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# Flame front analysis of ethanol, butanol, iso-octane and gasoline in a spark-ignition engine using laser tomography and integral length scale measurements

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ABSTRACT

Direct-injection spark-ignition engines have become popular due to their flexibility in injection strategies and higher efficiency; however, the high-pressure in-cylinder injection process can alter the airflow field by momentum exchange, with different effects for fuels of diverse properties. The current paper presents results from optical studies of stoichiometric combustion of ethanol, butanol, *iso*-octane and gasoline in a direct-injection spark-ignition engine run at 1500 RPM with 0.5 bar intake plenum pressure and early intake stroke fuel injection for homogeneous mixture preparation. The analysis initially involved particle image velocimetry measurements of the flow field at ignition timing with and without fuelling for comparison. Flame chemiluminescence imaging was used to characterise the global flame behaviour and double-pulsed Laser-sheet flame tomography by Mie scattering to quantify the local topology of the flame front. The flow measurements with fuel injection showed integral length scales of the same order to those of air only on the tumble plane, but larger regions with scales up to 9 mm on the horizontal plane. Averaged length scales over both measurement planes were between 4 and 6 mm, with ethanol exhibiting the largest and butanol the smallest. In non-dimensional form, the integral length scales were up to 20% of the clearance height and 5–12% of the cylinder bore. Flame tomography showed that at radii between 8 and 12 mm, ethanol was burning the fastest, followed by butanol, *iso*-octane and gasoline. The associated turbulent burning velocities were 4.6–6.5 times greater than the laminar burning velocities and about 13–20% lower than those obtained by flame chemiluminescence imaging. Flame roundness was 10–15% on the tomography plane, with largest values for ethanol, followed by butanol, gasoline and *iso*-octane; chemiluminescence imaging showed larger roundness (18–25%), albeit with the same order amongst fuels. The standard deviation of the displacement of the instantaneous flame contour from one filtered by its equivalent radius was obtained as a measure of flame brush thickness and correlated strongly with the equivalent flame radius; when normalised by the radius, it was 4–6% for all fuels. The number of crossing points between instantaneous and filtered flame contour showed a strong negative correlation with flame radius, independent of fuel type. The crossing point frequency was 0.5–1.6 $mm^{-1}$. The flame brush thickness was about 1/10th of the integral length scale. A positive correlation was found between integral length scale and flame brush thickness and a negative correlation with crossing frequency.



## 1. Introduction

### 1.1. Background

#### 1.1.1. Combustion of alcohols in engines

Climate change and security of fuel supply both dictate diversification towards more sustainable bio-derived fuel stock. Ethanol is one of the preferred renewable additives to gasoline. Amongst its favourable properties is the high Research Octane Number (RON). Ethanol's high latent heat of evaporation can also be exploited in parallel to its high RON by enabling higher compression ratios for greater thermal efficiency. Gasoline already contains 5–10% ethanol

*Abbreviations:* AFR, air to fuel ratio; AIT, after ignition timing; ATDC, after intake top dead centre; BTDC, before compression 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; IMEP, indicated mean effective pressure; IVC, intake valve closure; IVO, intake valve open; LDV, laser doppler velocimetry; 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; TKE, turbulent kinetic energy.

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in many countries (E5–E10) and can be made compatible with existing fuel and combustion systems; however, its use will have limited impact on $CO_2$ emissions. Therefore, some markets are demanding much higher blending ratios, like E85, or even pure ethanol. However, such blends can lead to problems from excessive charge cooling and poor evaporation [1]. Butanol is a new alternative fuel with potential to play a strong role. Butanol's compatibility with common materials means that no major modifications are required to existing systems for fuel transportation and fuel injection in engines. Butanol is also less hygroscopic than ethanol with higher heating value. Fundamental understanding of the behaviour and effects of ethanol and butanol on in-cylinder combustion processes is an essential challenge in managing fuel flexibility and achieving lower $CO_2$ emissions. Several studies of ethanol combustion have been carried out in SI engines, focusing mainly on performance characteristics and exhaust emission measurements. However, most of these were done with Port Fuel Injection (PFI) systems [2–11]. Butanol has been studied in the literature much less than ethanol, *e.g.*, see [12–17]. Very few alcohol 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, many of those studies illustrate diverse effects over different mixture preparation methods and regimes of operation [18–23].

