PIV Experiments and In-Cylinder Flow Structure Analysis of a Motored Engine Equipped with Inclined Crown Pistons

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ABSTRACT
This paper deals with experimental investigations of in-cylinder tumble flows in a motored single cylinder internal combustion engine with two piston shapes at an engine speed of 1000 rev/min., during cold flow using Particle Image Velocimetry (PIV). The two-dimensional in-cylinder flow measurements and analysis were carried out in the combustion space on a vertical plane passing through the cylinder axis. To analyze the flow structure, ensemble average velocity vectors are used. To characterize tumble flow, tumble ratio and average turbulent kinetic energy are used. From the results, it is found that tumble flow structure is strongly dependent on piston shape and crank angle position. At end of compression stroke, inclined-bowl piston showed an improvement in tumble ratio of 13.58% and average turbulent kinetic energy of 18.12% compared to inclined piston. The present study will be useful in understanding effect of bowl in t piston on nature of the in-cylinder tumble flows in modern spark ignition engines under realistic conditions.

Keywords: Inclined piston, Bowl, In-cylinder motion, Tumble ratio.

INTRODUCTION
In the present scenario, gasoline direct injection (GDI) engine is becoming very popular because of its low fuel consumption and exhaust emissions. In GDI engine, gasoline is injected directly into cylinder late during compression stroke. In these engines, main requirement is to create charge stratification i.e., rich mixture near spark plug and overall lean mixture. Generally, charge stratification is achieved by well guided in-cylinder rotating air flows. In lean burn engines, cycle-by-cycle variations are more due to lean combustion. In these engines, practical approach to improve combustion stability is to shorten combustion duration by enhanced mean in-cylinder flows and turbulence [1]. Therefore, for optimization of modern IC engines, it is very much essential to understand in-cylinder air flow behavior under different operating conditions and configurations of the IC engine. Today, an optical tool like Particle Image Velocimetry (PIV) is extensively used for in-cylinder flow measurements due to its many advantages over other contemporaries. Earlier, many experimental and computational studies have been carried out on in-cylinder flows in IC engines with a limited work using different piston shapes. Generating a significant vortex flow (swirl and tumble) inside Internal Combustion (IC) engine cylinder during the intake stroke generates high turbulence during later stage of compression stroke leading to fast burning rates [2]. The quantified in-cylinder flows during induction and compression strokes in a four-valve, single-cylinder, pentroof chamber, optical SI engine by LDV and correlated them to combustion process under lean mixture conditions [3]. The rotating flows can significantly increase turbulence during combustion period leading to reduced burning time and increased thermal efficiency in premixed SI engines [4]. The studies on effect of the in-cylinder flows on flame initiation and propagation in modern four-valve SI engines reported that spark plug orientation relative to the mean flow using shadowgraphy visualization technique. They reported that high mean flow velocities and turbulence levels can shorten combustion duration in lean mixtures [5]. The engine in-cylinder flow studies using Particle Tracking Velocimetry (PTV) and reported that combustion control can be achieved through turbulence in a premixed lean burn engine and control of air-fuel mixing in a GDI engine [6]. The study on effect of curved piston configurations on tumble flows in a four-valve engine using LDV technique reported that main tumble is initially located under inlet valve/s and moves towards exhaust valve/s during compression [7]. Instantaneous velocity of motion measurements from LDV experiments at different engine
speeds, results shown that almost linear dependence of mean motion and turbulence on engine speed in range investigated [8]. The various PIV experimental measurements on various types of IC engines reported that flow structure changes substantially along cylinder length due to the geometry of intake port and occurrence of tumble motion during intake stroke [9]-[11] In-cylinder flow measurements using PIV at end of intake stroke on a plane between intake valves of a single-cylinder optical engine at engine speeds of 750, 2000 and 3500 rpm. They reported that tumble ratio significantly changed for engine speeds in between 2000 and 3500 rev/min [12] The experimental investigations using Laser Doppler Anemometer (LDA) reported that fluid flow structure during intake stroke was very much affected by intake valve lift and also observed that a strong flow reversal just below the intake valve at time of intake valve closure [13], [14]. Engine in-cylinder flows using PTV reported that swirl and tumble flows should be optimized for achieving good combustion [15] The above discussion clearly depicts that a good understanding of engine in-cylinder flow structure in an IC engine is very much vital for optimization of combustion chamber. Therefore, aim of present study is to measure in-cylinder tumble flow structures in a single-cylinder, two-valve, IC engine with two piston shapes under motored conditions at an engine speed of 1000 rev/min., at various crank angle degrees (CADs) during suction and compression strokes using PIV.

