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Effects of exhaust gas recirculation at various loads on diesel engine performance and exhaust particle size distribution using four blends with a research octane number of 70 and diesel

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ABSTRACT

Partially premixed combustion using gasoline-like fuels on compression ignition engines shows great potentials to break the soot-nitrogen oxides trade off and reduce both emissions simultaneously. By simply adjusting the dilution strategies and injection events, the control of partially premixed combustion is relatively easier compared to other low-temperature combustion concepts. However despite these advantages, recent research shows this concept tends to emit ultra-fine particles. Most previous work on partially premixed combustion only focuses on the soot emissions while the particulate matter in terms of number concentration and size distribution are not well investigated. Ultra-fine particles are dangerous to human health and are getting increasing attentions. Thus the detailed particulate matter emission from partially premixed combustion needs to be further investigated. In this work four gasoline-like ternary fuel blends are designed and experimentally tested under partially premixed combustion. The test blends all share the same two base fuels and blended with different additives. The fuel composition is varied to have the same research octane number. Tests are conducted under different engine loads and dilution strategies since the temperature and oxygen concentration are the key factors in the formation and oxidation of soot. Standard diesel is also tested under the same conditions as a comparison. It is found that these blends are capable of running under partially premixed combustion at low and medium loads and they produce near zero soot emissions when using high exhaust gas recirculation rate. However, these blends do emit smaller particles than diesel under all test loads. Besides, blends with oxygen content yield less soot emissions and smaller particles compared to non-oxygen blends.

1. Introduction

Heavy-duty (HD) diesel engines are vital to the modern society due to their high torque capability, reliability, as well as good fuel economy. However, conventional diesel engines suffer from high nitrogen oxides (NOx) and soot emissions due to a wide range of local in-cylinder equivalence ratios and temperatures [1]. These emissions cannot meet the strict emission standards if not controlled by exhaust after-treatment technologies. However, after-treatments often require maintenance and decrease fuel economy. Many advanced in-cylinder measures have been proposed and investigated, including new combustion concepts such as homogenous charge compression ignition (HCCI), reactivity controlled compression ignition (RCCI), and partially premixed charge compression ignition (PPC). The latter two often combined with high exhaust gas recirculation (EGR) rates. The significant advantages of these low-temperature combustion (LTC) strategies are low NOx, soot emissions and high efficiency.

Onishi et al. [2] proposed a combustion concept "Active Thermo-Atmosphere Combustion" (ATAC) in 1979, which differs from conventional gasoline and diesel combustion processes. With ATAC the fuel consumption and exhaust emissions of two-stoke cycle spark-ignition engines are remarkably improved, and there is the possibility of employing this combustion process in other types of engines. Najt and Foster [3] showed an initial investigation of HCCI in 1983, their research concentrates on producing an overall understanding of the basic mechanisms involved in HCCI combustion. After several decades of research on HCCI, the lack of efficient control of combustion process particularly under transient conditions and vary narrow running range are still its major draw-

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Nomenclature

AD	aerodynamic diameter
ATDC	after top dead centre
ATAC	active thermo-atmosphere combustion
BTDC	before top dead centre
CR	compression ratio
CN	cetane number
CAD	crank angle degree
CA10	crank angle where 10% of the heat has been released
CA50	crank angle where 50% of the heat has been released
CO	carbon monoxide
EGR	exhaust gas recirculation
EEPS	engine exhaust particle sizer
FSN	filter smoke number
HD	heavy duty
HC	hydrocarbons
HCCI	homogeneous charge compression ignition
ID	ignition delay
IMEP	indicated mean effective pressure
IMEPg	gross indicated mean effective pressure
LTC	low-temperature combustion
LHV	lower heating value
MON	motor octane number
NOx	nitrogen oxides
PF	premixed fraction
PPC	partially premixed charge compression ignition
RCCI	reactivity controlled compression ignition
RON	research octane number
SOI	start of injection
SMPS	scanning mobility particle sizer

