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# Experimental analysis of ethanol dual-fuel combustion in a heavy-duty diesel engine: An optimisation at low load

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## HIGHLIGHTS

- Dual-fuel combustion offers promising results on a stock heavy-duty diesel engine.
- The use of split diesel injections extends the benefits of the dual-fuel mode.
- Ethanol–diesel dual-fuel combustion results in high indicated efficiencies.
- NOx and soot emissions are significantly reduced.
- Combustion efficiency reaches 98% with an ethanol energy ratio of 53%.

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## ABSTRACT

Conventional diesel combustion produces harmful exhaust emissions which adversely affect the air quality if not controlled by in-cylinder measures and exhaust aftertreatment systems. Dual-fuel combustion can potentially reduce the formation of nitrogen oxides (NOx) and soot which are characteristic of diesel diffusion flame. The in-cylinder blending of different fuels to control the charge reactivity allows for lower local equivalence ratios and temperatures. The use of ethanol, an oxygenated biofuel with high knock resistance and high latent heat of vaporisation, increases the reactivity gradient. In addition, renewable biofuels can provide a sustainable alternative to petroleum-based fuels as well as reduce greenhouse gas emissions. However, ethanol–diesel dual-fuel combustion suffers from poor engine efficiency at low load due to incomplete combustion. Therefore, experimental studies were carried out at 1200 rpm and 0.615 MPa indicated mean effective pressure on a heavy-duty diesel engine. Fuel delivery was in the form of port fuel injection of ethanol and common rail direct injection of diesel. The objective was to improve combustion efficiency, maximise ethanol substitution, and minimise NOx and soot emissions. Ethanol energy fractions up to 69% were explored in conjunction with the effect of different diesel injection strategies on combustion, emissions, and efficiency. Optimisation tests were performed for the optimum fuelling and diesel injection strategy. The resulting effects of exhaust gas recirculation, intake air pressure, and rail pressure were investigated. The optimised combustion of ethanol ignited by split diesel injections resulted in higher net indicated efficiency when compared to diesel-only operation. For the best emissions case, NOx and soot emissions were reduced by 65% and 29%, respectively. Aftertreatment requirements that are generally associated with cost and fuel economy penalties can be minimised. Combustion efficiency of 98% was achieved at the expense of higher NOx emissions.

## 1. Introduction

Heavy-duty (HD) diesel engines have been widely utilised in on and off-road transportation sectors due to their high torque capability, reliability, as well as superior fuel conversion efficiency [1]. However, conventional diesel combustion incurs a wide range of local in-cylinder equivalence ratios and temperatures which can result in NOx and soot formation [2]. These emissions can adversely affect the air quality if not controlled by exhaust aftertreatment technologies and in-cylinder measures. Several combustion concepts have been developed, arising from costly aftertreatment systems and strict fuel efficiency and emissions regulations [3]. In addition, according to economic growth

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projections, it is predicted an increase in the demand for petroleum and other energy sources by more than 30% from 2010 to 2040 [4]. This may result in elevated prices for liquid fuels as well as compromise their cost competitiveness, opening opportunities for improved sustainability and greenhouse gas (GHG) emissions reduction via biofuels [5].

The alternative combustion technologies are generally centred on improved fuel atomisation and mixture preparation, lower local equivalence ratios, reduced peak in-cylinder temperatures, and faster burn rates. This is usually referred to Low Temperature Combustion (LTC) [3]. Among the combustion strategies proposed is Homogeneous Charge Compression Ignition (HCCI). This is characterised by early fuel injections promoting a fully premixed charge, long ignition delays, and short combustion durations. However, the lack of direct control of ignition timing and combustion phasing, particularly under transient conditions, is still the major drawback. It also exhibits elevated combustion losses, combustion noise, and sensitivity to temperature [6–8]. In comparison, some slightly more heterogeneous combustion concepts have been developed. Premixed Charge Compression Ignition (PCCI) [9–12], Partially Premixed Charge Compression Ignition (PPCI) [13], Modulated Kinetics (MK) [14], and Uniform Bulky Combustion System (UNIBUS) [15] name a few. These allow a higher degree of combustion phasing control at low and medium loads while maintaining low soot and NOx emissions. However, these less premixed combustion modes tend to suffer from lower indicated efficiency, increased unburnt hydrocarbons (HC) and carbon monoxide (CO) emissions, and limited load range due to high exhaust gas recirculation (EGR) and boost requirements.

