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EXPERIMENTAL INVESTIGATION ON TUMBLE MOTION DURING COLD FLOW OF ENGINE EQUIPPED WITH BOWL PISTON

Murali Krishna. B[1], J. M. Mallikarjuna[2]

[1]*Department of Mechanical Engineering, Sri Sivani College of Engineering, Srikakulam, AP, (India)*

[2]*Internal Combustion Engine Laboratory, Department of Mechanical Engineering Indian Institute of Technology Madras, Chennai, (India)*

ABSTRACT

Fluid flow characteristics have a great influence on fuel and air mixture formation, and therefore combustion process and emissions of an internal combustion engine. The flow analysis of engine is important for optimum design of combustion chamber. The objective of this work is to investigate in-cylinder tumble flow characteristics of a single cylinder optical engine during suction and compression using Particle Image Velocimetry (PIV) at particular speed of 1000 rev/min using flat and flat-with-bowl pistons under motored condition. For this, two-dimensional in-cylinder tumble flow measurements are carried out. The ensemble average velocity vectors are used to analyze tumble flow structures. The tumble ratio (TR) and average turbulent kinetic energy (TKE) are evaluated and used to characterize the tumble flows. From analysis of results, it is observed that, at end of compression (330 CAD), flat-with-bowl piston shows highest TR of 0.13 and TKE of 5.52 m^2/s^2 compared to flat piston. That is 18.9% higher of TR and 48.3% higher of TKE is achieved with flat-with-bowl piston compared to flat piston. On whole, it can be concluded that flat-with-bowl piston is effective than flat piston in achieving and preserving higher tumble at the end of compression which is desirable for the stratified combustion conditions.

Keywords: Flat-With-Bowl, Image, Piston, TKE, TR, and Velocity Field

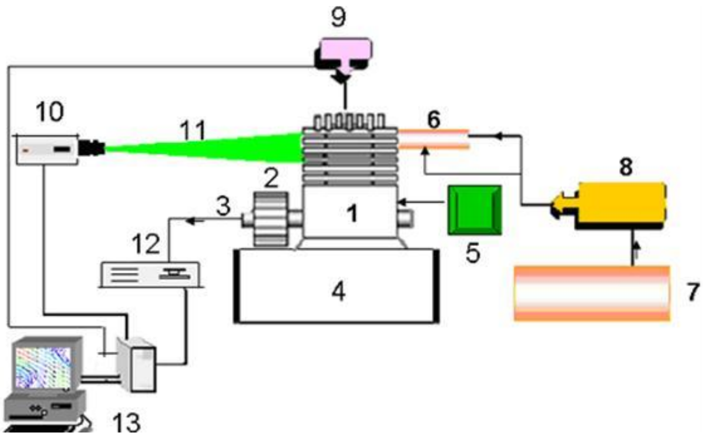
I. INTRODUCTION

Today, modern spark ignition (SI) internal combustion (IC) engines like stratified charged and gasoline direct injection (GDI) engines are becoming very popular because of their low fuel consumption and exhaust emissions. In GDI engines, the main requirement is to create charge stratification i.e., rich mixture near the spark plug and overall lean mixture. Generally, charge stratification is achieved by the well guided in-cylinder rotating air flows. For optimization of modern IC engines, it is very much essential to understand the in-cylinder air flow behavior. In the present scenario, optical diagnostic technique like Particle Image Velocimetry (PIV) is used for the complex in-cylinder flow measurements. The important features of PIV are: non-intrusive, high spatial and temporal resolution, also it is possible to visualize the entire flow field instantaneously. Generating a significant vertical flow motion (swirl and/or tumble) inside the engine cylinder during the intake process is one of the more promising ways to achieve fast burning rate *(Heywood 1988).* In-cylinder flow of engines can be distinguish by two types of motions: swirl flow commonly found in diesel engines and tumble flow commonly found in gasoline engines, these rotational motions occur about an axis parallel and perpendicular to the cylinder axis respectively. The magnitudes of both these components are heavily dependent on port design, intake valve geometry, bore to stroke ratio, shape of combustion chamber. In general, swirl motion keeps the charge to concentrate near periphery of the piston cavity while tumble keeps the fuel vapors deflected by the piston cavity in the vicinity of spark plug. *Fraidal et al. (1996) and Zhao et al. (1999)* assessed that GDI is the ultimate strategy for fuel economy improvements. They have suggested that to have late injection and stratified charge combustion during part-load operation; early injection and homogeneous charge combustion during full-load operation. *Hill and Zhang (1994)* have reported that rotating flow can significantly increase turbulence intensity during the combustion period, led to a reduced burning period and increased thermal efficiency in premixed SI engines. *Kuwahara and Ando (2000)* made engine in-cylinder flow studies using Particle Tracking Velocimetry (PTV) and reported that; combustion control was achieved through turbulence for the premixed lean burn engine and air-fuel mixing for the GDI. *Valentino et al. (1993), Reeves et al. (1999), Yasar et al. (2006) and Stansfield et al. (2007)* had conducted PIV measurements on various engines and reported that the flow structure changes substantially along the cylinder length due to the geometry of the intake port and there was tumble motion generated during induction process. *Khalighi (1991),* reported that swirl and tumble motions should be maximized to maximize the turbulence still obtaining the best combustion using PTV measurements. Also, reported that, the intake flow field is dominated by a strong single vortex in the region between the cylinder head and the piston. This vortical motion is generally known as a tumble vortex. *Li et al. (2002)* applied digital PIV system to study the in-cylinder flow in a single cylinder engine and obtained velocity depending parameters like turbulent length scale, vorticity and strain rate distribution.

