Tumble Motion Evolution for GDI Engine Using Particle Image Velocimetry (PIV)

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ABSTRACT

In internal combustion engines (ICE), the intake generated flows are known to have a fundamental influence on the combustion both in spark ignition (SI) and compression ignition (CI) engines. The present study illustrates an experimental study on the airflow inside the cylinder of a gasoline direct injection (GDI) engine under steady-state conditions using particle image velocimetry (PIV). PIV measurements were conducted through the central vertical tumble plane, passing through the middle of the cylinder. The results illustrate how the flow direction was transferred from reverse tumble motion at low valve lifts to normal tumble motion at high valve lifts with non-dimensional rig tumble of -0.23 and 0.69 at valve lift 1 and 9 mm respectively.

Keywords: *Vorticity; Tumble motion; Airflow; GDI engine; Particle image velocimetry.*

ISSN 1823- 5514, eISSN 2550-164X
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Universiti Teknologi MARA (UiTM), Malaysia.
Received for review: 2017-10-11
Accepted for publication: 2018-06-26
Published: 2018-11-30

Introduction

Motor vehicles are considered to be one of the major sources of outdoor air pollution by exposing a huge sector of populations to different types of harmful emissions e.g. carbon monoxide (CO), unburned hydrocarbons (HC) and oxides of nitrogen (NOx) [1]. The exposure to these harmful emissions is associated with a range of serious and chronic diseases which in the worst cases lead to early death. In addition, many of pollutants are not only associated with adverse health outcomes but also are implicated in climate change [2]. Besides these issues of strict pollutant emissions regulations and environmental concerns worldwide, another key role issue is gaining influence, and that is the price of fuel. In recent years, much interest has been shown for the development of gasoline direct injection (GDI) engines as one of the most promising solutions to meet these demands. GDI engines offer a number of merits over PFI systems in terms of, preventing fuel wall film in the intake port, reducing the pumping losses, increasing the compression ratios and volumetric efficiency and hence thermal efficiency, and reducing the fuel consumption, CO_2 and HC emissions [3]. Fundamentally, the in-cylinder flow field that exists during the inlet and compression strokes is one of the key factors in the process of mixture preparation in an internal combustion engine generally, and particularly in GDI engine [4].

In-cylinder flow structures can be classified into two large-scale motions swirl and tumble. Swirl is a rotational flow around the vertical axis of the cylinder and usually is denoted for CI engines. On the other hands, tumble is a rotational flow around an axis perpendicular to the vertical axis of the cylinder and usually is associated with SI engines [5]. These large-scale motions are dependent on the bore/stroke ratio, intake valve geometry, intake port profile and the shape of the combustion chamber [6, 7].

Modern GDI engines are characterized by tumble-dominated flow fields because of the issues associated with preserving the mixture stability during stratification mode. The tumble vortex generated during the intake stroke is expected to break up during the compression stroke into small-scale structures which enhance the turbulence intensity at the time of ignition and subsequently compensating for the slow flame speed during stratification mode [8].

Particle image velocimetry is a class of methods used in experimental fluid mechanics in order to determine instantaneous velocity vector fields by measuring the displacement of numerous fine particles that accurately follow the motion of the fluid. One of the main advantages of PIV is that it can provide complete and instantaneous velocity fields. This makes the method particularly suitable for measuring velocities in unsteady or non-repeatable flows which might be impossible to investigate with standard single point techniques. PIV is also the only full-field method in no-intrusive fluid velocity metrology and is thus complementary to laser Doppler anemometry (LDA) for which full-field measurement is fundamentally difficult and time-consuming. In recent years, PIV has been successfully applied to the study of the turbulence properties [9, 10], cycle-to-cycle variability [11], flow during injection and ignition [12], flow during the intake stroke including swirl and tumble measurements. [13, 14, 15,16], etc.

In the automotive sector, steady-state flow bench is considered as a standard and economical way of characterizing the in-cylinder flow motion using a number of integral parameters, for instance, discharge coefficient, flow coefficient, tumble ratio and swirl ratio [15]. It is worth recalling also that steady-state flow rigs are the most adopted procedures for the quantification of tumble motion during the early stages of engine design [1]. Therefore, the objective of the current paper is to examine the use of particle image velocimetry as a quantitative method, and the steady-state flow rig as a qualitative method for the assessment of the evolution of the tumble motion generated inside the cylinder of a GDI at different valve lifts under steady-state conditions.

