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Inter-cycle variability of ignition delay in an ethanol fumigated common rail diesel engine

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ABSTRACT

An experimental study has been performed to investigate the ignition delay of a modern heavy-duty common-rail diesel engine run with fumigated ethanol substitutions up to 40% on an energy basis. The ignition delay was determined through the use of statistical modelling in a Bayesian framework—this framework allows for the accurate determination of the start of combustion from single consecutive cycles and does not require any differentiation of the in-cylinder pressure signal. At full load the ignition delay has been shown to decrease with increasing ethanol substitutions and evidence of combustion with high ethanol substitutions prior to diesel injection have also been shown experimentally and by modelling. Whereas, at half load increasing ethanol substitutions have increased the ignition delay. A threshold absolute air to fuel ratio (mole basis) of above ~110 for consistent operation has been determined from the inter-cycle variability of the ignition delay, a result that agrees well with previous research of other in-cylinder parameters and further highlights the correlation between the air to fuel ratio and inter-cycle variability.

Numerical modelling to investigate the sensitivity of ethanol combustion has also been performed. It has been shown that ethanol combustion is sensitive to the initial air temperature around the feasible operating conditions of the engine. Moreover, a negative temperature coefficient region of approximately 900–1050 K (the approximate temperature at fuel injection) has been shown with for *n*-heptane and *n*-heptane/ethanol blends in the numerical modelling. A consequence of this is that the dominate effect influencing the ignition delay under increasing ethanol substitutions may rather be from an increase in chemical reactions and not from in-cylinder temperature. Further investigation revealed that the chemical reactions at low ethanol substitutions are different compared to the high (>20%) ethanol substitutions.

1. Introduction

In the mid-term to mitigate fossil fuel usage in diesel engines, the dual-fuel approach, particularly with ethanol, has been of research interest for decades [1–9]. This research area exists because of the serious need to move toward more sustainable fuels [10–13]. However, in the current literature there is very little experimental published research on dual-fuel operation of heavy-duty common-rail diesel engines, such as would be found in common practical applications [14].

Sahin et al. [15] have shown that the introduction of up to 8% fumigated ethanol (by vol.) has a negligible effect on the in-cylinder pressure parameters, as compared to neat diesel fuel. They have shown that increasing the ethanol above this percentage causes significant changes to the heat release diagram. In their setup, increasing substitutions of ethanol cause the heat release diagram to have more pre-mixed combustion, shown by an increasing peak slightly before TDC (top dead centre). A significant change in the heat released was also shown by Sarjovaara et al. [16]. At half fuel delivery rate, Sahin et al. [15] showed that ethanol fumigation did not significantly improve the performance enough to warrant the additional running costs. An improvement in NO_x emission was shown for all loads using fumigated ethanol. Improved NO_x in dual-fuel engines, using ethanol, is well supported by the current literature [4,8,15,17,18].

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Terminology and abbreviations

DXXXEYYY	DXXXEYYY represents the nominal XXX% of diesel fuel by energy and the nominal YYY% substitution of ethanol by energy
Neat diesel	neat diesel refers to the case where the engine is run on automotive diesel fuel only, no ethanol substitution
EMS	engine management system
Kernel density estimate	an estimation of the probability density function
TDC	top dead centre (0 and 360 crank-angle degrees)
COV	coefficient of variation – standard deviation normalised by the mean

Ignition delay is an important parameter in alternative fuel studies owing to its correlation to emission [5,8,19]. At constant injection timing, an increase in ignition delay is an indicator of a lower temperature throughout the cycle, causing a reduced CO oxidation reaction rate [8]. Moreover, a longer ignition delay can aid mixing prior to combustion, improving NO_X and smoke emission [19]. Whilst some studies have highlighted the importance of investigating ignition delay, there has been limited investigation on the inter-cycle variability of ignition delay, with the notable exception of the engine research group at the National Technical University of Athens [20,22], and limited investigation into new techniques to improve the accuracy of its calculation [23].

The engine research group at the National Technical University of Athens have investigated numerous alternative fuels, including: methane, methanol and dodecane [24] and ethanol [20]. They have also investigated using supplementary diesel and gasoline as a fumigated fuel [27,28]. However, this work was all performed on a low power naturally aspirated single-cylinder engine (in their investigation high load corresponds to a BMEP (brake mean effective pressure) of 5.37 bar. It should be noted that alternative fuel research at the National Technical University of Athens has not been limited to the single-cylinder engine, but has also been performed on a heavy-duty, turbo-charged, direct injection six-cylinder engine [29].

