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Modulation of integral length scales of turbulence in an optical SI engine by direct injection of gasoline, *iso*-octane, ethanol and butanol fuels

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ABSTRACT

In-cylinder air flow structures are known to play a major role in mixture preparation and engine operating limits for spark-ignition engines. In this paper PIV measurements were undertaken in an optical spark-ignition at 1500 RPM, part-load with 0.5 bar intake plenum pressure. One of the PIV planes was vertical, cutting through the centrally located spark plug (tumble plane). The other plane was horizontal 1 mm below the spark plug ground electrode (swirl plane). The effect of engine head temperature was also examined by using engine-head coolant temperatures of 20 °C and 80 °C. The flow field was examined late in the compression stroke at typical ignition timing. The study was conducted under air-only motoring engine conditions but also under fuelled conditions in the early intake stroke using direct injection of gasoline, *iso*-octane, ethanol and butanol fuels. The flow field under air-only motored conditions showed velocities between 3 and 5 m/s predominantly from intake to exhaust. Little differences were observed between hot and cold engine-head temperature; typically ~10% larger mean velocity and turbulent kinetic energy was seen on the intake side. Integral length scales were on the tumble plane between 2 and 4.5 mm in the vertical and 4–7 mm in the horizontal direction. The swirl view showed scales between 4 and 10 mm, larger at cold than at hot engine-head conditions. The vertical length scales appeared to be limited by the clearance height, scaling typically by about 10–15%. The horizontal components scaled to the cylinder bore diameter by about 5–12%. The fuel injection process in the early intake stroke led to little differences in the general mean flow structure at ignition timing, except for a small increase in the maximum velocities, ~10%. The turbulent kinetic on the tumble plane was highest towards the exhaust side of the engine under non-fuelled engine conditions but fuel injection resulted in highest values on the intake side. The integral length scales with fuel injection were of the same order of magnitude to those of air only measurements on the tumble plane, but showed distinctly larger areas with length scales up to 9 mm on the swirl plane. Differences between fuels for their fuel specific injection duration were small, with average length scales between 4 and 6 mm. Ethanol exhibited typically largest scales and butanol smallest.

1. Introduction

1.1. Background

Direct Injection Spark Ignition (DISI) technology is increasingly commonplace within the automotive industry as a replacement for port fuel injection. Benefits are associated with improved efficiency due to the charge cooling effects and increased flexibility in mixture formation by a variety of injection strategies. Understanding the in-cylinder air flow is of great importance for DISI engines because it is inherently coupled to mixture formation via spray-flow interactions. Although early Particle Image Velocimetry (PIV) studies on engine flows had highlighted the issue of bias in the statistical analysis of small batches of engine cycles [1,2], data storage issues and processing time have forced most researchers to use no more than 50–200 cycles for their analysis [3–6]. More recently kHz range high-speed PIV has been utilised for typical 2D flow mapping but also with volume-based characterisation that can be used for validation of Large Eddy Simulation (LES) of engine flows [7–9]. High-speed PIV allows crank-angle resolved measurements to be undertaken and has been shown to give insights into the field of cycle-to-cycle flow variability, including spray-flow

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and flame-flow interactions [10–16], nevertheless at the expense of data storage requirements, especially if large numbers of cycles are sought after for statistical analysis. Moreover, for turbulent time scale analysis at engine speeds of 1500 RPM or higher, tens of kHz imaging frequency is necessary to achieve sub-crank-angle resolution. This poses further camera and storage challenges when one needs to maintain whole-field spatial image resolution and over a series of many hundreds of cycles. Therefore, 'low-speed' cycle-resolved PIV still has its own merits as an experimental tool for in-cylinder flows because it can provide with relative ease the number of samples needed for faithful statistical analysis of the flow at a specific crank angle, especially if information on Turbulent Kinetic Energy (TKE) and integral length scales is aimed for.

1.2. Present contribution

Cycle-resolved PIV experiments were undertaken in a pentroof geometry DISI optical engine at 1500 RPM, part-load conditions with 0.5 bar inlet plenum pressure. Two in-cylinder planes were considered: one vertical 'tumble' plane passing through the centre of the combustion chamber and one horizontal 'swirl' plane close to compression Top Dead Centre (TDC), both imaged at ignition timing. The main aim was to quantify, apart from 'mean' velocity and turbulence intensity, maps of integral length scales of the flow field at ignition timing that do not really exist in the literature at such engine operating conditions (most earlier studies on integral length scales in 4-valve engines focused on 600–1200 RPM wide-open-throttle, without direct pentroof access, e.g. [3,4]). More importantly, the PIV measurements at ignition timing were taken under non-fuelled motoring engine conditions (i.e. air only operation), but also with fuelling in the early intake stroke using direct injection of gasoline, *iso*-octane, ethanol and butanol fuels. The flow field at ignition timing was characterised for fixed injection pulse width with all fuels, as well as for fuel-specific injection duration corresponding to stoichiometric conditions, in an attempt to distinguish between fuel type and injection duration effects on the flow field at ignition timing. Two engine head temperatures were applied for the PIV measurements, 20 °C and 80 °C. To the best of the authors' knowledge this is the first time that such a set of measurements is provided in the literature.