EXPERIMENTAL PROCEDURE

A single-cylinder, vertical, two-valve, air-cooled engine (Table 1) was coupled to an induction motor of 3.7 kW through an electronic speed controller. The maximum speed of motor was 1500 rev/min. In this study, motor along with engine was run at a speed of 1000 rev/min. In order to facilitate PIV measurements, an extension of cylinder liner was made using a transparent cylinder ring of plexiglass to a height of 35 mm above original metal liner. It facilitated a field of view (FOV) of size 87.5x35 mm. In order to maintain required compression ratio of 10:1, piston crown height was raised accordingly (for all piston shapes). Intake manifold of engine was connected to a plenum to mix and supply the air and seeding particles with uniform distribution among them. The schematic and photographic view of experimental setup is shown in Figs.1 and 2 respectively. Figure 3 shows optical access made in engine for PIV measurements.

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<th>Table I. Engine specifications</th>
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<td>Exhaust valve opening (CAD bBDC)</td>
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The PIV system consists of a double pulsed ND-YAG laser with 200 mJ/pulse energy at 532 nm wave length, a CCD camera of resolution 2048x2048 pixels with a frame rate of 14 per second and a set of laser and camera controllers, and a data acquisition system and a software (Fig.1).
Fig.1. Schematic diagram of experimental setup

The triggering signals for the laser and camera were generated by a crank angle encoder mounted on the engine crankshaft with a resolution of one CAD. These signals were supplied to the controllers via a signal modulator. A master signal of the crank angle encoder was set to occur at the suction top dead center (TDC) of the engine (considered as a zero CAD). The triggering signals for laser and camera at the required CAD can be set within the software. A seeding unit was used to generate the fine particles of one micron size with Di-Ethyl-Hexyl-Sebacat (C_{26}H_{50}O_{4}) as a seeding material. The seeding density was controlled very accurately by varying the amount of pressurized air supplied to the seeding unit. The laser sheet of 0.5 mm thickness was aligned with and camera was placed to view the FOV which was set on a vertical plane passing through the axis of the cylinder.

Fig.2. Photographic view of experimental setup

Fig.3. Modified cylinder liner for optical access

In this study, in-cylinder tumble flow measurements have been carried out during suction (30 to 180 CADs) and compression (210 to 330 CADs) strokes in steps of 30 CAD and at every measuring point, 500 image pairs were recorded and stored. The time interval (Δt) between the two images of an image pair was evaluated (6 µs for suction and 8 µs for compression strokes) based on the pixel shift (< 5 pixels), FOV, maximum expected velocity of the flow in FOV and the resolution of the camera [16], [17]. To minimize the light reflections, a band-pass filter with central wavelength of 532 nm was mounted on the camera. LaVision DAVIS (Data acquisition and visualization software) was used for image acquisition and data post-processing. During post-processing, interrogation window size of 32x32 pixels with multi-pass cross-correlation algorithm has been used [18]. The ensemble average velocity vectors were computed from 500 raw image pairs at the required CAD.

The typical raw images at 30 CAD are shown in the Fig.5 for the piston shapes considered in this study. It was observed that, at an engine speed of 1000 rev/min, the maximum amplitude of vibration of the cylinder...
liner at the point of measurement was equal to 0.0167 microns during Δt, the separation time between the images, whose effect on the error of measurement can be neglected. Before conducting experiments, the calibration of the in-cylinder environment as a whole was done along with Plexiglass liner. The calibration procedure was repeated until a root mean square (rms) fit error was less than 1.5 [16]. During the experiments, it was also ensured that clear images were captured every time.

The objective of this work is to study effect of two piston crown shapes on in-cylinder tumble flows. The pistons with different crown shapes used in this study are shown in Fig.4 with a symbol in braces representing them. Both piston shapes were fabricated such that a compression ratio of 10:1 was maintained.

