, a result of ethanol's lower calorific value. Brake thermal efficiency (BTE) decreased at low engine loads by 5–13%, but increased at medium and high engine loads by 2–9% [17]. Emissions were reduced as follows: carbon dioxide by up to 7.2%, nitric oxides by up to 20%, and particulate matter (PM) by up to 57% [16,17]. Additionally, ethanol fumigation increased unburned hydrocarbon (HC) emissions in all load ranges [17].

For several years, great efforts have been devoted to studying ethanol injection using reactivity control compression ignition (RCCI), or port fuel injection (PFI) in the intake manifold. This is a diesel engine dual fuel operation technique [2,21–32] in which two fuels with different autoignition characteristics (one of high reactivity, such as diesel, and the other of low reactivity, such as gasoline or ethanol) are blended inside the combustion chamber [32]. The low reactivity fuel is introduced using port fuel injection, while the high reactivity fuel is directly injected into the cylinder. Combustion phasing is controlled by the relative ratios of these two fuels, and the combustion duration is controlled by spatial stratification between the two fuels [32].