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Low intake valve lift in a port fuel-injected engine

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ABSTRACT

A phenomenological study of the airflow and fuel spray interaction in a variable valve gasoline engine is presented. Experiments were performed in a steady-state flow rig fitted with a modified production cylinder head. The intake valve lift was varied manually. The mass flow rates of air and fuel through the test rig were adjusted to match typical engine operating conditions. Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) measurements of the airflow showed the breakdown of a single, forward tumbling vortex-like structure into a pair of high-speed, turbulent jets at low valve lifts.
Two transitional phases in the flow at the valve gap were identified for valve lifts less than 1.5 mm and greater than 3 mm. At the lower limit, a jet flapping instability was recorded. A port fuel injector (PFI) spray was characterised in a quiescent, chamber and within the test rig. High Speed Photography (HSP) and Phase Doppler Anemometry (PDA) were used to measure the effects of varying valve lift upon the fuel droplet characteristics. The in-cylinder measurements showed a reduction in mean droplet diameter of up to 50%, close to the valve gap, for peak valve lifts of less than 3 mm.

1. Introduction

Variable valve technology is rapidly becoming the next industry standard on gasoline engines. By far the most common production application is camshaft-phasing (variable valve timing, VVT), where both emissions and torque curve enhancements arise from a simple strategy applied to the intake valves [1,2]. Other systems additionally phase the exhaust camshaft timing. Production examples of such systems have been introduced by Honda and Toyota. These systems switch from low to high valve lift at higher engine speeds in order to improve volumetric efficiency.

The series production Bayerische Motoren Werke (BMW) Valvetronic configuration is an advanced mechanical system that has continuously variable valve lift (CVVL). The valve opening duration is dependant upon valve lift but the phasing of both the intake and exhaust camshafts can be controlled independently via the Double Vanos system. This flexibility allows the engine to operate under throttle-less load control. The induction process can be controlled through a low valve lift event, resulting in a part load reduction in pumping losses. Fuel efficiency improvements with a low lift strategy, are claimed to be in the region of 10% over the drive cycle and 20% at idle with the throttle valve closed and a stoichiometric air to fuel ratio [3,4]. Maintaining a stoichiometric mixture has a distinct advantage over stratified gasoline direct injection, as additional de-NO_x catalyst after-treatment and sulphur free fuel are not required.

Emerging throttle-less, variable valve strategies in gasoline engines use a range of low intake valve lifts to overcome the reduction in flow velocity at the valve gap that is detrimental to the mixture preparation processes at low speeds and loads. Many studies have measured the mean and turbulence characteristics of the gas phase within the combustion chamber as the valve lift is varied, e.g. Ref. [5]. Other studies have reported that a low valve lift significantly increases the flow velocity through the valve orifice [6,7], finely atomising the fuel spray through the promotion of secondary, wind-assisted, droplet break-up [8,9]. As the valve lift is reduced, the mechanisms of fuel break-up become far more complex with the introduction of fuel films, stripping, coalescence and gravitational valve slide-off. At very low valve lifts, intake jet flows govern the liquid fuel atomisation and generate in-cylinder conditions for increased charge homogeneity (turbulent dispersion) [10,11]. At the engine idle condition, the lowest valve lift is utilised which significantly alters the flow of the mixture of gas and fuel through the valve gap and within the combustion chamber [8,9]. Flow instability in the jet leaving the port has been reported [12]. The energy conserving, large scale, rotating bulk flow structures typically observed in pent-roof chambers (in the forward tumble plane) no longer exist. The effect of the volume of fuel in the valve gap at low valve lift has been shown to lead to fuel pooling, wall film stripping and gravitational slide effects [13,14].

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Nomenclature

L_v	valve lift [mm]
R_t	Ricardo tumble ratio [–]
C_d	discharge coefficient [–]
ρ	gas density [kgm^{-3}]
U_r	relative velocity between gas and droplet [ms^{-1}]
d	droplet diameter [m]
σ	surface tension [Nm^{-1}]
We	droplet Weber number [–]

Most of these studies are generally qualitative and the breakdown of the mean flow structures and its effect upon the fuel spray is rarely measured in situ. A series of experiments were devised to investigate the processes of droplet break-up and airflow distribution with varying valve lift in a BMW Valvetronic cylinder head.

2. Experimental methods

2.1. Experimental approach

Experimental measurements were organised in two phases. In the first instance, a baseline study was performed, whereby the fuel spray was characterised in isolation, in a fixed volume, atmospheric pressure, quiescent chamber. Secondly, the air motion and fuel spray were quantified in the port and cylinder of a modified BMW Valvetronic engine fitted to a steady-state blowing rig. The specification of the engine and fuel injection system is given in Table 1.