![Inclined piston (I)](image1)

![Inclined-bowl piston (Iᵇ)](image2)

Fig.4. Pictorial view of inclined pistons demonstrating crown shapes

![Typical raw images at 30 CAD](image3)

Fig.5. Typical raw images at 30 CAD

**RESULTS AND DISCUSSION**

For most of the modern stratified charge and direct injection SI engines, tumble flow is more crucial than the swirl for the proper mixing of air and fuel, and also for high flame propagation rate. The tumble motion must be evaluated under transient conditions due to the significant effect of the piston shape and its motion on it unlike swirl. Swirl ratio can be obtained through steady flow experiments [15]. This study deals with the in-cylinder tumble flows under transient engine conditions. Figures 6-9 show the ensemble average velocity vectors of in-cylinder tumble flows with superimposed streamline patterns during suction and compression strokes at various CADs. In all these figures, constant length for the velocity vectors is used with colour scale to represent their magnitude. Each of these figures has its own colour scale to represent the vector magnitudes. In these figures, it is to be noted that intake valve and piston positions are shown over the velocity vector fields just to represent the relative position of them at a given CAD.
A. Flow Pattern during Suction Stroke

In this work, inclined piston was assembled such that the piston top surface was inclined down towards exhaust valve. The main intention of using the inclined piston is to provide more space at the cylinder right side where more air flow takes place such that the air jet entering cylinder would strike piston top surface at a longer distance than flat piston. This may assist in the formation of a larger in-cylinder tumble vortex.

![Fig.6. Ensemble average velocity vectors of inclined piston during suction stroke](image-url)

Figure 6 shows the ensemble average velocity vectors with superimposed streamline patterns during suction stroke at an interval of 30 CAD for an inclined piston. Figure 6(a) shows the ensemble average velocity vectors for 30 CAD during suction stroke. At this CAD, opening of the intake valve is about 15%. Also, at the left side of the intake valve, there is a very narrow passage between the cylinder wall and the intake valve causing a small amount of air to enter the cylinder at that side. More air flows at the right side and enters the cylinder in the form of a jet. Air jet after striking the right cylinder wall diverted towards piston top surface in a clockwise (CW) manner. In the similar manner, air jet entering the cylinder space at the left side, strikes the left side cylinder wall diverted towards piston top surface and moves to right side.

At 60 CAD (Fig. 6(b)), the inlet valve has opened by about 60% and air jet at the right side of the intake valve is bent downwards. Due to downward bending of the air jet, some amount of air is also forced to the cylinder space just below the cylinder head (right top corner). However, major part of the air is flowing towards the right cylinder space. Due to comparatively large opening of the intake valve, air flow rate has been increased. At this CAD, more cylinder space also exists above the piston top. Air jet entering the cylinder space strikes the piston top surface forming a large CW vortex at the right cylinder space. In the left cylinder space also, similar type of flow takes place, but a counter clock wise (CCW) vortex has been formed by the air motion. Since the air flow is mainly occurring at the right and left side of the cylinder space, there could be a low pressure region at the central cylinder space because the intake valve acts like a bluff body. This may also assist in the formation of the vortices in the cylinder space. In addition, because of the flow diversification at the right cylinder space, there exists a flow bifurcation zone and it can be seen as a thick streamline in Fig.6(b). In the similar way, another bifurcation zone has been created at the left side where CW and CCW vortices interacting each other.

At 90 CAD (Fig.6(c)), the intake valve has opened about 90% (full opening occurs at 110 CAD). The piston reaches its maximum velocity at this point and therefore, the air flow rate is also maximum at this condition. At this CAD, the air jet at the right side of the intake valve is moving with full speed. Air jet, after striking the piston top surface and also due to low pressure region below the intake valve, forms a large CW tumble vortex. The formation of the large tumble vortex is the result of a strong jet flow which emerges from the intake valve into the cylinder (Khalighi, 1991). At the right cylinder space, air flow striking the right cylinder wall moves downward and forms another CW vortex. The two vortices formed are interacting each other.
resulting in the formation of the bifurcation zones as shown in Fig. 6 (b). In addition, near the left cylinder wall, randomness in the flow is also observed. It may be due to higher turbulence at the engine speed considered here or it may be due to reflections of light from the metal surface also (Fig. 6).

