INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 37 (2012) 1797–1812

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# Flame chemiluminescence and OH LIF imaging in a hydrogen-fuelled spark-ignition engine

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ARTICLE INFO

*Article history:*
Received 17 July 2011
Received in revised form
1 October 2011
Accepted 4 October 2011
Available online 26 October 2011

*Keywords:*
Spark ignition engines
Hydrogen combustion
Flame chemiluminescence
OH Laser Induced Fluorescence

ABSTRACT

Research into novel internal combustion engines requires consideration of the diversity in future fuels in an attempt to reduce drastically $CO_2$ emissions from vehicles and promote energy sustainability. Hydrogen has been proposed as a possible fuel for future internal combustion engines. Hydrogen's wide flammability range allows higher engine efficiency with much leaner operation than conventional fuels, for both reduced toxic emissions and no $CO_2$ gases. This paper presents results from an optical study of combustion in a spark-ignition research engine running with direct injection and port injection of hydrogen. Crank-angle resolved flame chemiluminescence images were acquired and post-processed for a series of consecutive cycles in order to calculate in-cylinder rates of flame growth. Laser induced fluorescence of OH was also applied on an in-cylinder plane below the spark plug to record detailed features of the flame front for a series of engine cycles. The tests were performed at various air-to-fuel ratios, typically in a range of $\varphi = 0.50–0.83$ at 1000 RPM with 0.5 bar intake pressure. The engine was also run with gasoline in direct-injection and port-injection modes to compare with the operation on hydrogen. The observed combustion characteristics were analysed with respect to laminar and turbulent burning velocities, as well as flame stretch. An attempt was also made to review relevant hydrogen work from the limited literature on the subject and make comparisons were appropriate.


## 1. Introduction

### 1.1. Background

#### 1.1.1. *Hydrogen fuelling*

Hydrogen has been suggested as a possible replacement for most fuels used today and can be produced from sustainable methods. The main advantage of burning hydrogen in internal combustion engines is its lack of carbon content, leading locally to no exhaust emissions of particulate matter, unburned hydro-carbons, CO and $CO_2$. The concept of an internal combustion engine running on pure hydrogen is as old as the engine itself. However, the lack of established technology necessary to handle some issues related to the properties of hydrogen, as well as the diversity of political opinions and projected infrastructure costs for the safe production and delivery of hydrogen on a large scale, have discouraged most automotive manufacturers from promoting hydrogen as a fuel for their engines. Nevertheless, sustainability issues and impeding stricter exhaust emissions legislation have made hydrogen the subject of much discussion, with new research for fundamental understanding of in-cylinder phenomena in hydrogen combustion systems critically needed.

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0360-3199/$ – see front matter 
doi:10.1016/j.ijhydene.2011.10.010

**Nomenclature**

| | |
|---|---|
| $p$ | Pressure |
| $T$ | Temperature |
| $u'$ | Turbulence intensity |
| $u_l$ | Laminar burning velocity |
| $u_t$ | Turbulent burning velocity |
| $\phi$ | Equivalence ratio |

*Abbreviations*

| | |
|---|---|
| AFR | Air-to-Fuel Ratio |
| AIT | After Ignition Timing |
| ATDC | After intake Top Dead Centre |
| BDC | Bottom Dead Centre |
| BTDC | Before Compression TDC |
| CA | Crank Angle |
| CFD | Computational Fluid Dynamics |
| COV | Coefficient of Variation |
| DI | Direct Injection |
| DISI | Direct Injection Spark Ignition |
| EGR | Exhaust Gas Recirculation |
| ETU | Engine Timing Unit |
| EVC | Exhaust Valve Closure |
| EVO | Exhaust Valve Open |
| LDV | Laser Doppler Velocimetry |
| LIF | Laser Induced Fluorescence |
| IMEP | Indicated Mean Effective Pressure |
| IVC | Intake Valve Closure |
| IVO | Intake Valve Open |
| MBT | Minimum spark advance for Best Torque |
| MFB | Mass Fraction Burned |
| PFI | Port Fuel Injection |
| PIV | Particle Image Velocimetry |
| PM | Particulate Matter |
| RPM | Revolutions Per Minute |
| SI | Spark Ignition |
| SOI | Start of Injection |
| TEA | TriEthylAmine |

#### 1.1.2. *Hydrogen properties*

A general review of the research done on hydrogen as a fuel for automotive applications up to the mid 90's has been given by Norbeck *et al.* [1]. More recent reviews have been published by White *et al.* [2] and Verhelst *et al.* [3,4] and Verhelst and Wallner [5].