2.2. Atmospheric quiescent chamber

A Siemens Deka, 4-hole PFI type injector was mounted vertically in the spray chamber. The chamber has a square cross-section and allows a full view of the spray jets without impingement on the walls. Phase Doppler Anemometry (PDA) and high-speed photography (HSP) were used to determine four important characteristics of the fuel spray: to verify the point of impingement of the fuel spray in the port (cone and jet separation angles); to compare the similarity between each pair of jets and to determine the mean droplet diameter and velocity distributions that dictate the break-up mechanisms.

The injector orientation was carefully selected to ensure that the measurement planes bisected two individual spray jets and matched the orientation in the intake port. A programmable traverse was used to move through the spray. The positional error was ± 0.1 mm. The measurement grid was chosen to cover the entire spray boundaries.

The PDA processor was triggered with the start of injection (SOI) pulse. Non-coincident data was collected for either 10,000 measurements or 60 s duration in the axial velocity direction (u) and 5,000 measurements or 60 s duration in the radial velocity direction (v) for each of the operating conditions. The optimisation of the PDA parameters and statistical accuracy of the measurements, specific to this spray, formed an important part of the study.

A comprehensive series of ciné films was acquired for visualisation and corroboration of the PDA results, using a Phantom V7.1 high-speed camera.

Table 1
Test specification.

Cylinder head	BMW Valvetronic N42B20
Chamber geometry	Pent-roof
Number of valves	2 intake, 2 exhaust
Valve lift range	0.34–9 mm
Port fuel injection	Brighton and Siemens Deka (4 hole)
Fuel pressure	3.5 bar
Fuel temperature	22 °C
Fuel type	Iso-octane (2, 2, 4 TMP)
Injection frequency	1 Hz

2.3. Steady-state flow rig

Experiments were performed using the fuel injection system, air box, intake manifold and cylinder head of a production BMW Valvetronic engine. Two cylinders of the cylinder head and one intake port were modified to allow optical access to the port, valve gap, pent-roof and in-cylinder volume. A polycarbonate rectangular box was used as the downstream ‘cylinder’. The rectangular section was considered the best compromise between optical access and data rate for the Laser Doppler Anemometry (LDA) and PDA instruments and the true engine geometry. It was not anticipated to affect the LDA and PDA measurements close to valve seat, in the upper regions of the pent-roof chamber. The affect upon the bulk flow patterns was observed to be greatest in the far corner regions, for measurements performed in the cross-tumble plane. The sectioned cylinder head is shown in Fig. 1a. A schematic of the test rig is given in Fig. 1b. The valve lift was varied using micrometer adjusters fitted to each individual valve stem. The accuracy in the valve lift was ± 0.005 mm. The use of individual adjusters permitted asymmetrical lifts to be explored. The test rig was instrumented with pressure transducers and thermocouples to record the flow conditions either side of the intake valves.

Two sets of experimental conditions were investigated: a fixed pressure drop of 40 mbar across the valve and a fixed mass flow rate through the test rig of 0.01 kgs^{-1}. These were chosen to simulate a low speed and low load engine condition. The preliminary results presented here are a combination of both fixed approaches. The airflow conditions were achieved by the use of a critical flow nozzle (Toroidal Venturi ISO9300).

Several laser diagnostic techniques were used to investigate the fuel and air mixing in the intake port, downstream of the near valve region and the distributions (homogeneity) in the combustion chamber. Mid-cylinder, mid-valve and near-wall, tumble and cross-tumble planes were studied. Firstly, 2-component, coincident, measurements of the air velocity were conducted using LDA. Secondly, the spatial distribution of bulk flow air motions was measured using Particle Image Velocimetry (PIV). A double frame, cross-correlation technique was applied with a grid spacing of 32 × 32 pixels and a 50% window overlap. A median filter was also applied. The image resolution was 1376 × 1040 pixels. Fifty image pairs were acquired per plane (per operating condition) to compute average and RMS images. In both cases, corn oil droplets with a mean diameter of 1–2 μm was used to seed the gas flow.

The test conditions were then repeated with fuel injection. HSP and Laser Light Scattering Imaging were applied in a sheet through the port and cylinder planes. These images (in conjunction with the LDA and PIV results) were used to define a series of locations for the PDA measurements. Droplet size and velocity distributions were measured at each of these points using the same criteria as described previously.

3. Results and discussion

3.1. Spray characteristics in chamber

The fuel spray was observed to comprise three distinct periods. Fig. 2 shows a comparison of the PDA results in these phases over consecutive injections in the vertical plane. The