At 120 CAD (almost full intake valve lift, Fig. 6(d)), the tumble flow pattern is almost similar in nature to that of 90 CAD. However, at this CAD, size of the vortices has been increased may be due to larger cylinder space above the piston top. In addition, a portion of the air jet at the right side cylinder wall, after striking the piston top surface and right cylinder wall, diverts upwards forming CCW vortex. At 150 CAD (Fig. 6(e)) also, the in-cylinder tumble flow pattern is similar to that of 120 CAD. Here, the air jet at the left side of the intake valve, after striking the left cylinder wall and piston top surface, forms CCW vortex. At 180 CAD (Fig. 6(f)), intake valve opening is very less and fresh air entry is also very less. However, the air which is already present in the cylinder is undergoing changes in the flow pattern. From Fig. 6(f), it can be observed that, a large CW vortex has been formed almost dominating the entire cylinder space with center of it lying almost at the center of the FOV. A well defined (strong single vortex) swirl and/or tumble flow structure is more stable than other large scale in-cylinder flows which may break up later in the cycle giving higher turbulence [15]. Also, from Fig. 6(f), it can be observed that the formation of a small vortex near the top left corner of the FOV. It may be due to the low pressure region at that point because of large a single vortex formation at the center cylinder space.

Next, the investigations of in-cylinder tumble flows with an inclined-bowl piston were done. In this case, the inclination and orientation of the piston was kept the same as that of inclined piston. The intention of having bowl in inclined piston is to provide a guiding surface for the smooth movement of the tumble vortex in addition to the more cylinder space at the right side. Figure 7 shows the ensemble average velocity vectors with superimposed streamline pattern during suction stroke for inclined-bowl piston. From Fig. 7, it can be observed that the in-cylinder flow pattern is similar to that of other piston shape considered in this study. However, at the end of suction stroke, a very clear single CW vortex has been formed. The size of the vortex looks smaller compared to that of inclined piston. This may be due to the effect of piston bowl which makes the vortex confined to rotate along with it. The better comparison of the flow patterns with different piston shapes is made later with the help of tumble ratio (TR) and average turbulent kinetic energy (TKE).

Fig. 7. Ensemble average velocity vectors of inclined - bowl piston during suction stroke

B. Flow Pattern during Compression Stroke

Figure 8 shows the in-cylinder tumble flow pattern for a inclined piston during the compression stroke on a central vertical plane from 210 to 330 CADs at an interval of 30 CAD at an engine speed 1000 rev/min.
At 210 CAD (Fig.8 (a)), a large single CW vortex created at the end of suction stroke has been shifted towards the left side of the cylinder. This may be due to the upward motion of the piston during compression stroke which squeeze the air flow pattern as a whole.

In addition, air flow from the other zones of the cylinder space after striking the right cylinder wall is forming another CCW vortex at the right cylinder space. Both these vortices are striking each other and forming a three bifurcation zones in the entire cylinder space.

At 240 and 270 CADs (Fig.8 (b) and (c)), the in-cylinder tumble flow pattern is almost similar in nature. But, only the size of the single large vortex formed earlier has been reduced. The bifurcation zones created earlier are also maintained as such. At 300 CAD (Fig.8 (d)), the piston has moved further up and thereby cylinder space has further reduced. Due to this, the CW vortex has become dominant compared to the flow pattern at
The tumble flow pattern looks more random due to the decay of the vortices formed earlier. Figure 8 (d) shows the in-cylinder flow pattern at 330 CAD. From Fig.8 (e), it is observed that there is a clear CW movement of the air flow as a whole. Normally, in the stratified charged and direct injection SI engines, the spark plug is located at the center of the combustion chamber. Therefore, once ignition starts, the turbulence of the flow in the combustion space would aid proper flame propagation leading to effective combustion [15]. Here, it is very much clear that irrespective of the formation of vortex and air flow patterns during early stages, a favorable tumble air flow pattern occurs at 330 CAD which is very much required.

Figure 9 shows the in-cylinder tumble flow patterns for inclined-bowl piston during the compression stroke at an interval of 30 CAD. In this case also, a dominant CW vortex has been observed. It may be due to the guiding effect of the piston bowl. The decrease in the flow velocity towards the end of compression stroke indicates the tumble deterioration. In the case of pistons with bowl, it is observed that tumble vortex is sustained till the end of compression which may be due to guiding effect of the piston bowl. The pistons with bowl located below the exhaust valves, the tumble vortex is more sustained at the end of compression stroke than with other types of piston shapes [7]. However, the effect of the piston shape on the in-cylinder tumble flows can be better understood with the help of tumble ratio and turbulent kinetic energy of the flow. In the following sections, they are discussed.