Materials and Methods

The experimental set up consists of three components, the cylinder head, the steady-state flow bench and the PIV set up.

Cylinder Head

The GDI cylinder head used in the current work is shown in Figure 1. It was four valves pent-roof cylinder head. The PIV measurements were carried out inside an optical cylinder manufactured from Plexiglas with 92.5 mm internal diameter, 3 mm wall thickness and 116 mm stroke length. The optical cylinder had two ports at its sides with an internal diameter of 32.4 mm

Figure 1 GDI cylinder head.

(35% of the cylinder bore diameter) for air outlet. Moreover, a flat piston was positioned at the bottom of the cylinder to take its effect on the tumble motion development into account.

Steady-state Flow Bench

A schematic of the steady-state flow rig is shown in Figure 2. The main principle of this rig is to simulate the engine intake stroke during the early stages of the engine design. The flow rig had a centrifugal compressor working under suction condition. The air was induced through the intake ports, intake valves, optical cylinder then finally discharges into the atmosphere. After applying a constant pressure difference of 150 mmH_2O across the air intake valves, the experiments were carried out at different valve lifts in order to access the tumble motion generated inside the cylinder through the rotational speed of the paddle wheel anemometer. For steady-state measurements, non-dimensional rig tumble (the ratio between the circumferential velocity of the tumble motion and the mean axial velocity of air in the cylinder) was calculated to evaluate the tumble motion.

The circumferential speed (C_T) of the tumble motion was calculated as follows:

$$C_T = 2 \times \pi \times N \times R_{MFL} \quad (1)$$

Where: N is paddle wheel speed, R_{MFL} (mean paddle wheel radius) $=0.36375 \times B$, where B is the bore diameter.

Likewise, the axial velocity of the air flow (C_A) in the cylinder was calculated as follows:

$$C_A = \frac{\dot{m_{real}}}{\rho_{cyl} \times A_V} \quad (2)$$

$$\rho_{cyl} = \frac{P_2}{R \times T_2} \quad (3)$$

$$A_V = n * \pi * D^2 * \frac{L}{D} * cos\emptyset \; (1 + sin\emptyset * cos\emptyset * \frac{L}{D}) \quad (4)$$

Where: $\dot{m_{real}}$ is the measured air mass flow rate by means of a rotara piston flow meter, ρ_{cyl} is air density inside the cylinder, kg/m^3, P_2 is air pressure downstream of the valves, T_2 is air temperature downstream of the valves, R is gas constant, A_V is the orifice area between the valve head and seat, D is the intake valve seat diameter, L is valve lift, n is number of intake valves per cylinder and $\emptyset$ is the valve seat angle.

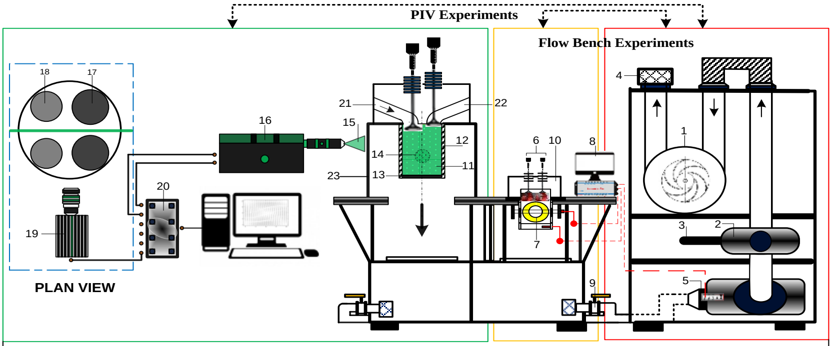

Figure 2 Schematic diagram for both steady-state flow bench and PIV experiments.