It is to be noted that, even though in-cylinder flow is influenced by many parameters as said above, interest of this work is to see the piston shape effect alone under flat bottom cylinder head condition. So that, this work is especially aimed to study the effect of piston crown shape on in-cylinder fluid flow field characteristics of a four-stroke, two-valve, single-cylinder engine under motored conditions at an engine speed of 1000 rpm., at various crank angle degrees (CADs) during suction and compression strokes using PIV technique. Two-valve engine is chosen since it provides cross flow within the cylinder which will be helpful in achieving a clear tumble motion. Also, two valve engines are very simple and good potential.

III. EXPERIMENTAL SETUP

The specifications of a single-cylinder, four-stroke, air-cooled engine used in this study are given in Table.1 of Appendix. The engine is coupled to an induction motor of 3.7 kW through an electronic speed controller. The schematic view of the experimental setup is shown in Fig.1. In this study, the motor along with the engine is run at a speed of 1000 rev/min. In order to facilitate the PIV measurements, an extension of the cylinder liner is made using a transparent cylinder ring. In order to maintain the required compression ratio of 10:1, the piston crown height is raised accordingly. In design and fabricating of pistons, the net volume of the both extended both flat and flat-with-bowl pistons (Fig.2) maintained same, so that the bowl effect can be seen under same compression ratio of 10:1. The PIV measurement system consists of 1).Double pulsed Nd YAG Laser with 200mJ output and 532nm wave length, 2).CCD Camera with resolution 2048 x 2048 and 3).Laser and Camera Controllers and 4).Data acquisition system. Test engine setup includes simulator and variable speed controller. The trigger signal was generated by a shaft encoder with a resolution of 1^0 CA via engine simulator at a pre-set crank angle (CA). The seeder unit was used to generate 1 micron droplets, type of seeder used in this study is Di-Ethyl-Hexyl-Sebacat ($C_{26}H_{50}O_4$-DEHS) and seeder was mixed with air in a particle generator and was mixed with the intake air supply. The seeding particle mist was introduced into the cylinder through a flexible pipe that was connected to the intake port via intake plenum of the engine to achieve uniform mixing. A precision pressure regulator was used to control the seeding density in the cylinder. At speed 1000 rpm, 500 image pairs were acquired at each crank angle. The camera and Laser head were controlled remotely through LaVision supplied DaVis 7.2.2 software. The recorded images were processed using Davis software. From this the local particle displacement between the two exposures and combined with the known time interval (Δt) between exposures will give velocity vectors in the FOV. The laser pulse separation (Δt) varied from 6μs to 8 μs to account for the change of the velocity during cold flow.



1. Engine, 2. Motor, 3. Encoder, 4. Test bench, 5. Speed controller, 6. Intake plenum,
7. Air compressor, 8. Seeder, 9. Camera, 10. Nd-YAG Laser, 11. Laser sheet,
12. Engine simulator, 13. Data acquisition system

Fig.1 Line Diagram of the Experimental Setup

During PIV recording, the optimum focus set to 3 and aperture number of 8 is maintained to obtain sharp particle images with less light reflections. The optimum density of particles within the FOV is chosen by monitoring the scattered laser light intensity and similarly time separation (Δt) was optimized based on pixel shift. DAVIS 7.2.2 software was used for image acquisition and post-processing. During the post-processing process, the image pairs were divided into small interrogation regions by using multi pass 32x32 pixels cross-correlation algorithm to determine the particle displacement.

