Simultaneous Study of Intake and In-Cylinder IC Engine Flow Fields to Provide an Insight into Intake Induced Cyclic Variations

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Abstract. Simultaneous intake and in-cylinder digital particle image velocimetry (DPIV) experimental data is presented for a motored spark ignition (SI) optical internal combustion (IC) engine. Two individual DPIV systems were employed to study the inter-relationship between the intake and in-cylinder flow fields at an engine speed of 1500 rpm. Results for the intake runner velocity field at the time of maximum intake valve lift are compared to in-cylinder velocity fields later in the same engine cycle. Relationships between flow structures within the runner and cylinder were seen to be strong during the intake stroke but less significant during compression. Cyclic variations within the intake runner were seen to affect the large scale bulk flow motion. The subsequent decay of the large scale motions into smaller scale turbulent structures during the compression stroke appear to reduce the relationship with the intake flow variations.

1. Introduction

Recent advances in laser diagnostic technology have allowed the detailed measurement of air flow motion generated within the combustion chamber of IC engines. Results from such studies have highlighted that in-cylinder air motion within IC engines has a significant affect on performance and emissions [1, 2]. Large scale bulk motions generated during the induction process are known to dissipate into smaller scale turbulent structures as the cycle progresses through the compression phase [3]. The small turbulent flow structures present at the point of ignition help to improve the flame propagation once the ignition kernel has grown to a size greater than the flow eddy size [4].

The presence of cyclic variation within the flow field of an IC engine has long been apparent, and hence, has been the subject of many investigations [5, 6]. Data suggesting a 10 % improvement in engine power output, for the same fuel consumption, through the elimination of cyclic variations has driven the quest for a greater understanding of the phenomenon [5]. Previous studies have shown cyclic variations are linked to variations in the fundamental engine processes such as ignition and subsequent flame front development. These are strongly influenced by variability in in-cylinder air motion and fuel mixing [5]. Increasingly over the last decade optical diagnostic techniques such as particle image velocimetry (PIV) have been applied to quantify IC engine in-cylinder air flow fields [7-9]. Measurements of planar flow fields within the cylinder have provided spatially resolved velocity data, helping to improve the understanding of unsteady flow fields.

It has been reported that changes to intake port geometries, such as port angle and internal radii, have a marked effect on the flow field structures appearing within the cylinder [10-12].
significant flow field differences are apparent particularly before bottom dead centre (BDC). However, as the cycle progresses through compression towards top dead centre (TDC), the difference between the flow fields diminishes. Fluid motion and turbulent structures established in the intake port manifest themselves in flow patterns around the intake valve and therefore in the cylinder. Thus, the intake runner flow has a significant affect on the generation of the in-cylinder bulk flow motion.

The majority of experimental engine based studies have concentrated on the in-cylinder flow field measurement. Comparatively few, however, have investigated the intake runner spatial flow field. This study presents simultaneous experimental DPIV data for the air flow field in both the intake runner and combustion chamber of a single cylinder motored optical IC engine. Instantaneous records of intake runner velocity at known crank angles are presented and compared to in-cylinder measurements on the same engine cycle.

2. Experimental

2.1. Optical Intake Runner and IC Engine

The single cylinder optical engine used in this study was supplied by the Advanced Powertrain Research Group at Jaguar Cars. The basic engine design consisted of a pent roof, four valve cylinder head, optical cylinder liner and extended optical piston. A novel feature of the engine design was the inclusion of an optical intake runner. The intake runner was manufactured using a rapid prototyping technique using a clear resin that allowed the replication of the standard geometry and the ability to polish the surface for optical access.

Motored operation of the optical engine was achieved using an electric motoring/absorbing drive system that allowed the engine speed to be set at 1500 rpm ±1 rpm. A 0.1 crank angle degree (CAD) incremental optical encoder attached to the crankshaft of the engine facilitated accurate measurement of engine crank angle position and speed. For the data presented in this study the intake manifold pressure was controlled to 700 mbar to replicate a recognised part-load engine operating condition.

2.2. Simultaneous DPIV Diagnostics

For the data presented in this study two identical commercial PIV systems were employed to capture flow fields in both the intake and in-cylinder regions. Figure 1 presents a schematic of the measurement system with respect to the optical research engine. Each independent PIV system consisted of a high resolution CCD camera and Nd:YAG double pulse laser. The cameras employed were of 1000 × 1016 pixel resolution, operating in a two frame capture mode and fitted with a 105 mm AF Micro Nikkor lens. The intake camera imaged a 30 mm × 30 mm region along the runner central plain close to the cylinder head. The in-cylinder camera imaged an area 35 mm × 35 mm, 10mm below the head gasket, along the bore centre line on the primary tumble plain. The imaged locations are shown in Figure 1. The light output from each laser was formed into a thin sheet approximately 40 mm wide × 1 mm in depth, generated using a spherical and a cylindrical lens. Each laser sheet was introduced via 45° mirrors into the measurement region as shown in Figure 1.

