ARTICLE IN PRESS

Fuel xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Fuel suitability for low temperature combustion in compression ignition engines

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HIGHLIGHTS

- ▶ Low temperature combustion enabling with diesel, gasoline, butanol and ethanol.
- ▶ Advanced control of fuel and air management in accordance to fuel properties.
- ▶ Clean combustion results with selected fuels for engine loads up to 1.65 MPa IMEP.
- ▶ High pressure direct injection of butanol shows promising potential of enabling LTC.
- ▶ The low reactivity fuel, such as ethanol, is suitable for high load LTC operations.

ARTICLE INFO

Article history:
Received 15 December 2012
Received in revised form 17 January 2013
Accepted 27 January 2013
Available online 11 February 2013

Keywords:
Fuel types
Low temperature combustion
Diesel engine

ABSTRACT

The high load operations under low temperature combustion (LTC) strategies are investigated by using diesel, gasoline, n-butanol and ethanol, on the high compression ratio engines. In order to best suit the LTC operations, the fuel delivery strategies are designed in commensurate with fuel properties, for either a single fuel or the dual fuel uses. Engine tests are conducted at load levels of 0.8–1.2 MPa of indicated mean effective pressure (IMEP) to study the impact of fuel dispatching ratios, exhaust gas recirculation rates, and intake boost levels, along with the modulation of the diesel injection events. As the baseline tests the single shot diesel injection is firstly investigated under different levels of the boost and injection pressure. The knowledge of the auto-ignition characteristics of the port fuelling is studied with gasoline and applied accordingly to other fuels.

The test results indicate that a volatile fuel, when delivered at an intake port, provides an advantage to enable LTC, i.e. suitable to produce a higher homogeneity for the cylinder charge. However, under a high compression ratio, a great deal of efforts is required for a port-dispersed fuel, such as gasoline or n-butanol, to withhold from the premature auto-ignition. The uncontrolled combustion events typically limit the engine load and worsen the soot and nitrogen oxides (NOx) emissions; whereas a lesser reactive fuel i.e. ethanol is preferred for the combustion control at high engine loads. The use of neat ethanol as a main energy supply along with the diesel fuel demonstrates superior performance of efficient combustion; whereupon under an optimized control, ultralow NOx and soot emissions are achieved for an engine load up to 1.7 MPa IMEP. When applied with a high-pressure direct injection strategy, an uncommonly tested fuel n-butanol is found more suitable to enable LTC than the diesel fuel.

1. Introduction

Empirical studies indicate that the low temperature combustion (LTC) is capable of producing simultaneously low nitrogen oxides (NOx) and dry soot emissions [1–3]. When enabled in conventional diesel engines, the LTC is growingly recognized as a viable clean combustion strategy that offers the diesel-like cycle efficiency, by taking advantage of the high compression ratio, and reduces the reliance on the exhaust gas after-treatments. However, due to the low volatility and high reactivity of the conventional diesel fuels, the efficient combustion of a highly homogenous cylinder charge is normally limited to low engine loads.

Extensive empirical work has been performed during the past decade, over the world and in the authors' labs, to study the diesel low temperature combustion, but most engine tests are performed in a very limited load range, as compared to that of the advanced modern engine practices. Fig. 1 shows that the high load prospects of a selection of typical modern gasoline and diesel engines from the unidentified manufacturers (represented by the markers) are much higher than what the majority diesel LTC research usually

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.01.049

Nomenclature

CA	crank angle	LTC	low temperature combustion
CA5	crank angle of 5% total heat release	NDIR	non-dispersive infrared detector
CA50	crank angle of 50% total heat release	NOx	nitrogen oxides
CO	carbon monoxide	PCCI	premixed charge compression ignition
CR	compression ratio	PF	port fuelling
DI	direct injection	ppm	parts per million
DS	double-shot	P_{inj}	pressure of injection
EGR	exhaust gas recirculation	P_{int}	pressure of intake
FPGA	field programmable gate array	PRRmax	maximum pressure rise rate
FTIR	Fourier transform infrared spectroscopy	RCCI	reactivity controlled compression ignition
THC	total hydrocarbons	SOI	start of injection
HCCI	homogeneous charge compression ignition	SOC	start of combustion
HCLD	heated chemiluminescence detector	SS	single-shot
HFID	heated flame ionization detector	TDC	top dead centre
HRR	heat release rate	TS	triple-shot
IMEP	indicated mean effective pressure		