PIV Set up

The fundamental design of the rig (combination of steady-state flow rig and PIV system) was to incorporate maximum flexibility in the optical access to the cylinder volume, as shown in Figure 2. An acrylic box manufactured from Plexiglas was designed to avoid corrosion and reflection of the laser light. The fundamental concept of PIV is to seed the flow with tracer particles and illuminate the field of view twice with a high power thin laser sheet. The side scattered light from the seeding particles can be captured by means of a CCD camera. A cross-correlation technique is applied to the raw images in order to calculate the velocity vector fields. The tracers used for the PIV measurements in the current work were solid particles (Titanium Dioxide). The particles were generated by a solid particle seeder and mixed with the air through the intake port.

The light source was Nd: YAG (Yttrium Aluminium Garnet) laser (Dual Power 65-15, DANTEC Dynamics) with a wavelength of 532 nm, 15Hz of maximum laser pulse frequency and a max energy of 400 mJ. A Flow Sense 2M DANTEC Dynamics CCD camera working in double frame mode was used to capture the scattering light of the particles. The optical axis of the camera was perpendicular to the plane of the laser sheet. The acquired images were post-processed using Dynamic Studio V3.41 software to obtain the velocity vector fields. 2D-PIV experiments were carried out in the vertical tumble plane at different valve lifts from 2 to 9 mm at 1 mm steps.

Results and Discussions

Steady-state flow bench results

The strength of tumble motion in terms of its magnitude and direction was gained from the rotational speed of the paddle wheel located inside the cylinder with an axis perpendicular to the vertical axis of the cylinder. Figure 3 depicts the variation of non-dimensional rig tumble with valve lift. It can be observed that the magnitude of non-dimensional rig tumble changed from negative to positive as the valve lift increased. This indicated that the flow rotation started in the clockwise direction (denoted as reverse tumble) at low valve lifts then at almost valve lift 5 mm the paddle wheel stopped rotating as there was no tumble motion at this valve lift. By increasing the valve lift beyond this value flow rotation reversed into a counter clockwise direction (denoted as normal tumble). This can be attributed to the concept of tumbling motion generation by directing a significant amount of air at high valve lifts towards the exhaust side. This flow interacted with the left cylinder wall and the flat piston in the bottom and hence a tumble motion was generated.

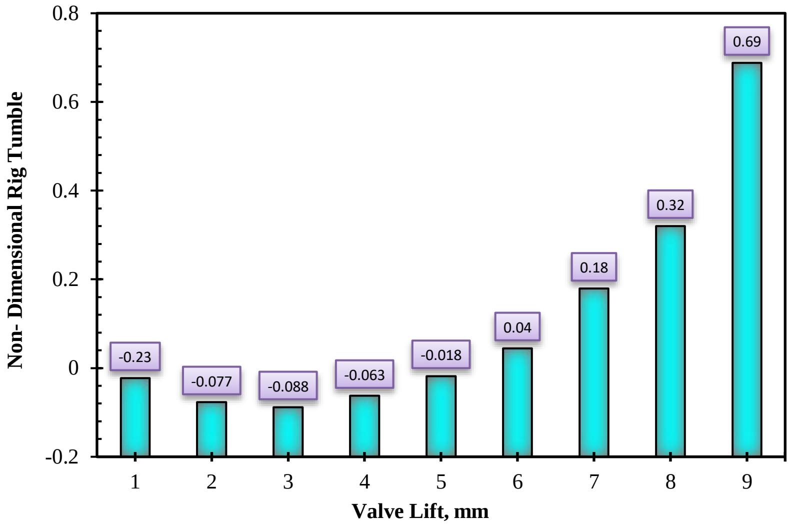

Figure 3 Non-dimensional rig tumble variations versus valve lift.

PIV results in tumble plane

Ensemble average velocity vector fields

Figure 4 depicts the ensemble average velocity vector fields at different valve lifts for the central vertical tumble plane. A number of observations were extracted, firstly, the air flow coming into the cylinder through the air intake valves formed two intake jets on both sides of the intake valves, the intake side jet and the exhaust side jet. The intake side jet was almost parallel to the cylinder wall while the interaction of the exhaust side jet with the left cylinder wall led to the formation of a counter clock-wise vortices behind the exhaust valves. Secondly, at low valve lifts, the flow was highly restricted at the right side of the air intake valves which led to the concentration of the high velocities towards the right side jet. This explains the rotation of the paddle wheel in the clockwise direction during the flow bench experiments. Thirdly, at valve lift 5mm, the effect of the flow restriction was less, therefore, there was a symmetrical velocity distribution between both air jets which explains the non-existence of a tumble in this case. Finally, at high valve lifts, because of the design of the intake ports, a significant amount of air was directed towards the exhaust side which led to the generation of strong tumble motion in a counter clockwise direction.