Flat piston	Flat-with-bowl piston

Fig.2 Flat and Flat-with-Bowl Pistons

III. RESULTS AND DISCUSSION

Figures 3 to 6 show the average velocity fields with superimposed streamline patterns for various CA positions at speed of 1000 rpm for both the pistons. From Fig.3 and 4, it is observed that, both flat and flat-with-bowl pistons there is a strong tumble was formed at the end of the suction. And it was sustained towards the end of the compression (Fig.5 and 6).

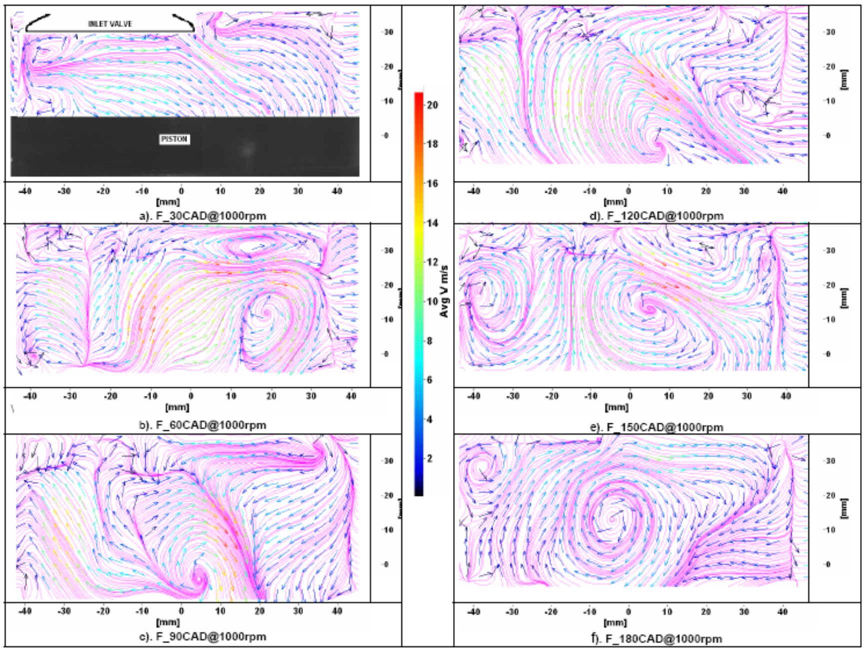


Fig.3 The Ensemble Average Velocity Vector Fields of Flat Piston During Intake Stroke

3.1Suction Flow Field

Figure 3 and 4 shows the main features of the induction flow fields in the central plane at a crank angle of 30° to 180° after TDC. The flow over intake valve forms rotating vortex towards exhaust valve. From Fig.3 and 4, during intake valve full opening (90 CAD) the emerged fluid flow forming single ordered vortex located more centrally within the cylinder. The tumble vortex can be observed clearly in the field of view (FOV) at 90 CA

BTDC. Further, flow gives rise to a simple and strong vortex flow towards end of suction stroke (180 CAD). The fluid flow emerging during valve opening hits the piston crown further turns and forms tumble flow within the cylinder. Also the emerging fluid flow at the same time strikes cylinder wall, rebounds and hits the intake valve face further forming two vortices due to flow separation. In this one is beneath the left side of in take valve face coinciding with earlier discussed big vortex and second one is right side of in take valve (i.e. beneath the exhaust valve) rotating in the opposite direction. Also, towards end of suction stroke intensity of tumble vortex flow are increasing and its center of rotation gradually shifting to the central part of combustion chamber. In addition, the vortex flow due to separation squeezed by tumble vortex flow and the other vortex flow due to separation is pushed towards the cylinder wall.

3.2 Compression Flow Field

Flow during compression is shown in figures 5 and 6 for both flat and flat-with-bowl piston crowns respectively. The fluid flow pattern at the beginning of compression is entirely different from end of compression not like suction flow pattern. The increase in tumble flow at vertical mid axis during compression promotes the destruction of all other small vortex flows. And at 330 CAD, center of rotation is entirely displaced towards the zone beneath the intake valve with stretching of vortex flow in the specified plane. This is due to the compression of fluid by piston movement. During suction and compression, the center of rotation of vortex flow is gradually displaced from exhaust valve region to intake valve region. As it known that the existence of tumble flow within the cylinder near TDC dominantly affects the flame propagation and shape. The tumble centre was also found to be located almost centrally between the piston and the cylinder head during the compression.

