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Ethanol utilisation in a diesel engine using dual-fuelling technology

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HIGHLIGHTS

- Premixed combustion of ethanol increases power output and reduces smoke emissions.
- No change of combustion phasing with ethanol fraction but diesel injection timing.
- Advanced diesel injection increases the power and the maximum ethanol fraction.
- Increased HC, CO, and NO_x but negligible smoke emissions were observed at tested conditions of this study.

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ABSTRACT

Renewable feedstocks and high octane rating make ethanol a promising alternative fuel. In contrast to the conventional approach of applying ethanol-gasoline blends in spark-ignition engines, this study investigates the potential of ethanol fuelling in a diesel engine to achieve higher efficiency. Experiments are performed using a single-cylinder version of a common-rail diesel engine that is widely used in passenger cars. A dual-fuelling technology is implemented such that ethanol is introduced into the intake manifold using a port-fuel injector while diesel is injected directly into the cylinder. The main focus is the effect of ethanol energy fraction and diesel injection timing on engine efficiency and tailpipe emissions. While these two parameters are varied, in-cylinder pressure measurement and subsequent analysis of indicated mean effective pressure, apparent heat release rate, ignition delay, combustion phasing, and burn duration are performed. From the ethanol energy variation tests at fixed diesel injection timing, it is found that increased ethanol energy fraction increases the engine efficiency until the operation is limited by misfiring associated with over-retarded combustion phasing. By energy fraction, up to 60% of diesel is replaced by ethanol, which achieves 10% efficiency gain compared with diesel-only operation. Detailed analysis of the results reveals that the decreased burn duration is the primary cause for the efficiency gain, i.e. the fast burning of ethanol improves the combustion. However, the burn duration appears to increase with advancing the diesel injection timing at a fixed ethanol energy ratio despite the fact that the highest indicated mean effective pressure of 1020 kPa is measured when the diesel injection timing is set at eight crank angle degrees before top dead centre, the most advanced diesel injection timing of this study. This is due to optimised combustion phasing such that the main heat release occurs near top dead centre, which outperforms the increased burn duration. Therefore, both burn duration and combustion phasing should be considered to explain trends in the indicated mean effective pressure or efficiency of dual-fuel combustion engines. The tailpipe emissions suggest that unburnt hydrocarbon, carbon monoxide and NO_x emissions increase with increasing ethanol fraction, which raises a question on the advantages of utilising ethanol in a diesel engine. However, negligible smoke emissions are measured at ethanol energy ratio of 20% or higher suggesting that optimisation of these emissions would be much easier compared with conventional diesel combustion.

1. Introduction

Ethanol is regarded as promising alternative to gasoline because of its compatibility with fuel injection systems in existing spark ignition (SI) engines [1–4]. Engine knocking is less problematic for ethanol due to its higher octane rating. Ethanol is produced from renewable feedstocks such as sugar cane, corn, starch, and

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algae, and therefore helps diversify the transportation fuel supply. As a result, ethanol has penetrated into the market and in some countries (e.g. Australia and USA) a blend of 10% ethanol and 90% gasoline (E10) is widely available. In Brazil, most new cars are capable of a selective utilisation of gasoline or neat ethanol (i.e. bi-fuel engine). Many fuel injector manufacturers produce E85-compatible models and car companies offer flex-fuel vehicles that auto-detect E85 and adjust the engine control.

However, the current approach, i.e. ethanol blended with gasoline and burned in conventional SI engines is not optimal for the following reasons: First, ethanol has a much higher resistance to knock, and can be burned in higher compression ratio engines resulting in higher efficiency; Second, to avoid phase separation, ethanol must not contain water [5], which costs a lot more to produce than ethanol containing small amounts of water; Third, ethanol has a high heat of vaporisation and a low vapour pressure compared to gasoline [6], leading to poor vaporisation and hence ignition problems especially during cold start [3]. These issues can be addressed by using ethanol in a dual-fuelling diesel engine where ethanol is delivered in the intake manifold and diesel is directly injected into the cylinder using two separate fuel injection systems [7–15]. The higher compression ratio of diesel engines offers efficiency advantages by exploiting knock resistance of ethanol. Also, hydrated ethanol can be directly used in diesel engines without any blending and hence water in ethanol would not be an issue. During the warm-up period, diesel-only combustion can be used to avoid the cold-start issue. In addition, ethanol is an oxygenated fuel and is likely to burn in a lean premixed mode, therefore helping to reduce harmful soot emissions that are problematic in conventional diesel engines [16].

