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Potential of internal EGR and throttled operation for low load extension of ethanol–diesel dual-fuel reactivity controlled compression ignition combustion on a heavy-duty engine

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HIGHLIGHTS

- Higher residual gas fractions enhanced the combustion process at light loads.
- Improvements in combustion and net indicated efficiencies were attained using iEGR.
- Throttled operation offered higher combustion efficiency without fuel economy penalty.
- Dual-fuel combustion reduced NOx and soot emissions of conventional diesel combustion.

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ABSTRACT

High levels of carbon monoxide (CO) and unburnt hydrocarbon (HC) emissions are some of the main limitations of ethanol–diesel dual-fuel reactivity controlled compression ignition (RCCI) combustion at light engine loads. In addition, low exhaust gas temperatures reduce the effectiveness of the oxidation catalyst, necessary to meet stringent emissions standards. Elevation of in-cylinder gas temperature and increased fuel/air equivalence ratio are desirable to reduce the CO and HC emissions and hence improve combustion efficiency and fuel conversion efficiency. In this work, experimental studies and engine modelling have been carried out to investigate the potential of internal exhaust gas recirculation (iEGR) and throttled operation for low load extension of ethanol–diesel dual-fuel RCCI combustion. The experiments were performed on a single cylinder heavy-duty (HD) diesel engine equipped with a variable valve actuation system capable of intake valve re-opening during the exhaust stroke. The engine model was built in a one-dimensional computational fluid dynamics software. The utilisation of higher residual gas fractions and higher global equivalence ratios increased the mean in-cylinder gas temperatures during combustion. The hotter combustion processes resulted in lower CO and unburnt HC emissions, and higher exhaust gas temperatures. The lower oxygen concentration and higher heat capacity of the in-cylinder charge using iEGR curbed nitrogen oxides (NOx) formation. Net indicated efficiency was improved with the use of iEGR and remained nearly constant while throttling the engine when compared to the dual-fuel combustion baseline at 0.32 MPa net indicated mean effective pressure ($IMEP_{net}$). Compared with conventional diesel combustion, ethanol–diesel dual-fuel RCCI combustion minimised NOx and soot emissions from 0.3 to 0.6 MPa $IMEP_{net}$ and increased efficiency at loads above 0.5 MPa $IMEP_{net}$.

1. Introduction

The transport sector was responsible for nearly one third of the total energy consumption of the European Union (EU) in 2012 [1], and was heavily dependent on imported fossil fuels [2,3]. Moreover, the sector has been one of the largest emitters of particulate matter (i.e. soot) and NOx emissions in the EU in recent years [4]. The utilisation of alternative renewable fuels, such as liquid and gaseous biofuels, has the potential to reduce oil dependency, greenhouse gas emissions, and air pollution [1].

The introduction and use of an alternative fuel is coupled with the availability of its feedstock, the complexity of the production process, and distribution infrastructure. It is also linked with the development and implementation of advanced combustion technologies [1]. Blending mandates, supply obligations, emission

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legislations, and financial incentives act as drivers for the rapid growth in the use of such fuels [5]. In the EU, biofuels can be blended with conventional fuels in small fractions, such as 10% of ethanol in gasoline and 7% of biodiesel in diesel [6]. Spark ignition (SI) engines compatible with 85% ethanol content in gasoline (E85) are already available in Sweden, France, Germany, and the Netherlands [1]. In the United States, ethanol is blended with gasoline to make E10, which is comprised of 10% ethanol and 90% gasoline in a volume basis (v/v). E85 has also been utilised, but is not as widespread in its use [7]. Brazil produces SI flex-fuel vehicles capable of running either on hydrous ethanol containing up to 5.5% v/v of water [8], on gasoline with 27% of anhydrous ethanol [9], or on any mixture of them in between. Both fuels can be found in most of the petrol stations throughout the country.

The utilisation of alternative fuels in advanced combustion processes can reduce the transport sector's dependence on oil [10]. RCCI has been shown as an attractive method to achieve ultra-low NOx and soot emissions with simultaneous improvement in engine efficiency [11]. This dual-fuel (DF) combustion strategy relies on equivalence ratio and reactivity stratification in the cylinder to control the combustion event [12,13]. Low reactivity fuel, such as gasoline, ethanol, or natural gas is delivered via port fuel injection. Direct injection of higher reactivity fuel (e.g. diesel) acts as an ignition source. Once the right conditions for auto-ignition (i.e. temperature) are achieved, the ignition of the more reactive fuel occurs and the charge is sequentially consumed from the more to the less reactive zones [10]. As a result, this operating regime can reduce peak combustion temperatures as well as combustion duration, minimising heat transfer losses [11]. However, low combustion efficiencies remain a challenge at light engine loads [14,15]. This is a result of non-uniform mixing and lower local combustion temperatures [12]. At the end of combustion, unburnt fuel and CO are typically found in the centre of the combustion chamber as well as in the crevice and liner regions [12]. The non-conversion of fuel combined with a fast heat release leads to relatively low late cycle in-cylinder temperatures. If the resulting exhaust gas temperature (EGT) is not high enough, the effectiveness of the oxidation catalyst may be compromised [16].