#### 1.1.2. Burning velocities of alcohols and hydrocarbons

A major aspect of understanding combustion of fuels in engines is their laminar and turbulent burning velocities in controlled environments and at engine-relevant conditions. Laminar burning velocities have been measured for a range of hydrocarbon and alcohol fuels at various conditions in [24–27] among others. More recently, results have been reported in [28,29] for ethanol, [30] for *iso*-octane, [31] for primary reference fuels and gasoline, [32,33] for butanol and [34–36] for most of these fuels. A large database of fuel structure effects has also been produced in [37]. These authors reported data derived from thermodynamic analysis of pressure traces from explosions in a combustion vessel, typically at 3 bar and 450 K, following the approach in [26]. However, the velocities obtained were larger than those of other existing data for alkanes and aromatics by as much as 30%. The authors commented that this was due to different measurement techniques, *i.e.* thermodynamic (heat release) *vs.* optical (entrainment). This highlights issues that can lead to differences among authors, *e.g.* flame cellularity effects at high pressure, the specifics of various methodologies used to derive unstretched values of burning velocity, *etc.* Furthermore, in most of the published databases, the effect of burned gas on laminar burning velocity has not been quantified in detail and hence very few data exist that are directly relevant to realistic in-cylinder conditions. The overall effect of burned gas residuals on burning velocities has been quantified to be much stronger than that of excess air, temperature or pressure; with residual fractions of 0.15–0.2, the laminar burning velocity of *iso*-octane has been found to decrease by 35–45% according to Metghalchi and Keck [26]. Such levels of residuals are commonly found in DISI engines at part-load operation or when Exhaust Gas Recirculation (EGR) systems are employed to control $NO_x$ formation over a range of loads. Marshall et al. [38] published recently measured laminar burning velocities at engine-like conditions with and without residuals for various liquid fuels, including *iso*-octane and ethanol and discussed several effects in comparison to the data in [26]. Vancoillie et al. [39] also presented a review of laminar burning velocities and new correlations for the operating range of alcohol-fuelled SI engines. The recent studies of Broustail et al. [40, 41] on the laminar burning characteristics of ethanol/*iso*-octane and butanol/*iso*-octane blends at engine-relevant conditions are also noteworthy. In contrast, limited data exist on turbulent burning velocities at engine-relevant conditions for liquid fuels [42–44]. Lawes and co-workers [45, 46] have published turbulent burning velocities for *iso*-octane, methanol and ethanol, but no complete data sets really exist with presence of residuals and for longer chain alcohols. Furthermore, despite efforts that have quantified turbulent flame speeds in DISI engines by direct flame visualisation (chemiluminescence) with a variety of fuels, including *iso*-octane, gasoline, ethanol, butanol and some of their blends [47–51], very little information exists on flame speeds obtained by planar imaging techniques in modern geometry SI engines, *e.g.*, see [52, 53], but no detailed planar data have been derived specifically with ethanol and butanol fuels in direct comparison to *iso*-octane and gasoline.

### 1.2. Present contribution

When one considers the need for fundamental understanding of in-cylinder combustion processes with diverse fuels it is surprising that no major studies have compared in detail the in-cylinder behaviour of typical liquid hydrocarbon fuels to that of ethanol and butanol in latest geometry DISI engines. Recently Aleiferis and co-workers [50,51] published combustion data of heat release, in-cylinder flame expansion speeds and flame centroid motion obtained by crank-angle resolve flame chemiluminescence imaging of *iso*-octane, gasoline, ethanol and butanol fuels in comparison to gaseous methane fuelling by port fuel injection. The present study aimed at going a step further by quantifying and discussing in-cylinder flame front topologies of ethanol, butanol, *iso*-octane and gasoline fuels obtained by planar Laser-sheet flame visualisation. The main objective was to quantify the degree of flame front distortion and wrinkling for these fuels with respect to in-cylinder flow and integral length scales. Therefore, the analysis also involved characterisation of the in-cylinder flow field and quantification of the integral length scales of turbulence at ignition timing by Particle Image Velocimetry (PIV). Laser Doppler Velocimetry (LDV) data from the same engine [54,55] were also consulted to assist the discussion. To the best of the authors' knowledge, this is the first time that such a set of complete data is presented for these fuels in a latest geometry SI combustion system. The presented measurements contribute towards a database of in-cylinder turbulent flame behaviour and combustion rates which are essential for developing our fundamental understanding of the underlying phenomena at realistic engine conditions. Such data can also be useful to combustion modellers because simulation and validation of in-cylinder flame growth phenomena with various fuels are still very challenging.

## 2. Experimental apparatus and procedures

### 2.1. Fuels

Four fuels were investigated: a typical commercial grade gasoline (RON95) without oxygenates, *iso*-octane, ethanol and *n*-butanol (1-butanol). A standard gasoline blend contains several hundred hydrocarbons, typically about 25–30% $C_5$ or lower, 30–40% $C_6$–$C_8$ and the remainder $C_9$–$C_{10}$ hydrocarbons. *iso*-Octane is one of the major single components of gasoline, with a boiling point of 99 °C at atmospheric pressure; *n*-butanol boils at 117 °C whilst ethanol boils at 78.4 °C. Table 1 provides a quick overview of various thermophysical properties of these fuels; the distillation curve of the specific gasoline used has been shown elsewhere [56,57]. Summarising published data, Aleiferis et al. [51] tabulated laminar burning velocities at $\phi = 1.0$ and $\phi = 0.5$ for these fuels at pressure and temperature conditions relevant to those expected at the start of combustion in SI engines. Table 2 displays mean values from that exercise for immediate reference where it is apparent that differences amongst fuels at high pressure are quite small. Although experimental uncertainties of the order 1 cm/s typically exist, there is a decrease in burning