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The effect of diethyl ether addition on performance and emission of a reactivity controlled compression ignition engine fueled with ethanol and diesel

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ABSTRACT

Reactivity controlled compression ignition has been introduced to implement controllable, clean, and high thermal efficiency without undermining the advantages of premixed combustion. However, simultaneous auto-ignition introduced by reactivity controlled combustion challenges the combustion under higher load operations. This experimental study incorporates a dual phase heat release concept with the purpose of improving the performance of reactivity controlled compression ignition engine. Different ratios of ethanol/diethyl-ether blends (from 0% to 40% diethyl ether and 70% premixed ratio) were applied to a light duty diesel engine at various combustion timings and engine loads. The diesel fuel was directly injected into the combustion chamber while ethanol/diethyl-ether blends were injected in the intake port. Engine performance and exhaust emissions were compared between the baseline operation and high blend ratios. An addition of 40% diethyl ether in the ethanol approximately resulted in 14% increase of the indicated mean effective pressure and 33% reduction in maximum pressure rise rate. The high reactivity of diethyl ether enhanced the oxidation of the hydrocarbons and resulted in lower hydrocarbon emissions. The higher volatility and better overall fuel-air mixing improved the combustion and reduced particle emission. Stable combustion was expanded at high load operating conditions due to double-stage heat release enhancement.

1. Introduction

The majority of the research into internal combustion engines are intended to resolve the emission of pollution and improve fuel conversion efficiency [1]. Diesel engines are well-established power trains for several applications due to their better fuel economy and higher torque capacities [2]. However, a conventional diesel engine produces a high rate of NOx and particulate matter (PM) emissions due to its rich mixture, heterogeneous combustion and lengthy diffusion combustion phase [3]. At present, a diesel particulate filter (DPF), selective catalytic reduction (SCR), and a lean NOx-trap (LNT) have been applied in many diesel vehicles to meet standard emission limits [4]. However, these after-treatment systems have led to an increase in the production cost of the vehicles. As a result, the clean combustion concept of low NOx and PM emissions needs to be further refined [5].

Homogeneous charge compression ignition (HCCI) engines are recognized as a combustion strategy in which features of both conventional compression ignition engines (CI) and spark ignition engines (SI) exist [6]. No throttling lost and a homogeneous premixed charge leads to high thermal efficiency, low NOx, and low PM emissions [7]. HCCI combustion is controlled by chemical kinetics so the lack of combustion phasing control and hydrocarbon emission are the main drawbacks of this type of combustion strategy [8].

To implement controllable, clean, and high thermal efficiency, number of improvements in the premixed combustion phase of CI engine have been introduced [9]. The leading portion of NOx and PM emissions emerges from the diffusion combustion stage [10]. Low temperature combustion (LTC) is achieved in diesel engines by advanced diesel fuel injection and high exhaust gas recirculation (EGR) rates [11]. The limited operating range of LTC concepts challenges the emission reduction results as being against conventional diesel combustion [12]. Enhancement of engine speed and engine load restricts the premixing time of the diesel fuel and air. As a result, the cylinder pressure rise rate (PRR) limits the load range of the partially premixed

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Nomenclature

AHRR	Apparent Heat Release Rate
CA	Crank Angle
CA50	Crank Angle At 50% Mass Fraction Burned
CI	Conventional Compression Ignition
DEE	Diethyl Ether
DI	Direct Injection
DICI	Direct Injection Compression Ignition
DPF	Diesel Particulate Filter
DP-HTHR	Dual Phase High Temperature Heat Release
HC	Unburned Hydrocarbon
HCCI	Homogeneously Charged Compression Ignition
IMEP	Indicated Mean Effective Pressure
IVC	Inlet Valve Close
LTC	Low Temperature Combustion
LTHR	Low Temperature Heat Release
MPRR	Maximum Pressure Rise Rate
PCCI	Partially Premixed Combustion
PFE	Premixed Fuel Energy Fraction (premixed ratio)
PM	Particulate Matter
PN	Particle Number
RCCI	Reactivity Controlled Compression Ignition
SCR	Selective Catalytic Reduction
SOI	Start Of Injection

combustion (PCCI) due to advanced injection of diesel fuel [13].

To avoid narrow load range and to gain better combustion phasing control, reactivity controlled compression ignition (RCCI) has been introduced as a representative of LTC combustion [14]. RCCI combustion is achieved by supplying low reactivity port fuel such as natural gas and gasoline as the major portion – by the energy- of the cylinder mixture with an early diesel injection as the pilot injection and combustion initiator. In this concept, a major portion of the port fuel is premixed and the homogeneous condition of the cylinder charge is improved [15]. RCCI combustion is considered as the hybrid of a premixed HCCI engine and a conventional diesel engine [16]. Optimized combustion phasing, various gradients of reactivity is obtained by adjusting the injection timing, the quantities and reactivity of fuels and the EGR fraction [17]. Simultaneous auto-ignition concept introduced by RCCI combustion will raise the maximum in-cylinder PRR and will limit the combustion under higher load operations [18].