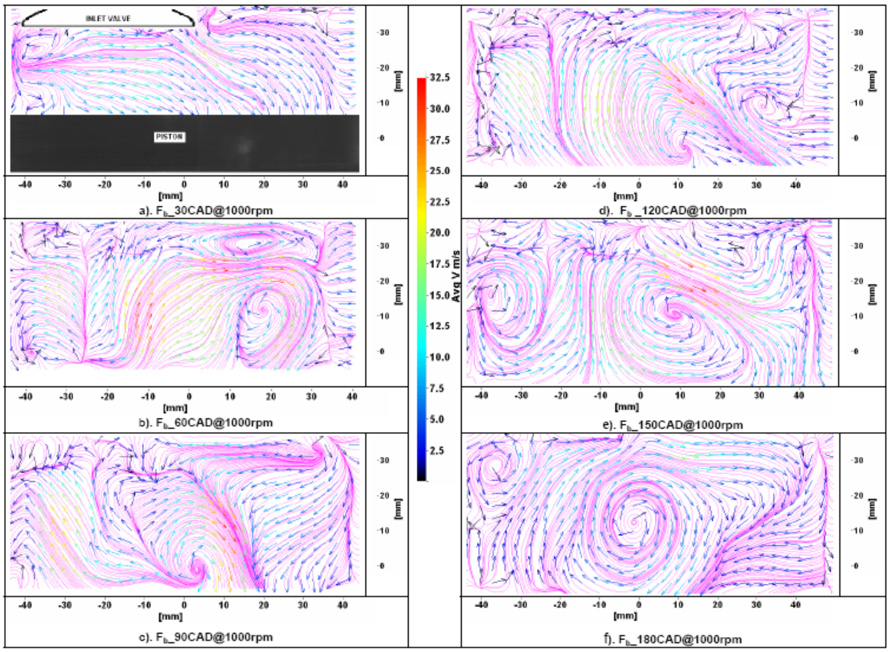


Fig.4 The Ensemble Average Velocity Vectors of Flat-with-Bowl Piston During Intake Stroke

During the first half of the compression stroke (upto 270 CAD) tumble flow was fully developed and the tumble centre is moved gradually towards the exhaust side of the cylinder while piston ascends. During the second half of the compression stroke, the tumble vortex was being pushed gradually by the piston into much less space above the piston. However, the tumble vortex remained evident in the cylinder at 330 CAD. The above results indicate that the large-scale tumble vortex can survive up to the late period of the compression and hence it will help to maintain the stratified charge pattern before ignition and further helpful in achieving stable ignition and combustion. Average velocity field presents an ideal flow pattern for the fuel stratification at 330CAD.

3.3 Variation of TR with CAD

The flow structures at considered plane with both pistons looking similar. Also, with these pistons the visual qualitative comparison is difficult to judge the significant difference of flow motions. In order to compare the strengths of tumble motion induced by both the pistons, a quantitative index called the Tumble Ratio (TR) was used to quantify the fluid flow motions. Figure 7 shows the variation of the TR at different CADs during intake and compression strokes. It can be noted that the TR up to 300 CAD was approximate, since the FOV was 1/3rd of the entire cylinder. Also, TR was declined in the middle stage of the compression stroke and then increased rapidly to a peak value at 270 CAD. The different changes (direction from CW to CCW) in TR during suction and compression may be due to the different flow boundary conditions imposed within the cylinder. Also, may due to that interaction of vortices moving into or out of either the plane or the field of view. Also due to change in the piston speed with respect to CAD, the direction of the piston movement during suction and compression strokes in addition to the flow associated with the spinning-up process, due to conservation of the angular momentum and reduction in the moment of inertia as the piston moves upwards.