Ethanol-only combustion in a diesel engine has great potential to achieve high-efficiency low-emissions combustion regimes such as homogenous-charge compression-ignition (HCCI) and stratified-charge compression-ignition (SCCI) [17–19]. A drawback of these combustion regimes is a limited operation range due to an excessive pressure rise rate at high-load conditions and poor combustion efficiency at low-load conditions [20,21]. More importantly, the start of combustion does not rely either on injection timing as in diesel engines or on spark timing as in SI engines but instead relies on chemical reaction rates that are highly sensitive to temperature and mixture fluctuations and hence hard to control. In a dual-fuelling engine, combustion of a premixed ethanol–air mixture starts with the in-cylinder injection of diesel (as will be demonstrated later) and therefore diesel injection timing controls the combustion phasing. Accordingly, dual-fuelling of ethanol and diesel is a practical solution to utilise ethanol in a diesel engine.

The dual-fuelling technology was first developed to utilise natural gas in diesel engines [22–25] due to increasing availability of natural gas. These studies report that dual-fuel combustion of premixed natural gas and mixing-limited diesel has advantages of increased efficiency and decreased smoke and nitrogen oxides (NO_x) emissions. One might expect similar advantages for the dual-fuel combustion of ethanol and diesel. Indeed, many have studied the dual-fuelling of ethanol and diesel in various engines [7–15]. It is interesting to note that the studies deliver mixed conclusions on the maximum ethanol fraction for successful engine operation. For example, some report the engine cannot run at over 15–20% ethanol fraction [7–9] due to engine knocking. It may be presumed that the increased premixed combustion associated with increased ethanol fraction caused a drastic rise of in-cylinder pressure. By contrast, others claim ethanol fractions of 60% or higher [10–12,14,15] are achievable. It was explained that the combustion phasing becomes over retarded with increasing ethanol fraction [8], which results in decreased peak cylinder pressure; however, the combustion phasing can be moved forward by advancing diesel injection timing and achieve up to 97% ethanol fraction [14]. It may be understood that both the increased rate of the pressure rise and retarded combustion phasing need to be considered to determine the maximum ethanol fraction. However, no detailed discussions are found in the literature in this context.

Engine-out emissions have been main discussion points in the previous studies and there is a consensus that the unburnt hydrocarbon (HC) and carbon monoxide (CO) emissions increase [7–9] or the combustion efficiency decreases [14] with increasing ethanol fraction. It was explained that some ethanol is trapped inside the crevice resulting in increased HC emissions [7]. Almost all studies report benefits of ethanol substituting diesel in reducing smoke emissions [7–15] because ethanol is oxygenated fuel and the ethanol–air charge is well mixed. The trends in NO_x emissions however are mixed. For instance, NO_x emissions decrease with increasing ethanol fraction when it is limited at 20% (or lower) [7–9] or the combustion phasing is retarded [10,11,14]. However, when a wide range of diesel injection timings are tested, the NO_x emission is found to increase with increasing ethanol fraction [13]. This trend relates to the increased peak heat release rate for advanced diesel injection timings, which leads to higher maximum temperatures and thus increased thermal NO formation.

Not only are the conclusions for the maximum ethanol fraction and NO_x emissions mixed but also an important question on the engine efficiency remains unanswered in the literature. In a dual-fuelling scenario, the fuel conversion efficiency of the engine can either be increased or decreased relative to a diesel-only baseline. Assuming relatively good combustion efficiency and roughly the same heat loss in both scenarios, this mainly depends on the timing (i.e. combustion phasing [13–15]) and duration of the combustion event. Timing is controlled by diesel injection but duration depends on the prevailing combustion mode and may be shorter or longer than diesel-only burn duration. Previous studies suggest that the dual-fuel combustion is initiated due to the heat generated from the diesel combustion that is transferred to the surrounding ethanol–air mixture [26,27]. It is also believed that the following main combustion can be driven either by turbulent flame propagation or by sequential auto-ignition depending on the equivalence ratio. If the diesel injection duration is long (i.e. low ethanol fraction), the overall combustion is largely driven by the mixing-controlled combustion of diesel [28]. In this study, we investigate the details of variations in the engine efficiency and tailpipe emissions for various ethanol energy fractions to better understand the dual-fuelling technology of ethanol and diesel. The dual-fuelling experiments were performed in a single-cylinder automotive-size diesel engine. Ethanol was supplied into the intake port using a conventional port-fuel injector (PFI) and the diesel direct-injection was conducted using a common-rail injection system. In-cylinder pressure and engine-out emissions of smoke, NO_x, HC and CO were measured for various ethanol energy fractions at a fixed total energy of ethanol and diesel per engine cycle. In-cylinder pressure traces were further analysed to determine the heat release rates, ignition delay, combustion phasing, and burn duration that explain the causes of observed trends in the efficiency and emissions.

2. Experiments

Experiments were conducted in a single-cylinder automotive-size, naturally-aspirated diesel engine. The engine specifications are listed in Table 1 and experimental setup is shown as a schematic in Fig. 1. Since a single-cylinder engine was used, pressure fluctuations in the intake and exhaust pipes were identified as a potential issue. To minimise them, large-volume (60 times the displacement volume of the engine) surge tanks were placed in both intake and exhaust sides. The engine has 83 mm bore and 92 mm