Gasoline Direct Injection Compression Ignition (GDCI) [16,17] and Partially Premixed Combustion (PPC) [18–20] are some alternatives to diesel LTC. They expand the high efficiency window and achieve very low NOx emissions operating up to full load with moderate-high EGR rates. As these concepts utilise gasoline, they do not reduce the dependence on liquid fossil fuels. They also require engine hardware modifications such as the piston and injection system, and ignition or lubricant improvers, depending on the fuel selected. Some drawbacks regarding soot levels at higher loads, due to low air–fuel ratio, accompanied with significant CO and HC emissions at low loads are also reported. Recent PPC studies with renewable fuels, including ethanol, have demonstrated high thermal efficiency and further soot reductions [21–23]. However, high acoustic noise and elevated peak heat release rates have been experienced due to a fast premixed combustion, requiring lower intake air pressures and larger amounts of EGR, which reduce combustion efficiency [24].

Dual-fuel (DF) combustion, such as Reactivity Controlled Compression Ignition (RCCI) [25–27], have been developed to overcome the majority of the previously mentioned issues. The concept uses different fuels to control the in-cylinder reactivity gradient while achieving a wide operating range with near zero levels of NOx and soot, acceptable pressure rise rate (PRR), and very high indicated efficiency [28]. The primary method of fuel delivery is the port fuel injection of a low reactivity fuel (i.e. gasoline, alcohol, propane, natural gas, etc.) to create a well-mixed charge of fuel–air-EGR. The high reactivity fuel (i.e. diesel) serves as the ignition source and is directly injected into the combustion chamber. However, RCCI is sensitive to variations in the intake air temperature and pressure. This is expected as the combustion is sufficiently premixed and governed by chemical kinetics [25]. Furthermore, the combustion phasing is generally controlled by varying the fuel reactivity (i.e. substitution ratio), which might not be the optimum at certain engine loads.

Ethanol is attractive as a low reactivity fuel because it can be produced from biomass and can offset the demand for petroleum-based fuels in internal combustion engines [29]. The elevated knock resistance and latent heat of vaporisation of the ethanol allow the use in high compression ratio and highly boosted engines [30]. Moreover, early dual-fuel results obtained from an optical engine showed that ethanol can suppress soot formation in high temperature regions of the conventional diesel combustion chamber [31]. Recent experimental analyses with ethanol–diesel DF combustion demonstrated noticeable NOx reductions at engine loads above 0.8 or 1.0 MPa net indicated mean effective pressure (IMEP) [32–36].

Asad et al. [37] investigated the load range of ethanol–diesel low temperature combustion using a single cylinder light-duty engine. The concept, named Premixed Pilot Assisted Combustion (PPAC), utilised high EGR levels and single diesel injections near firing top dead centre (TDC). The main challenge encountered was the elevated levels of unburnt HC and CO emissions at low loads, as observed by other ethanol dual-fuel combustion studies [38,39]. Asad et al. [37] attributed these losses to the resistance of ethanol to auto-ignition and proposed an alternative combustion strategy to enable clean combustion and higher efficiencies at these specific conditions. From idle to low loads, the engine would operate under conventional diesel combustion, utilising high levels of EGR and boost combined with retarded injections and elevated rail pressures. After the engine reaches a certain load, the combustion would switch to ethanol dual-fuel combustion. However, high levels of EGR might not be feasible and would place greater demand on the boosting system to maintain the required equivalence ratio.

Sarjovaara et al. [40] studied the effect of diesel injection parameters on ethanol dual-fuel combustion using a modified six-cylinder diesel engine with a compression ratio of 14.2:1. The use of small pilot injections corresponding to approximately 10–20% of the total diesel fuel injected helped maintaining acceptable PRR levels while running with high ethanol percentages. However, the maximum ethanol substitution ratio was limited to only 39% at 25% load, and exhaust gas emissions were neglected.

Considering the previous works, an experimental study was carried out on a single cylinder HD engine. The combustion system remained stock, with a re-entrant piston bowl design and a geometric compression ratio of 16.8:1. Ethanol was port fuel injected while diesel fuel was directly injected into the cylinder. The objective was to reduce combustion losses and maximise the use of ethanol while maintaining low levels of NOx and soot emissions. The diesel injection strategy tested uses a pre-injection to adjust mixture flammability and reduce PRR, and one injection around TDC to maintain combustion control. This concept is slightly different from conventional dual-fuel using a single diesel injection near TDC for ignition [33–37,41]. The strategy also differs from the early diesel injections utilised in RCCI combustion [25,26,28].

The experiments were performed at 1200 rpm and 0.615 MPa IMEP, with varying ethanol energy fractions up to 69%. The impact of different diesel injection strategies on combustion, emissions, and efficiency were explored. Pre-injections corresponding to up to 60% of the total diesel fuel injected were evaluated without EGR. Subsequent investigation of the pre-injection timing and quantity was performed for the optimum fuelling and injection strategy using an EGR rate of 25%. Finally, the effect of higher intake air pressure and diesel injection pressure were explored. The best dual-fuel results were compared against diesel-only operation.

## 2. Experimental setup

The experiments were carried out on a single cylinder HD diesel engine equipped with a high pressure common rail diesel injection system, representing the engine of a modern heavy goods vehicle