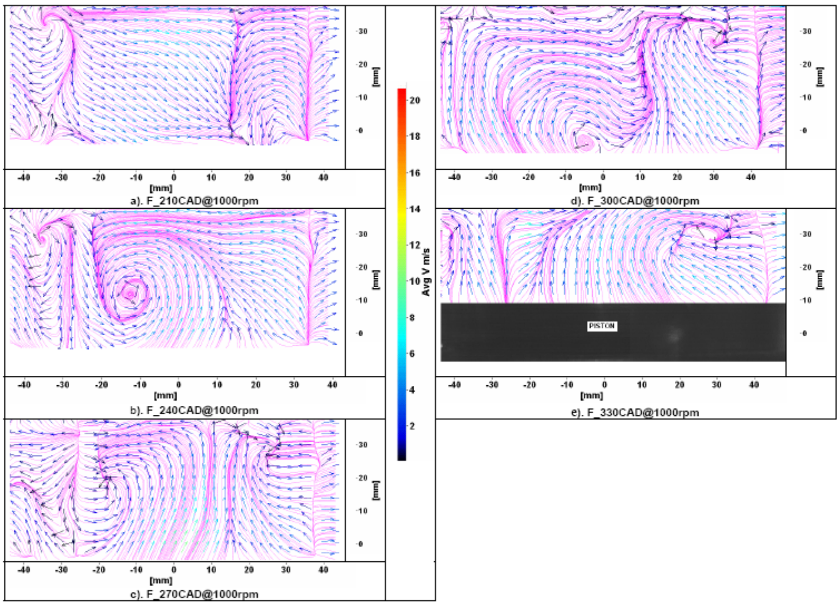


Fig.5 The Ensemble Average Velocity Fields of Flat Piston During Compression

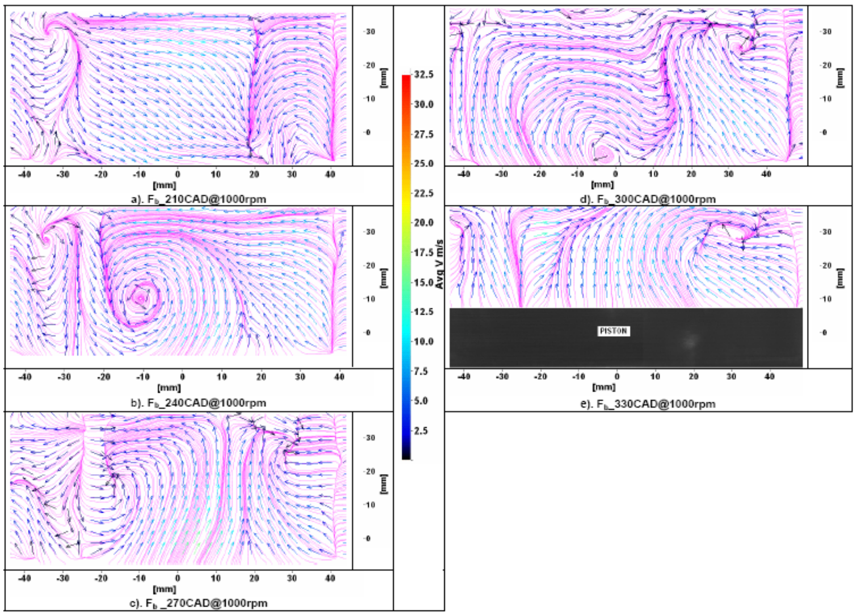


Fig.6 The Ensemble Average Velocity Vectors of Flat-with-Bowl Piston During Compression

It is to be noted that upto from 60 to 300 CAD, we can observe the trend alone (limitation of FOV).The actual magnitudes of TR may be higher or lower the magnitudes of TR shown here within this CAD range. From Fig.7, it is observed that the TR is large with the flat-with-bowl piston during both suction and compression for most of CAD. It may be due that the bowl of the piston helps in retaining the fluid motion the way which is formed. At interested 330 CAD (at the end of compression), TR is 0.11 and 0.13 corresponds to flat and flat-with-bowl pistons respectively i.e.18.9 % higher tumble with flat-with-bowl piston compared to flat crown piston. At the end of compression (330 CAD), TR is the more with bowl piston which is desirable for stratified combustion. Tumble can increase the mean level of turbulence intensity during compression, which in turn enhancing the fuel burn rates (*Li et al., 2002*) further improves the thermal efficiency.