Vorticity contours

Figure 5 depicts the vorticity contours at different valve lifts in the central tumble plane. Vorticity is defined as the curl of the velocity vector. It was calculated from the velocity components acquired from the PIV measurements in the x and y directions. Generally, the vorticity strength increased with increasing the valve lift. As can be seen from the figure, significant differences can be found between the lower and higher valve lifts. At low valve lifts, the flow inside the cylinder was divided into two regions. The region behind the intake valves was characterized by a clock-wise vortices while the area behind the exhaust valves was characterized by counter clock-wise vortices. However, at high valve lifts, the cylinder was dominated by a strong tumble vortex in the counter clockwise direction except in the small area behind the intake valves.

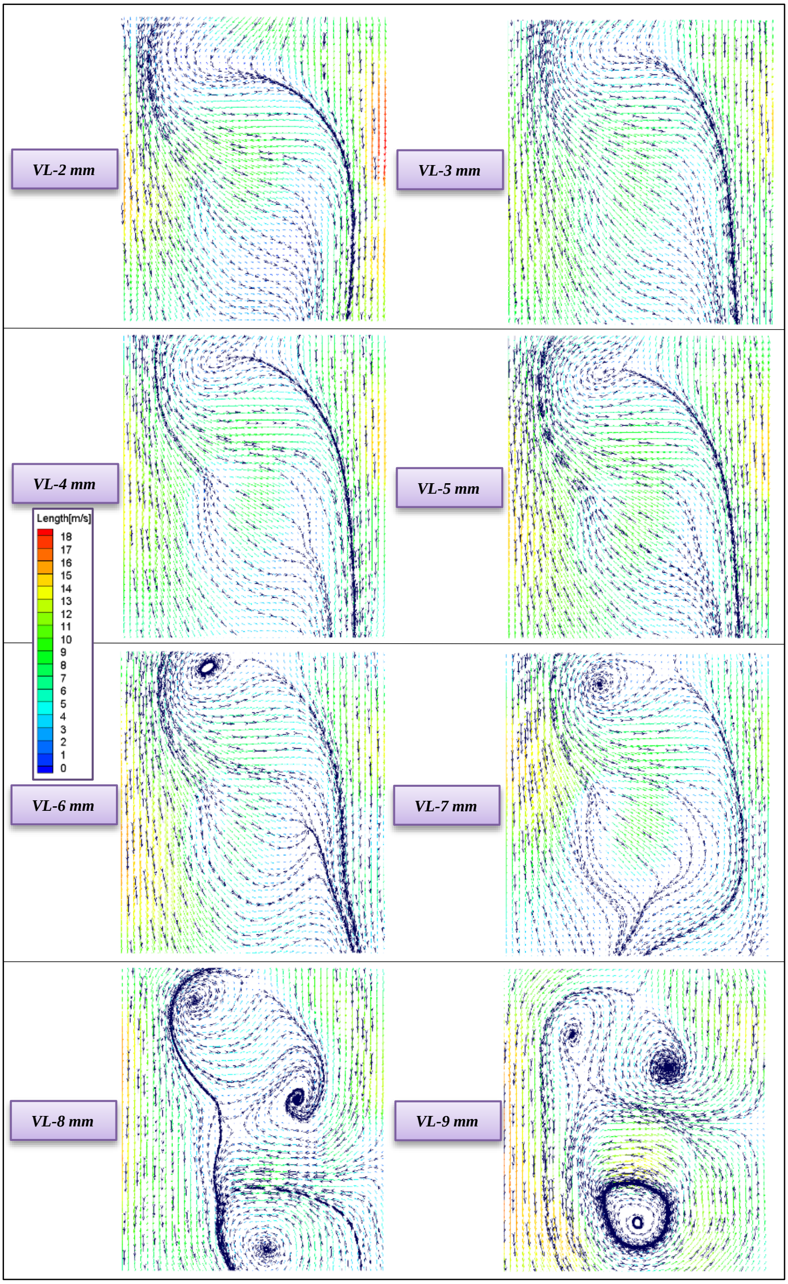

Figure 4 Ensemble averaged velocity vectors at different valve lifts.

