Fuel 129 (2014) 11–19

Contents lists available at ScienceDirect

Fuel

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

Combustion and emissions characteristics of Diesel and soybean biodiesel over wide ranges of intake pressure and oxygen concentration in a compression–ignition engine at a light-load condition

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HIGHLIGHTS

- Intake pressure effects were substantial on thermal efficiency.
- Oxygen concentration impacts on NOx and soot were significant.
- Biodiesel exhibited higher NOx than Diesel.
- Biodiesel exhibited much less soot than Diesel at low oxygen concentration.

ARTICLE INFO

Article history:
Received 6 September 2013
Received in revised form 7 March 2014
Accepted 12 March 2014
Available online 27 March 2014

Keywords:
Diesel
Biodiesel
Low temperature combustion
Intake pressure
Oxygen concentration

ABSTRACT

The objective of this study is to understand the effects of intake pressure and intake oxygen concentration on combustion and emissions of ultra-low sulfur diesel ("Diesel") and 100% soybean methylene ether biodiesel ("B100") and investigate on the low-temperature combustion (LTC) regime that has a potential to simultaneously reduce nitric oxides (NOx) and soot emissions. The present study is an experimental investigation with a 1-liter single-cylinder direct-injection diesel engine. Engine experiment was conducted under intake pressures and oxygen concentrations of 100–250 kPa absolute and 5–19% by volume (vol%), respectively.

Thermal efficiency and carbon monoxide (CO) contour maps revealed two distinctive regions divided at an intake oxygen level of 8 vol% (or an equivalence ratio of 0.85). In the oxygen-sufficient region intake pressure exhibited dominant impacts on combustion duration, stability, and thermal efficiency. The NOx–soot contour map clarifies the location and size of the "soot barrier" in Diesel, which was not observed in B100. B100 achieved simultaneous NOx and soot reduction to 0.2 g/kW h and 0.1 filter smoke number (FSN), respectively, at 150 kPa intake pressure with 11 vol% intake oxygen concentration. Corresponding thermal efficiency was approximately 43%. Increased intake pressure over 150 kPa lowered thermal efficiency at the maximum brake torque (MBT) timing. The apparent net heat release rate traces indicated that most heat release event occurred before top dead center (TDC) and burn duration was elongated when intake pressure was above 150 kPa.

1. Introduction

Diesel combustion has been studied in numerous aspects for decades. Among a variety of engine operating parameters intake pressure and exhaust gas recirculation (EGR) are considered as primary system variables responsible for combustion and emissions characteristics. The two variables are of particular significance in an effort to develop a combustion strategy that provides simultaneous NOx and soot reduction without fuel penalty for upcoming stringent emissions and efficiency standards. Since those two variables are inseparable and fixed at a given engine speed and load in stock engines, most studies on intake pressure and EGR effects were conducted with a single-cylinder engine equipped with a simulated intake system. LTC is one of the strong candidates that have a potential to meet the NOx, soot, and fuel economy targets [1–3]. A well-known downside of Diesel LTC is

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http://dx.doi.org/10.1016/j.fuel.2014.03.022
0016-2361/

Nomenclature

Diesel	ultra-low sulfur diesel
B100	100% soybean methylene ether
LTC	low-temperature combustion
NOx	nitric oxides
CO	carbon monoxide
FSN	filter smoke number
MBT	maximum brake torque
TDC	top dead center
EGR	exhaust gas recirculation
ISFC	indicated specific fuel consumption
NO	nitric monoxide
AC	alternating-current
Conrod	connecting rod
CRDI	common-rail direct-injection
CO_2	carbon dioxide
N_2	nitrogen
LFE	laminar flow element
CA	crank angle
LHV	lower heating value
SOIc	start of injection command
COV_{IMEP}	coefficient of variation in indicated mean effective pressure
CA05	timing of 5% heat release
CA50	timing of 50% heat release
BD0550	duration between CA05 and CA50
IP	indicated power
IMEP	indicated mean effective pressure
HC	hydrocarbon
PPC	partially premixed combustion
SOC	start of combustion
aTDC	after top dead center

that sufficient EGR levels for NOx reduction often lead to unstable combustion and combustion efficiency drop. Thus, a number of LTC studies have focused on the optimization of the combustion chamber, flow characteristics, and injection strategies [4–8]. Recently, biodiesel blending starts to be considered as a remedy to reduce the combustion deterioration under high EGR operations.