Modern common-rail engines tend to have later injection than their predecessors. Subsequently, this later injection has an effect on the performance and emission output of the engine. In dual-fuel operation with ethanol late injection has a significant effect on the inter-cycle variability [14]. The current literature, which is focused on pump-line-nozzle injection systems, suggests that fumigated ethanol causes longer ignition delays owing to the higher specific heat capacity of ethanol, when compared to the air charge without ethanol [14]. The so-called ‘cooling effect’ of ethanol. Moreover, the significantly higher injection pressure, with common-rail engines, enhances the atomisation and fuel penetration [30]; hence, higher injection pressures cause more homogeneous combustion and reduced ignition delay times.

Rothamer and Murphy [31] compared the six commonly used in-cylinder pressure methods of determining ignition delay in a recent study. The six methods compared were:

1. location of 50% of pressure rise due to premixed burn combustion;
2. extrapolation of the peak slope of pressure rise due to combustion to the zero crossing point;
3. location of the first peak of the second derivative of the pressure signal;
4. location of the first peak of the third derivative of the pressure signal;
5. location of 10% of the maximum heat release rate in the premixed burn; and,
6. a repeat of (5) using a low-pass (threshold 2000 Hz) filtered in-cylinder pressure signal.

All of the methods tested by Rothamer and Murphy [31] required differentiation, which has the effect of decreasing the signal-to-noise ratio. Of note in this study is that the methods which showed the greatest reliability were also the ones that required the least amount of differentiation. The method employed in this paper [23] requires no differentiation and therefore does not suffer from the effects of the decreased signal-to-noise ratio.

Rodriguez et al. [32] found that the inter-cycle variation in ignition delay of their engine, run with biodiesels derived from palm oil and rapeseed oil, was as great as 2.2%. However, the representative values reported in their work were based on the analysis of the average of 50 consecutive in-cylinder pressure cycles. This value is similar to that reported by Assanis et al. [33], who found an inter-cycle variation of 2%. Rodriguez et al. also argue that in-cylinder pressure analysis for the determination of ignition delay is preferable to other methods, particularly those utilising luminosity detectors, as in-cylinder pressure changes are often detectable prior to other indicators of combustion [32,34].

A promising method for determining the start of combustion is with the use of vibration or acoustic emission signals [35–37]. Even in constant volume bombs there is good agreement between the sudden increase in pressure and the mechanical vibration [38]. The technique for determining the start of combustion with a vibration signal is to simply identify the sharp onset of the mechanical vibration. In a practical application, the use of an accelerometer is a cheap alternative to the more expensive in-cylinder pressure transducer. However, the engine setup under investigation in this current work has an in-cylinder pressure transducer, details in Section 3; therefore, the use of vibration signals has not been explored. Carlucci et al. [37] have explained that the high-pass filtered in-cylinder pressure signal is analogous to the vibration signal—the start of combustion results shown in this work are determined through the use of high-pass filtered in-cylinder pressure signals and are therefore assumed to match those that could have been obtained with vibration signals.

Recent work by Bodisco et al. [14,23] has shown the use of high-pass filtered in-cylinder pressure signals as a means for determining the start of combustion in a heavy-duty diesel engine. The current work will explore the statistical modelling technique employed in Ref. [23] to investigate the inter-cycle variability of the start of combustion, and hence ignition delay, in a heavy-duty Cummins common-rail multi-cylinder diesel engine operated with fumigated ethanol up to 40% by energy. In the earlier work [14], it was shown that at high ethanol substitutions and high loads, hence at high in-cylinder temperatures, that the fumigated ethanol undergoes auto-ignition and can reduce ignition delay. However, that study was limited to 200 consecutive cycles owing to the analysis tool used.

The conclusion to the ignition delay study in the full load portion of Ref. [14] was left uncertain. Shown was that the nominal ignition delay for the 40% ethanol substitution was longer than that of the 30% substitution—going against the trend showing a decrease in ignition delay with increasing ethanol substitutions. However, it was not known if this result was true or an artifact of the low number of cycles analysed. The limited number of analysed cycles also prohibited an investigation into the relationship between the inter-cycle variability and the air to fuel ratio. Moreover, although it was suspected, it was not conclusively shown if auto-ignition occurred prior to diesel injection at the high ethanol substitutions.