offers (approximately symbolized by the light grey area). The figure is made to emphasize the inadequacy of the prevailing status of LTC in diesel engines, including the extensive data publicized by our own laboratories. For illustrative purposes, the load range of diesel LTC normally covers only up to 25–30% of the full loads of the production diesel engines, which, though being valuable to the light-duty applications, is shy of the heavy-duty applications. In order to accommodate higher loads, the engine compression ratio and thus the expansion ratio for the prevalent engine designs needs to be substantially lowered, i.e. closer to those of the contemporary gasoline engines; consequently the engine energy efficiency is significantly reduced. The dark grey and meshed areas represent the recent work, where the low Cetane fuels and the dual fuel application have been employed along with the lowered compression ratios; whereupon the applicable engine loads of LTC cycles are increased significantly [4–7]. However, it is desirable to keep the high compression ratio feature, for higher cycle efficiency; whereas the engine load shall be extended by applying prudent LTC enabling techniques as revealed in this work, which is indicated by the black arrow in Fig. 1.

At high compression ratios, a major challenge of high load LTC is the lack of direct controls on the ignition timing and thus the combustion phasing. In order to lower the flame temperature, it is preferred to have a fuel/air mixture that is lean, diluted and nearly homogeneous. It is therefore particularly critical to establish a

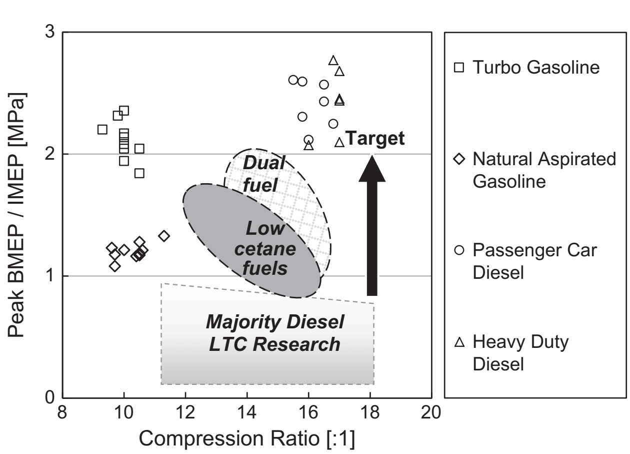

Fig. 1. Engine load prospects – the laboratory researches versus the engine product practices.

sufficient duration of ignition delay that, in favor to LTC, allows the fuel to properly mix with the intake charge. In the case of a homogeneous charge compression ignition (HCCI) engine, where the fuel is typically delivered at the early stage of the compression stroke, the start of combustion (SOC) is mainly determined by the compression temperature and the chemical reaction kinetics of the fuel/air mixture. High compression ratios lead to high compression temperature, thereby increasing the tendency of premature auto-ignition, especially when the fuelling rate is increased for higher loads [8]. The overall homogeneity often worsens as the fuel injection quantity increases. The incursion of an early event of main combustion, on high loads, often results in high peaks of the cylinder pressure and pressure rise rate (PRR) that, to the extremes, can cause serious engine damage [9,10]. An extensive use of exhaust gas recirculation (EGR) is necessary to withhold the cylinder charge from the premature auto-ignition, which requires a higher level of boost to compensate, and a higher degree of competence in engine control [11].

Another challenge of the high load LTC is the heavy dependence on the EGR usage. Under considerably high EGR rates, the diesel LTC can also be enabled with the single-shot injection, near the top dead center (TDC). The EGR application prolongs the ignition delay, enhances the fuel/air mixing, and subdues the formations of NOx and even dry soot. However, certain extremely high EGR rates, though achievable on the laboratory research platforms, may not be readily feasible on production engines. In addition, high levels of intake boost are required to compensate the oxygen amount at high EGR rates, and consequentially the cylinder pressure can peak beyond the engine limit, especially when approaching high loads. The empirical work at the authors' lab has shown the efficacy of the compression ratio, EGR, intake boost, injection pressure and injection scheduling on the diesel LTC enabling, and also suggested that the single-shot EGR enabled LTC was limited within narrow corridors of these control parameters [12,13].

Keeping the high compression ratios intact, it can be advantageous to change the diesel fuel properties or use different types of fuels for high load LTC operations. Although most regulation authorities over the world require a minimum, but sufficiently high, Cetane number of diesel fuels, the recent studies show that lower Cetane fuels that are lesser prone to auto-ignite can produce longer durations of ignition delay, thereby helping enable the LTC operations [14,15]. In addition, the high pressure direct injection of the high octane gasoline has been applied for partially premixed combustion and shown promising high load results, but invariably at lowered compression ratios [4,5,16]. In general, the lowering of