C. Variation of Tumble Ratio
Unlike the swirl ratio, the tumble ratio (TR) must be evaluated under transient conditions due to the significant effect of the piston shape and its motion on the in-cylinder tumble flows. Also, during compression, tumble flow is found to be more effective than swirl, both in extracting the energy from the piston and transferring it into turbulence [15]. Also, at compression TDC, the pure tumble flow generated the highest fuel concentration in the vicinity of the spark plug at given engine speed and injection timing [20]. In this study, in-cylinder tumble flows are characterized by tumble ratio (TR) calculated as per [21]. Here, the TR is defined as the ratio of the mean angular velocity of the vortices on the target plane to the average angular velocity of the crank. The negative or positive magnitudes of TR indicate that the overall direction of in-cylinder tumble flows in a given plane as CW or CCW respectively.

Figure 10 shows the variation of the TR at different CADs during suction and compression strokes at an engine speed of 1000 rev/min., for both piston shapes. The air jet emerging into the cylinder space through the intake valve strikes the cylinder walls and piston top surface forming CW and CCW vortices. In general, with these pistons, the air movement is predominant at the right cylinder space than at the left. Therefore, at most of the crank angle positions, air movement is from right to left cylinder space. Also, it is to be noted that the tumble flow patterns obtained in this study are similar to those obtained by [15].

The overall air movement at the end of compression stroke gives a better idea for the engine designers to fix the position of the spark plug and the fuel injector in modern SI engines. Good charge stratification is crucial and it is achieved with strong tumble flow [19]. Even though, the present study, deals only with the in-cylinder air flow pattern, however it almost depicts the mixture flow pattern as well, because the mixtures are very lean in these SI engines. Therefore, study of tumble air flow pattern at 330 CAD is very much useful especially for the stratified charged and direct injection SI engines.

From Fig.10, at 330 CAD, inclined-bowl pistons have higher TRs compared to their corresponding plain inclined piston. It may be due to that, in case of this piston, the guiding effect of the piston bowl helps to retain the tumble vortex generated during suction stroke till the end of compression stroke. Stronger the tumble motion during the suction stroke; more the TKE released by its breakdown during late compression stroke leads higher turbulence levels at the time of ignition [1]. It is found that, I₆ piston have resulted in 13.58% improvement in TR compared to its respective plain inclined piston.

D. Variation of Average Turbulent Kinetic Energy
Figure 11 shows the variation of average turbulent kinetic energy (TKE) for various CADs during suction and compression strokes for both the piston shapes considered. TKE is proportional to the level of the flow velocities within the cylinder.
The variation of the average TKE obtained in this study with crank angle position is similar in nature with those of [19]. The TKE of the flow indicates its strength as a whole. From Fig.11, for both the piston shapes, the magnitude of TKE is highest at 60 CAD. It may be due to that, at this CAD, the piston has moved sufficiently down, inlet valve has also opened enough and cylinder space is optimum for better air flow to occur, thereby increases the TKE. From figure 11, at 330 CAD the TKE is more for Ib compared to I piston. Ib piston showed an improvement in TKE of about 18.12 % compared to its corresponding plain inclined piston.

**CONCLUSIONS**

The following conclusions are drawn based on the experimental study carried out:

For both the piston shapes considered, it is observed that the main tumble vortex formed during suction stroke is initially located beneath the intake valve and later moves towards the exhaust valve at the end of compression stroke. And the average turbulent kinetic energy is reaching its peak value at about 60% of intake valve opening position.

- At the 330 CAD, inclined-bowl piston showed an improvement in tumble ratio and average turbulent kinetic energy by about 13.58 % and 18.12 % respectively compared to inclined piston.
- On the whole, inclined-bowl piston showed a good improvement in tumble ratio as well as average turbulent kinetic energy at the end of compression stroke compared to plain inclined piston. This study will be useful for understanding the effect of bowl in piston crown shapes on the in-cylinder tumble flow patterns under realistic conditions.

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**REFERENCES**