Fuel 109 (2013) 256–278

Contents lists available at SciVerse ScienceDirect

Fuel

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

Characterisation of flame development with ethanol, butanol, *iso*-octane, gasoline and methane in a direct-injection spark-ignition engine

P.G. Aleiferis [a,*], J. Serras-Pereira [a], D. Richardson [b]

[a] *Department of Mechanical Engineering, University College London, UK*
[b] *Jaguar Advanced Powertrain Engineering, Coventry, UK*

HIGHLIGHTS

- ▶ Flame growth was fastest for ethanol, followed by butanol, gasoline and iso-octane.
- ▶ Differences in visual contrast and luminosity between the flames of all fuels.
- ▶ Differences in the direction of flame motion between different fuels.

ARTICLE INFO

Article history:
Received 11 November 2012
Received in revised form 22 December 2012
Accepted 31 December 2012
Available online 25 January 2013

Keywords:
Ethanol
Butanol
iso-Octane
Methane
Combustion

ABSTRACT

Research into novel internal combustion engines requires consideration of the diversity in future fuels that may contain significant quantities of bio-components in an attempt to reduce CO_2 emissions from vehicles and contribute to energy sustainability. However, most biofuels have different chemical and physical properties to those of typical hydrocarbons; these can lead to different mechanisms of mixture preparation and combustion. The current paper presents results from an optical study of combustion in a direct-injection spark-ignition research engine with gasoline, *iso*-octane, ethanol and butanol fuels injected from a centrally located multi-hole injector. Methane was also employed by injecting it into the inlet plenum of the engine to provide a benchmark case for well-mixed 'homogeneous' charge preparation. Crank-angle resolved flame chemiluminescence images were acquired and post-processed for a series of consecutive cycles for each fuel, in order to calculate in-cylinder rates of flame growth and motion. In-cylinder pressure traces were used for heat release analysis and for comparison with the image-processing results. All tests were performed at 1500 RPM with 0.5 bar intake plenum pressure. Stoichiometric ($\phi = 1.0$) and lean ($\phi = 0.83$) conditions were considered. The combustion characteristics were analysed with respect to laminar and turbulent burning velocities obtained from combustion bombs in the literature and from traditional combustion diagrams in order to bring all data into the context of current theories and allow insights by making comparisons were appropriate.

1. Introduction

1.1. Background

1.1.1. Combustion of alcohol blends in engines

Understanding the effect of biofuels on in-cylinder combustion processes is an essential challenge in managing fuel flexibility and achieving lower CO_2 emissions. Gasoline already contains 5% ethanol in many countries (E5) and can be compatible with existing engine fuel and combustion systems; however, its use will have limited impact on CO_2 emissions. Therefore, some markets are demanding much higher proportions, like E85, or even pure ethanol. The benefits of ethanol addition to gasoline have always been recognised for practical reasons. Apart from the variety of sources which it can be produced from, ethanol can raise the octane rating of gasoline due to its better anti-knock characteristics, allowing the use of higher compression ratios and higher thermal efficiencies. However, ethanol's high latent heat of vaporisation can cause problems for cold engine starting due to excessive charge cooling and poor evaporation [1]. On the other hand in hot climates ethanol fuelling can result in adverse effects such as vapour lock. Ethanol's water solubility and incompatibility with some engine materials are other disadvantages, hence compatibility issues with current fleet of vehicles and fuelling systems need to be resolved for high-content ethanol blends to become mainstream.

* Corresponding author. Address: Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK. Tel.: +44 (0)20 76793862; fax: +44 (0)20 73880180.
E-mail address: p.aleiferis@ucl.ac.uk (P.G. Aleiferis).

0016-2361/$ - see front matter
http://dx.doi.org/10.1016/j.fuel.2012.12.088

Nomenclature

Da	Damköhler number
K	Karlovitz stretch factor
Ka	Karlovitz number
Le	Lewis number
Re_L	Reynolds number with respect to integral length scale
δ_l	flame thickness
Ma	Markstein number
T	temperature
P	pressure
u'	turbulence intensity
u'_k	effective turbulence intensity
u_l	laminar burning velocity
x, *y*	co-ordinates
η	Kolmogorov microscale
τ_l	timescale of laminar burning
τ_η	timescale of turbulent straining
ϕ	equivalence ratio

Abbreviations

AIT	After Ignition Timing
ATDC	after intake top dead centre
CA	crank angle
COV	Coefficient Of Variation (=Mean/RMS)
DISI	direct injection spark ignition
EGR	Exhaust Gas Recirculation
EVC	exhaust valve closure
EVO	exhaust valve open
FFID	fast flame ionisation detector
IMEP	Indicated Mean Effective Pressure
IVC	intake valve closure
IVO	intake valve open
LIF	Laser Induced Fluorescence
MFB	Mass Fraction Burned
PFI	Port Fuel Injection
PIV	Particle Image Velocimetry
RMS	root mean square
RPM	revolutions per minute
SI	spark ignition
WOT	Wide Open Throttle