Dual phase high temperature heat release (DP-HTHR) inflects the combustion process because it reduces the maximum pressure rise rate (MPRR) and extend the combustion operational range to improve load conditions [19]. HTHR in two different stages was investigated by Iijima and his coworkers [20]. Their experimental results revealed that premixed fuel blends such as DME with methane under controlled conditions will produce a 2-stage HTHR, which will eventually moderate combustion [20]. Fuel inhomogeneity and the concentration distribution was studied by Ikeda and his coworkers [21]. They investigated the equivalence ratio for controllability of the interval and height of the heat release peaks. The results showed that fuel inhomogeneity in an actual engine combustion chamber results in HTHR at two different stages. The key point to achieve DP-HTHR combustion and modulate the inflection point of heat release lies in the difference in ignitability and reactivity of the blended hydrocarbons [19]. Sufficient mixing ratio and a certain temperature of the mixture governs the mixture formation process and will promote pre-combustion and chemical reactions, respectively [22]. Diethyl ether (DEE) as an oxygenated fuel has the potential to be used as the high reactive part of the ternary mixture to achieve HTHR in the two split phases [17]. The physical and chemical properties of DEE such as lower ignition temperature have been investigated by Ikeda and his colleagues [21]. It has been observed that a much longer magnitude of ignition delay is associated with DEE/diesel than the corresponding pure diesel fuel. Lower kinematic viscosity, density, and the bulk modulus of DEE compared to diesel may lead to it retarding the dynamic injection duration so as to influence the combustion process [23]. These observations are in agreement with many other researchers [24,25]. The higher cetane number of DEE implies that ignition enhancement and heat release rate improvement are able to be achieved in fuel blends, particularly at richer mixtures of the cylinder charge [26]. Moreover, supplementary oxygen and hydrocarbon molecules can collide repeatedly for earlier combustion phasing.

The higher octane number and higher ignition temperature of ethanol, principally in leaner mixtures, restrains earlier igniting of the fuel blends [27] and can be considered to be the low reactive part of the mixture used to attain RCCI with inflection of heat release. Ethanol is an oxygenated (34.8% by weight) fuel and is capable of moderating particulate emissions in conventional CI engines. It has the potential to be a replacement for conventional fuel in SI engines owing to its high ignition resistance quality. However, the low cetane quality of ethanol is a hindrance when using it as a substitute for diesel in CI engines applications [28].

RCCI combustion demonstrates acceptable control of combustion phasing without undermining the advantages of HCCI combustion. However, high load operation is a combustion challenge needs to overcome. Apart from introduced strategy for RCCI high load condition, comparative investigation on the effects of partial replacement of low reactive fuel by DEE to initiate inflection of HTHR is unnoticeable. Hence, in the present study the authors have considered the operation of RCCI combustion by the ternary oxygenated blends and resultant DP-HTHR. With this prime focus, the existing study's objective is to incorporate the DP-HTHR concept in order to improve the performance of RCCI operation and higher load condition. DEE as an oxygenated fuel has the potential to be used as the high reactive component of a premixed fuel to achieve a two-phase HTHR. Different ratios of ethanol/diethyl-ether blends (from 0% to 40% DEE and 70% premixed ratio) were applied to a light duty diesel engine at various combustion timings and engine loads. The diesel fuel was directly injected into the combustion chamber while ethanol/DEE blends were injected in the intake port. The variable lambda and conserved charge energy (at port energy fraction of 70%) as two different test procedure were implemented. Also, the effect of premixed ratio on combustion and exhaust emissions of DEE20 fuel is investigated.

2. Experimental setup

Several series of experiments were performed on a single-cylinder diesel engine. The detailed description of this water cooled, naturally aspirated, direct injection diesel engine is given in Table 1. The intake and the exhaust port of this engine were redesigned to integrate an EGR valve, a back pressure regulator, and controllers of inlet air pressure and temperature. The intake air facilities were customized to deliver

Table 1
Technical specification of test engine.

Engine name	FARYMANN 18W
Engine type	Single cylinder, four stroke, water cooled
Bore (mm)	82
Stroke (mm)	55
Connecting rod length (mm)	95.55
Compression ratio	16.5
Displacement volume (cc)	290
IVC (°ATDC)	−150