backs. Unlike HCCI and PPC engines which only use a single fuel, RCCI is a dual-fuel principle [4] that uses direct injection of high-reactivity fuels to trigger the ignition and combustion of low-reactivity fuels typically supplied through a port-fuel injection system. Reitz et al. [5] have done many research on RCCI. RCCI provides more efficient control over the combustion process and is able to increase fuel economy and reduce pollutant emissions. The difference with a conventional dual fuel engine is the early timings of the direct injection event. PPC uses a single fuel and it effectively correlates the ignition timing with injection timing to make a good control of combustion process [6]. Zhang et al. [7] indicated that PPC consists of a two-stage combustion process: in the first stage the stratified fuel/air mixture auto-ignites, which leads to partial oxidation of fuel in the fuel-rich zone and a mixture of radicals and hot products in the fuel-lean region. In the second stage the partially oxidized fuel/air mixture is further oxidized in a thin diffusion flame where the diffusion and chemical reaction both play an important role. According to the experimental research from Lund University [8] on a Scania D12 HD engine with a compression ratio (CR) of 12.4, diesel PPC can produce low NOx and soot emissions simultaneously at 8 bar indicated mean effective pressure (IMEP) if more than 70% EGR is applied. Unfortunately the high EGR level and low CR resulted in a combustion efficiency below 90%. Kalghatigi introduced the concept of gasoline PPC in 2006 [9], inspired by the fact that a longer ignition delay can be achieved with a fuel that is harder to ignite even without using high EGR rates, too early injection timings or too low compression ratios. Fuels with a research octane number (RON) of 70 are identified to be close to optimal for PPC [10].

In our previous work [11], blends with a RON of 70 were experimentally investigated using an injector which has 7 holes of 207 μm and its spray cone angle is 150°. The results showed that the three blends are capable of running under PPC mode when IMEP is below 8 bar. When the IMEP continues to increase, the three blends start to present short ignition delay and produce high soot emissions (1–3 Filter Smoke Number (FSN)) due to the reduced premixedness. The effect of dilution strategies on soot emissions using blends of RON 70 under PPC mode was also investigated [12]. Previous research [11–13] only focused on soot emissions in g/kW h or in FSN. However, recent studies correlate fine particulates and ultra-fine particulates to adverse human health effects [14]. The porous particulate agglomerations could deposit in the deep lung and cause diseases like asthma, pneumonectasis and nasopharyngeal darcinoma [15] and [16]. PPC mode may contribute to more fine and ultra-fine particles. Load, dilution and fuels can be the major influences. Therefore, it is necessary to acquire knowledge about the particulate matter in terms of number concentration and size distribution when using blends of RON 70.

In this study, four blends with a RON of 70 have been designed. The first blend only consists of *n*-heptane ($CH_3(CH_2)_5CH_3$) and *iso*-octane ($(CH_3)_3CCH_2CH(CH_3)_2$) and is denoted as PRF. The other three blends use *n*-heptane and *iso*-octane as base fuels and blended with ethanol (CH_3CH_2OH) or *n*-butanol ($CH_3(CH_2)_3OH$) or toluene ($C_6H_5CH_3$) separately. They are denoted as ERF, BRF and TRF, respectively. The fuel composition is varied to have the same RON of 70. The limited number of components makes that the fuels can be handled in numerical simulations, in addition, the chemical and spectral purity makes them suitable for use in optically accessible engines as well. Moreover, given this desired reactivity, the influence of fuel structure and oxygen content on particulate emissions can also be investigated. Diesel is also tested under the same experimental conditions for reference. A latest type of injector which matches the bowl shape better is used to optimize combustion and extend the upper load range of PPC. Moreover, the combustion characteristics and particulate emission characteristics including particle number concentration and size distribution using the fuels with a RON of 70 are also investigated. The effects of EGR on combustion parameters and particulate emissions are discussed as well.

2. Experimental details

In this section, firstly the test setup including engine and emission testing equipment are introduced. Secondly, how to design the test blends are talked about and their properties are given. Thirdly, related parameters used in this paper are defined. Lastly, the experiment conditions are discussed.

2.1. Test setup

Experiments were conducted on a modified 12.6 L in-line six cylinder DAF XE355c engine. Cylinder 1 with a CR of 15.7 was isolated as a test cylinder, configuration is depicted in Fig. 1. The high pressure fuel system is composed of a Resato high pressure pump and a pressure regulator. Intake pressure is provided by the air compressor and up to 5 bar can be achieved. Exhaust pressure is also adjustable to ensure sufficient EGR rate, and it was set to 0.3 bar higher than intake pressure during the experiments. A heater was used to heat up the intake charge to a desired temperature.

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