For the laser diagnostic technique olive oil particles, of nominal diameter 1-2 µm, were introduced into the intake air to act as flow tracers. The seed particles were generated using a multi jet atomiser and were introduced downstream of the engine throttle. Calculations showed the olive oil particles to have adequate flow following fidelity, whilst providing sufficient light scattering for accurate positional measurement. It was calculated that the recorded imaged particle diameter, when using a lens aperture f-number of 11, was greater than 2 pixels helping to increase the calculation accuracy of sub-pixel particle movements. The laser pulse separation was controlled to maintain the particle displacement below a quarter of an interrogation region, between the two PIV image pairs, to reduce errors within the PIV cross correlation routines.
An in house engine timing unit utilising marker pulses provided by the crankshaft encoder controlled timing of the two measurement systems. The timing was set such that the second in-cylinder PIV system would record flow fields at a known time delay following the capture of the intake image pair. For the data presented in this study the intake PIV system was triggered to capture flow field data at peak valve lift, 149 CAD after TDC intake. The time delay between intake and in-cylinder measurements was set so that data capture could occur between 149 CAD and 320 CAD, spanning a portion of both the intake and the compression strokes of the engine cycle.

Analysis of the PIV image pairs utilised a two frame cross correlation technique incorporating an FFT algorithm with Gaussian peak search routine and a 50 % Nyquist overlap of the interrogation regions. Image pairs were analysed utilising a 32 pixel $\times$ 32 pixel interrogation region size, which equated to a 1.12 mm square area with 0.56 mm interrogation region spacing within the cylinder and 0.96 mm square regions with a spacing of 0.48 mm within the intake runner.

3. Results and Discussion

Ensemble average velocity vectors calculated over 100 engine cycles for the intake and three in-cylinder crank angle cases are shown in Figure 2. All the in-cylinder data presented was recorded simultaneously with intake data at 149 CAD, on the same engine cycle. Average in-cylinder cases at 149 CAD, 240 CAD and 300 CAD after TDC are presented, showing the flow field progression through the engine cycle. The intake flow field in Figure 2a, shows a uniform velocity distribution across the runner with an angular bias towards the top surface. Analysis of the flow field with respect to the intake runner design would suggest that this angular bias is a result of the preceding geometrical radius. Figure 2b shows the corresponding ensemble average in-cylinder flow field at the same crank angle. The dominant flow is a tumble motion which appears to be driven by an intake flow stream. Later in the engine cycle at 240 CAD, the dominant recirculation (tumble) is still present as shown in Figure 2c. However, the velocity magnitude has noticeably reduced during the compression stroke. At 300 CAD after TDC moving towards the end of the compression stroke, there is no longer a dominant recirculation as seen previously.
Figure 2 shows a compilation of flow fields, where the intake case presented in section (a) and the in-cylinder case show in section (b) were taken simultaneously at maximum valve lift. For further comparison of in-cylinder flow fields sections (c) and (d) have been selected from independent cycles with closely matching intake flow fields. Three differing cases (i, ii, iii) of intake flow structures have been selected to demonstrate the impact that cyclic variations within the intake runner flow field and the effect it can have on the development of in-cylinder flow structures.