Improvements in combustion efficiency [12] and elevation of the EGT [12,17] can be influenced by the intake charge temperature. However, rapid temperature increase of the inlet mixture may not be feasible in real world applications, particularly during cold start and transient operating conditions. Higher fuel/air equivalence ratios achieved via intake throttling also showed potential to increase EGT at the expense of higher fuel consumption and NOx emissions [18]. These drawbacks can be attributed to higher peak combustion temperatures and elevated heat transfer losses [19].

Other effective means for increasing in-cylinder and exhaust gas temperatures is to retain hot residuals from the previous cycle. This strategy is generally called internal exhaust gas recirculation (iEGR) [20]. The residual gas fraction (RGF) can be defined as the burnt gas mass divided by the total in-cylinder mass (burnt and unburnt) prior to the start of combustion (i.e. at intake valve closing). The amount of exhaust gas trapped inside the cylinder depends on factors such as the valve timing, engine speed, and pressure differentials [21]. Means of adjusting the RGF generally rely on mechanisms such as two-stage cam-lift [20,22,23], camshaft phasing [24], variable valve actuation [25–29], and fully variable valve actuation [30–32]. There are several valve timing strategies utilised to aid the combustion process and the aftertreatment system, including:

- Early exhaust valve opening (EEVO). This approach increases the EGT and reduces the catalyst light-off time, enhancing the CO and unburnt HC conversion in the oxidation catalyst [33]. However, the utilisation of EEVO results in lower engine efficiency due to the reduction in the effective expansion ratio and the higher fuelling needed to maintain the load output [32,34].
- Exhaust valve re-opening (2EVO) or rebreathing during the intake stroke. This strategy allows for the return of the burnt gases from the exhaust manifold into the combustion chamber. The utilisation of a 2EVO can help the auto-ignition of the in-cylinder charge and to achieve the catalyst light-off temperature [22]. Improvements in thermal efficiency and combustion efficiency were also reported as a result of a more appropriate combustion phasing [29]. The drawbacks of the 2EVO strategy are the reduction of the intake air flow rate and influence on in-cylinder mixture motion [35], as well as the increase of RGF and temperature stratification, which can shorten the ignition delay and increase NOx and soot emissions [36].
- Intake valve re-opening (2IVO) or rebreathing during the exhaust stroke. In this case, residuals are pushed into the intake port and re-inducted into the cylinder during the intake stroke [37]. A 2IVO strategy may result in relatively colder and higher RGF than a 2EVO strategy, further reducing NOx emissions [23] while lowering CO and HC emissions [36].
- Negative valve overlap (NVO), which is a symmetrical interval to top dead centre (TDC) from an early exhaust valve closing (EEVC) to a late intake valve opening (LIVO). The EEVC increases the RGF and the in-cylinder gas temperature by reducing the scavenging process [27]. The use of NVO can result in lower net indicated efficiency due to higher heat transfer losses during the recompressions and reduced gas exchange efficiency compared to the 2EVO strategy [31].

The current work is focused on exploring the potential of iEGR and throttled operation to extend the low load operating range of ethanol–diesel dual-fuel RCCI combustion. The effects of the iEGR and intake throttling on combustion, emissions, and efficiency have been investigated. The experiments were performed on an HD diesel engine. Fuels were supplied via port fuel injection of ethanol and direct injection of diesel. The iEGR was introduced using a 2IVO provided by a variable valve actuation (VVA) system. The retention of hot residuals is used to enhance the mixture preparation and accelerate the occurrence of auto-ignition in high reactivity zones. Throttling is used to increase the global fuel/air equivalence ratio, which elevates mean in-cylinder gas temperatures during combustion and can help improving the conversion of the charge. One-dimensional (1D) computational fluid dynamics modelling was used to estimate the RGF and the in-cylinder gas temperature.

Initially, dual-fuel RCCI experiments and modelling were carried out at 0.32 MPa $IMEP_{net}$ and 1200 rpm. This test point represents an engine operating condition with high combustion losses, low exhaust gas temperatures, and possibly reduced aftertreatment efficiencies. After determining the optimum strategy, further experimental and numerical studies were performed on the same engine speed between 0.3 MPa $IMEP_{net}$ and 0.6 MPa $IMEP_{net}$. The later represents a high residency area in a modern HD engine cycle (i.e. World Harmonised Stationary Cycle). The proposed approach with iEGR was compared to the baseline dual-fuel combustion (e.g. without a 2IVO strategy) and conventional diesel combustion (CDC).

2. Experimental setup

2.1. Engine specifications and experimental facilities

All experiments were carried out on a single cylinder HD diesel engine coupled to an eddy current dynamometer. The main engine specifications are given in Table 1. Fig. 1 depicts the experimental