Intake pressure effects on Diesel combustion have been reported in a number of literatures. Boosting increases in-cylinder pressure as well as the in-cylinder mixture mass. Increased mass and lower specific heat ratio of the mixture of higher intake pressure lead to lower average combustion temperature and consequently to lower heat transfer loss. Increased in-cylinder pressure brings the mixture more ignition-friendly environment and thus improves combustion stability, which returns higher efficiency, if adequate combustion timing is obtained by a proper injection strategy. Added oxygen in the mixture improves the mixture quality contributing to soot reduction as well as an efficiency gain [9]. Naber and Siebers [10] reported that injections under higher ambient density resulted in shorter spray travel distance and greater dispersion angles due to higher air entrainment rate. As a result, higher intake pressure provides improved mixture quality. Sarangi et al. [11] reported the lowest gross indicated specific fuel consumption (ISFC) with 180 kPa intake pressure over 120 and 150 kPa cases. However, when intake pressure reaches a certain level, the in-cylinder mixture becomes over-lean and combustion event slows down, in other words, elongated burn duration. These two effects compromise the advantages of higher intake pressure and lead to increased CO and greater combustion phasing loss. Colban et al. [12] presented that 150 kPa intake pressure exhibited the highest indicated mean effective pressure (IMEP) at the MBT timing with the same injection command duration among three tested intake pressure conditions, namely, 100, 150, and 200 kPa.

Intake oxygen concentration impact on combustion and emissions of LTC is also substantial. Replacing oxygen with inert gases of CO_2 and N_2 results in decreased combustion temperature and elongated ignition delay leading to NOx reduction [9]. On the other hand, longer ignition delay deteriorates combustion stability with the consequence of increased uncertainty in start-of-combustion timing. Kook et al. [13] found that decreased oxygen concentration elongated burn duration and ignition delay subsequent to advanced optimal injection timings in terms of the fuel conversion efficiency. The fuel conversion efficiency was maximized at an intake oxygen level of 14 vol% resulting from interactions among combustion efficiency, work conversion efficiency, and heat losses. Colban et al. [12] observed the "soot bump" in a dilution-controlled LTC operation as in [10]. Although both reported that the soot bump located at higher EGR rate in higher intake pressure, only Colban et al. [12] found the soot bump reduction by increased boost. Naber and Siebers [10] also observed the similar soot response to intake pressure variation as in [12]. Intake pressure effects on NOx were rather differentiated among the three studies aforementioned. While Sarangi and Noehre et al. [11,14] reported increased NOx in higher intake pressure, Colban et al. [12] found otherwise. Injection timings were set for a fixed timing of 50% heat release (CA50) in [11,14], whereas injection timings were set at MBT in [12].

Several recent studies investigated on potentials of biodiesel-blended LTC operation under various intake conditions. Zhu et al. [15] observed substantial soot reduction with biodiesel-blended ethanol (biodiesel 80%), which eliminated the soot bump at the intake oxygen level around 10–12 vol%. No significant differences were shown in CO and HC, while NOx was clearly increased with biodiesel blending. One generally accepted mechanism is that soot reduction by the oxygenated fuel of biodiesel lowers radiative heat transfer, which leads to a mixture temperature increase. Mueller et al. [16] extensively investigated on the origin of the NOx increase with biodiesel blending. The six proposed hypotheses included (1) advanced injection timing by higher bulk modulus of biodiesel, (2) advanced combustion phasing by higher cetane number, (3) greater premixed burn by fuel oxygen, (4) different prompt nitric monoxide (NO) formation, (5) higher adiabatic flame temperature of biodiesel, and (6) reduced radiative heat transfer due to lower soot [16]. The study concluded that the NOx increase resulted from a number of coupled mechanisms interacting each other. Lešnik et al. [17] observed increased injection pressure and promoted rate-of-injection with biodiesel in both spray visualization experiment and computational simulation. As a result, biodiesel fuel injection exhibited longer spray penetration. It was noted that the experimental injection system was a mechanically-controlled injection system in [17].

Zhu et al. [18] explored the high-efficiency premixed LTC mode with Diesel, biodiesel, and biodiesel–ethanol fuels under a wide range of IMEP. When three criteria were applied, namely, NOx of 1 g/kg-fuel, smoke of 0.5 filter smoke number (FSN), and combustion efficiency of 96%, the experimental result proposed that biodiesel–ethanol blended fuel achieved the widest operating range of 0.35–0.85 MPa IMEP among the three fuels.