2. Experimental arrangement

2.1. Optical engine

The optical engine on which the present work was performed was a single-cylinder research engine designed and built by MAHLE Powertrain Ltd., specifically for optical studies on air flows, fuel sprays and combustion systems. The engine head was based on a serial production 4-cylinder 2-litre 16-valve DISI engine with side injector located between the two intake valves. The Bowditch style piston allowed for a 45° mirror to be positioned inside the extended hollow piston core and give optical access to the combustion chamber through a titanium piston crown equipped with a sapphire circular window. The cylinder liner was fully optical and contoured at the top to fit the pentroof gable ends; it was clamped in place by four hydraulic rams. Sealing was achieved by the installation of a silicon gasket in a spark-eroded groove on the underside of the engine head. The piston rings were made of high-temperature-grade Torlon material in order to provide good sealing and wear resistance in a non-lubricated environment. Fig. 1 shows an image of the optical liner in place along with the optical piston crown. Schematics of the combustion chamber and axes definition used throughout this paper have also been included in Fig. 1. The intake manifold design consisted of an intake runner of similar diameter and length to that of the commercial engine. A large volume intake plenum chamber was connected upstream the intake runner to allow damping of the manifold impulse pressure fluctuations. The valve timings were of 'standard' type with maximum valve overlap of 11 °CA (measured to 0.02 mm lift). The spark plug was of triple ground electrode type with asymmetric orientation inside the combustion chamber. To avoid confusion it is noted that the exact orientation of the spark plug ground electrodes in the schematics of Fig. 1 is not representative of the real spark plug; the real spark plug positioning is visible in the combustion chamber pictures of Fig. 1. The basic specifications of the engine are presented in Table 1. All timings given in °CA refer to the 'crank angle time equivalent' at 1500 RPM, with one 1 °CA corresponding to 0.111 ms. 1500 RPM corresponded to a mean piston speed of 4.25 m/s. More details about the engine can be found in previous publications [17–19].

2.2. Engine operating parameters

Due to the need for prolonged engine running, all PIV measurements were undertaken at motoring conditions. However, these were set to match nominally as nearly as possible those of previous work published on this engine by the current authors on spray formation and combustion with various fuels, e.g. [18]. The load at 1500 RPM was controlled by throttling to 0.5 bar (±0.01 bar) absolute pressure in the intake plenum. The crank and cam shafts were equipped with shaft encoders resolving 1800 increments per revolution. An AVL427 engine timing unit was employed for injection control, as well as for provision of synchronised triggering to lasers and cameras. Acquisition of pressure and temperature data was realised by a 12-bit National Instruments (NI) PCI-6023E DAQ card capable of a sampling rate of 200 kS/s for 16 channels. Pressure sensors with respective amplifiers for in-cylinder pressure, intake plenum pressure, intake runner and exhaust pressure were used, logged and referenced as needed (Kistler 6041A, 4075A10V39, Kistler 4045A2V39, Kistler 7531, respectively). Their digitisation rate corresponded to 0.2 °CA at 1500 RPM. Temperatures were recorded on a separate low-speed data acquisition system which formed part of the dynamometer control system, as were all other engine running parameters.

2.3. Fuels

Four fuels were investigated: a typical commercial grade gasoline (RON95), *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_{12} 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 2 provides a quick overview of various thermophysical properties of these fuels; the distillation curve of the specific gasoline used has been shown elsewhere [20,21]. A single-hole swirl-type DI injector was mounted on the intake side of the combustion chamber between the two intake valves. The nozzle hole was at an off-axis centre angle of 10°. The injector was mounted at a 22° angle, resulting in a nominal nozzle hole or spray-cone centre line angle of 32° to the horizontal; see Fig. 1. The fuel was supplied to the injector by a Heypac GX30 pneumatic pump and regulator; the injection pressure was fixed at 80 bar. The injection timing was fixed to 60 °CA ATDC (after intake TDC) for 'homogeneous' mixture preparation; this was based on earlier work with various injection timings and fuels that had optimised injection timing in order to allow maximum time available for evaporation up to ignition timing but also minimise piston-crown spray