Examining Figure 3 case (i), shows that there is a well distributed velocity field of approximately 5 ms\(^{-1}\) within the intake runner as shown in image (a). It is expected that even though third component (i.e. out of plane) motions will exist within the runner, at the point of maximum valve lift the flow towards the intake valves will dominate. This velocity field exhibits an angular bias towards the top surface of the runner. As discussed previously the imaging region for intake runner flow follows a radius in the runner geometry, resulting in a small positive bias in angle. The corresponding in-cylinder flow field at 149 CAD, image (b), highlights a clearly defined inlet flow in the upper right hand section of the image. The presence of this flow field appears to generate a tumbling bulk flow motion, however, smaller scale structures are clearly visible within the solid body rotation. Progressing to 240 CAD, image (c), the in-cylinder flow field still exhibits a rotating motion, however, the strength of rotation is seen to have diminished in a similar manner to that presented in the ensemble average case. Notably, small scale fluctuations within the bulk flow are increasingly visible. Finally at 300 CAD, image (d), the tumble motion has subsided with increased presence of apparent small scale structures. The findings shown for this example case, fit well with results previously presented in literature with respect to the break down of bulk flow motions during the engine cycle [3].
Figure 3 – Simultaneous Intake and In-Cylinder Flow Fields. Velocities shown in ms\(^{-1}\).
Case (ii) shows an intake flow exhibiting a well distributed velocity profile, at a magnitude of approximately 4 ms\(^{-1}\). The reduced velocity is seen to have an affect on the in-cylinder flow field structure. Image (b) presents the in-cylinder flow field, recorded simultaneously with the intake field at 149 CAD, highlighting a reduction in the ordered bulk flow motion. In comparison to the previous case, (i), where an ordered tumble was visible, there now appears an increased presence of small scale structures. As the cycle progresses to 300 CAD, there is a further reduction in any bulk flow motion. The initial intake structure variations in both cases (i) and (ii) have resulted in a similar amount of small scale structures. In both cases the large scale bulk flow motion has substantially decayed.

In contrast to the previous cases presented, case (iii) presents a strong velocity gradient across the intake runner. The flow in the top portion of the runner appears stronger than that in the lower section. Peak velocities are seen to be approximately 6 ms\(^{-1}\) with a gradient of around 2 ms\(^{-1}\) across the runner towards the lower boundary wall. Progressing into the cylinder at 149 CAD it is apparent that the intake flow has generated a strong jet flow through the valve curtain in comparison to the previous cases. The flow acts to generate a strong tumble motion with a more prominent large scale bulk flow. At 240 CAD, image (c), the tumble motion is still dominant, exhibiting a rotation of higher velocity than in case (i). Later in the cycle, at 300 CAD, the bulk flow field recirculation has largely decayed and appears similar to the previous examples presented at the same crank angle. The results further highlight that the break down into small scale structures becomes dominant over the remaining large scale bulk flow motions during the later stages of compression.

Previous studies [10, 13] have shown that there is a clear relationship between intake port geometry and in-cylinder motion. Therefore, it seems reasonable to suggest that changes in the flow approaching a fixed port geometry, will create differences in the in-cylinder flow field. Results presented in this study show that the approach angle and velocity magnitude of the flow field within the runner differ from cycle to cycle. These variations result in changes to the large scale bulk flow motion generated during induction.

It is worth noting that the 15 Hz PIV technique employed in the present study only provides spatial velocity field data at a single point in time. The application of laser Doppler velocimetry (LDV) would provide temporal information regards the velocity field, but no spatial data. For the environment of the IC engine intake runner and in-cylinder flow fields, pressure waves and time scales are competing for control of the mixture motion. Thus comparison of cyclic variations based on measured PIV data may be difficult. Figure 4 displays two example cases where the intake runner flow fields appear similar, however, the in-cylinder flows differ. Analysis of the in-cylinder flow fields shows that image pair (a) exhibit a flow field lacking in strong, large scale bulk flow motion similar to that presented in Figure 3 case (ii). Image pair (b) presents a much stronger in-cylinder bulk flow motion more representative of that seen in Figure 3 case (i). The instantaneous cycle resolved PIV technique used, gives no information about the time history of the flow field. This makes full characterisation of a flow field that has a strong reliance time history difficult. In addition, the lack of optical access within the intake port region adds uncertainty to the actual flow field progression through the intake port and into the cylinder. Thus, similar flows within the intake measurement region may exhibit variations in in-cylinder flow field structure as a result of differing flow development during progression through the intake port.
4. Conclusion

The paper has reported a novel technique to quantify simultaneous intake and in-cylinder flow field structures within a motored IC engine. Flow velocity data has been presented for a motored SI engine operating at 1500 rpm with a manifold pressure of 700 mbar. Preliminary results highlight a relationship between intake flow cyclic variations and in-cylinder flow cyclic variations.

The PIV technique used provided instantaneous spatial flow field information. However, for dynamically changing flows, as in this application, the lack of time history means that the interaction of differing time scales within the intake runner generates variations over the course of the induction process, that are not shown within the results presented. These effects will detract from the correlation between the measured intake flow field at maximum valve lift and the recorded in-cylinder flow field development. Further work utilising a ‘time resolved’ PIV system (relative to the engine cycle) capable of capturing velocity fields at 5 kHz will help provide an improved insight into these effects.

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