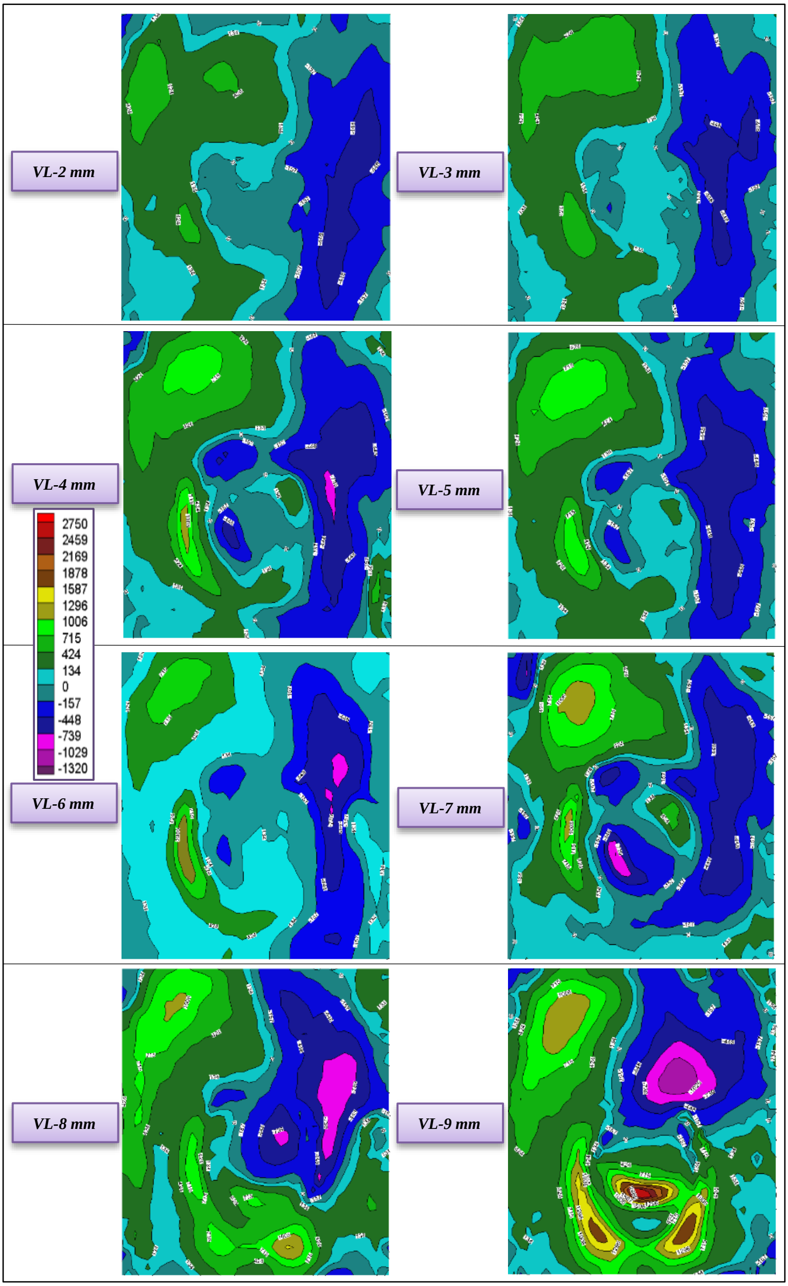

Figure 5 Vorticity contours at different valve lifts.

Conclusion

The aim of the current research work was to illustrate the evolution of tumble motion generated inside the cylinder of a GDI engine at different valve lifts using particle image velocimetry. The following conclusions were drawn from the current study:

- At low valve lifts, the flow was dominated by a reverse tumble motion. At valve lift 5 mm, the symmetrical velocity distribution behind the air intake valves led to the suppression of tumble motion.
- At high valve lifts, the flow was dominated by a strong normal tumble motion with vorticity strength increasing as the valve lift increased.
- There was a good qualitative agreement between the ensemble-average velocity distribution with the measured steady-state flow integral parameters.

Acknowledgements

The authors are grateful to the Universiti Teknologi PETRONAS.

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