Combustion studies with ethanol in SI engines have been carried out by [2–7], focusing on performance characteristics, while others [8–11] have concentrated on engine emission measurements; most of these were done on Port Fuel Injection (PFI) engines. Very few studies have been conducted in latest technology Direct Injection Spark-Ignition (DISI) engines that are typically very sensitive to fuel properties; more to the point, in some of those studies, certain trends illustrate great diversity. For example, Zhu et al. [12] recently reported the combustion characteristics of a single cylinder SI engine with (a) gasoline PFI and DI, (b) gasoline PFI and ethanol DI, and (c) ethanol PFI and gasoline DI. The DI fuelling portion varied from 0% to 100% of the total fuelling, whilst the engine's air-to-fuel ratio was kept constant. It was shown that the indicated work output per unit volume (Indicated Mean Effective Pressure, IMEP) decreased by as much as 11% as DI percentage increased, except in case (b), where IMEP increased by 2% at light load. The combustion duration increased significantly at light load as DI fuelling percentage increased, but only moderately at full load (*i.e.* Wide Open Throttle, WOT). In addition, the percentage of ethanol in the total fuelling played a dominant role in affecting the combustion characteristics at light load; however, at full load the DI fuelling percentage became the important parameter, regardless of the percentage of ethanol in the fuel. Some of these findings are different to those of Aleiferis et al. [13] with PFI and DI fuelling which showed that DI increased the rate of heat release in general with both gasoline and gasoline/ethanol blends at low-load conditions. One reason for this discrepancy might be that Zhu et al. [12] used a low pressure multi-hole side injector with a nine-hole orifice plate at 20 bar injection pressure compared to the swirl-injector at 80 bar used in [13]. Although both injectors in these studies were side-mounted, the differences in injector types and injection pressures would lead to different atomisation mechanisms and different injection durations. Similar discrepancies have been found with centrally-mounted injectors run with gasoline and E85 [14]. Such comparisons illustrate the difficulties in drawing general conclusions from experimental data in the literature, especially when considering that changes in hardware and operating strategies can so easily change the outcomes of a test. This also highlights the importance of the injection system and its correct optimisation, as well as the need for experiments under the same nominal conditions, in order to draw more confident conclusions when comparing the effects of a variety of fuels.

Butanol has also been suggested as a future fuel bio-component; it is more compatible with materials used in current fuelling systems but it has physical properties that can lead to poorer spray atomization. Butanol also lags behind ethanol in terms of commercial production. Butanol's performance has been studied less in the literature than ethanol's, even in PFI engines. Szwaja and Naber [15] showed marginally higher indicated efficiency for pure butanol fuelling and a faster 0–10% MFB period than that of gasoline in a PFI engine at 900 RPM with various engines loads. Engine stability (quantified by the Coefficient Of Variation of IMEP, COV_{IMEP}) was also marginally better for butanol. Other blends of butanol in gasoline showed that these effects were gradual with increasing volume fraction of butanol. Studies with PFI fuelling by Aleiferis and co-workers [16,17] reported that addition of 25% butanol to *iso*-octane led generally to faster 0–10% MFB period than pure *iso*-octane fuelling, closer to gasoline's, and to better engine stability. However, trends were sensitive to equivalence ratio, spark timing, engine temperature and valve overlap. Very few studies on butanol combustion in DISI engines exist in the literature. Wallner et al. [18] studied the combustion performance of 10% ethanol and 10% butanol addition to gasoline in a 4-cylinder DISI engine. Data were taken at engine speeds in the range 1000–4000 RPM. Relatively minor differences were found between all three fuels in terms of heat release rate, 50% mass fraction burned, and COV_{IMEP} at low and medium engine loads. Pure butanol combustion data are relatively hard to find. Smith and Sick [19] studied *iso*-octane, ethanol and *iso*-butanol mixing and combustion with late injection strategy for stratified operation in an optical DISI engine and found that ethanol tended to ignite faster but otherwise burned similarly to the other fuels. Combustion phasing with *iso*-butanol was very similar to that of *iso*-octane, despite a longer ignition delay. Stable operation with the latter fuels was possible over a window of spark timing from 5° to 8° CA after the end of injection, whilst ethanol required an even narrower window of 5–7° CA.

1.1.2. Burning velocities of alcohols and hydrocarbons

A major aspect of understanding combustion of alcohols in engines and decoupling some of the observed effects is the laminar