Some of hydrogen's properties, particularly relevant to in-cylinder mixture formation and combustion, are summarized in Table 1 in comparison to those of gasoline and methane [6–8]. Hydrogen has very low density and, although its heating value on a mass basis is very high in comparison to other fuels (120 MJ/kg for hydrogen, 43.5 MJ/kg for gasoline), on a volume basis this is the lowest among common fuels (10.2 MJ/m$^3$ for hydrogen, 216.4 MJ/m$^3$ for gasoline). Hydrogen's minimum ignition energy is about one order of magnitude less than that of gasoline; hydrogen also has a small quenching distance which means that hydrogen can autoignite easily and its flame can get past a nearly closed intake valve more readily and backfire into the intake manifold. Additionally, $NO_x$ emissions from stoichiometric combustion of hydrogen are comparable to those from engines fuelled by gasoline or common gaseous fuels. However, hydrogen has a wide range of flammability, hence it is possible to burn it in much leaner/cooler flames than gasoline or natural gas, *i.e.* with Air-to-Fuel Ratio (AFR) greater than the stoichiometric or, differently, for $\phi$ = AFRstoic/AFR<1. This leads to quite low $NO_x$ emissions, especially for $\phi < 0.5$; Exhaust Gas Recirculation (EGR) can also be used to control the combustion duration, knocking and $NO_x$ emissions in SI hydrogen engines [9–13].

#### 1.1.3. *Hydrogen injection*

Particularly due to pre-ignition/backfire and $NO_x$-related problems, injection systems and mixture preparation strategies for hydrogen engines have attracted a lot of attention. However, no commercial injectors have been fully developed yet specifically for the life-cycle of a hydrogen engine because much larger volumes of fuel must be injected per stroke due to the very low density of hydrogen; hydrogen's low lubricity also leads to severe durability problems for injectors that have been designed for common fuels [14]. Nevertheless, commercially available Port Fuel Injection (PFI) systems for common gaseous fuels can be adopted for engine operation

**Table 1 – Properties of Hydrogen, Gasoline and Methane.**

| Parameter | Hydrogen | Gasoline | Methane |
|---|---|---|---|
| Density [kg/m$^3$] | 0.09 (0 °C) 71 (−253 °C) | 5.1 (vapour) 730–780 | 0.72 (0 °C) 423 (−162 °C) |
| Stoichiometry [$kg_{Air}/kg_{Fuel}$] | 34.3 | 14.7 | 17.2 |
| Lower Heating Value [MJ/kg] | 120 | 43.5 | 50 |
| Lower Heating Value at $\phi = 1$ [MJ/kg] | 3.40 | 2.83 | 2.72 |
| Boiling Temperature [°C] | −253 | 25–215 | −162 |
| Ignition Limits [Volume%, $\phi$] | 4–75, 0.1–6.67 | 1.0–7.6, 0.71–2.5 | 5.3–15, 0.48–1.43 |
| Minimum Ignition Energy at $\phi = 1$ [mJ] | 0.02 | 0.24 | 0.29 |
| Autoignition Temperature [°C] | 585 | 350 | 540 |
| Quenching Distance [mm] | 0.64 | 2.0 | 2.03 |
| Kinematic Viscosity [m$^2$/s] | $110 \times 10^{-6}$ | $1.18 \times 10^{-6}$ | $17.2 \times 10^{-6}$ |
| Thermal Conductivity [W/m K] | $182.0 \times 10^{-3}$ | $11.2 \times 10^{-3}$ | $34.0 \times 10^{-3}$ |
| Diffusion Coefficient in Air [m$^2$/s] | $6.1 \times 10^{-5}$ | $0.5 \times 10^{-5}$ | $1.6 \times 10^{-5}$ |