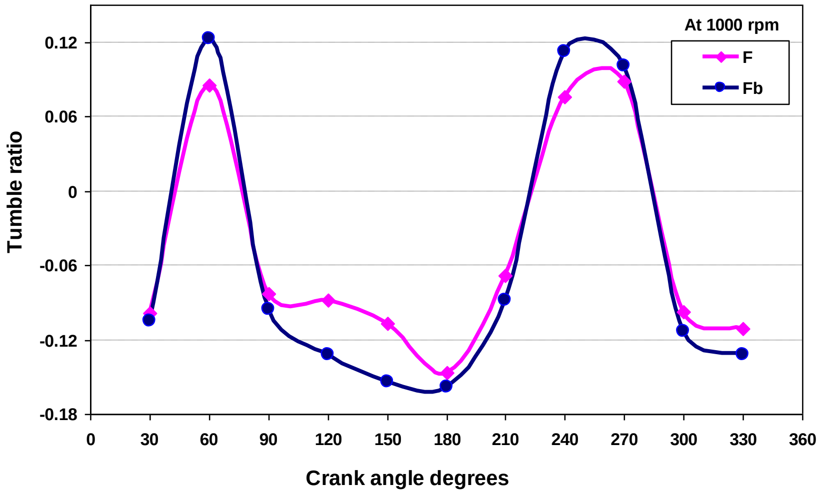


Fig.7 Tumble ratio with Crank Angle Positions

3.4 Variation of TKE with CAD

The TKE is an important parameter to characterize in-cylinder flows in IC engines. The TKE at the later stages of compression stroke becomes extremely important in SI engines, because at that position, ignition occurs and higher TKE dissipated as turbulence would assist in higher flame propagation rate *(Li et al., 2002)*. Therefore, in the subsequent sections, TKE at 330 CAD is used as main parameter to characterize the in-cylinder tumble flows. The variation of TKE of the in-cylinder tumble flows at the target plane at various CADs is shown in Fig.8. It is observed that peak TKE occurs at about 60 CAD during intake stroke.

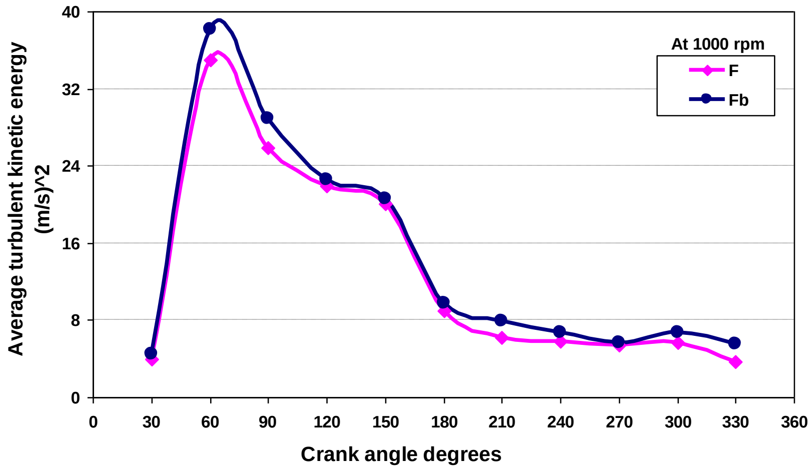


Fig.8 Turbulent Kinetic Energy Against Various Crank Angles

From Fig.8, the following distinct stages can be identified based on TKE profile which is similar to that of literature review of *Achuth and Mehta (2001).* The destruction of the mean vortex before TDC gives rise to turbulence enhancement, by supplying the mean flow energy contained in the vortex for the purpose, which will be helpful in reducing the combustion duration *(Li et al., 2002)*. Turbulence generated by tumble motion is very helpful in increasing speed of already reduced flame speed of lean mixture at end of compression stroke. The TKEs of in-cylinder flows at symmetry plane at various crank angles are shown in Fig.8. The flat-with-bowl piston produced higher TKE than the flat crown piston at all CAD. At the end of compression (330 CAD), TKE of flat and flat-with-bowl pistons are 3.73 and 5.53 m^2/s^2 respectively. This shows that the flat-with-bowl piston induces 48.3% higher TKE is achieved with flat-with-bowl piston compared to flat piston.

IV. CONCLUSIONS

- Strong tumble was formed at end of the suction and sustained towards end of compression.
- The strength of the tumble motion attains maximum between crank angles of 120 CAD and 180 CAD. Tumble vortex was evident with in the cylinder at 330 CAD, indicated that the large-scale tumble vortex can survive up to the late period of the compression and hence it will help to maintain the stratified charge pattern before ignition.
- At the end of compression (330 CAD), Flat-with-bowl piston generated higher TR, which is 18.9 % higher compared to flat crown piston.

- At the end of compression (330 CAD), flat-with-bowl piston generated higher TKE, which is 48.3 % higher compared to flat crown piston.

On whole, flat-with-bowl piston is effective than flat piston in keeping the tumble motion at the end of compression which is desirable for stratified combustion.

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Appendix-I

Table1: Engine Specifications

Engine type	4-stroke, 2-valve
No. of cylinders	1
Bore X Stroke (mm x mm)	87.5 x 110
Compression Ratio	10:1
Max. Valve lift (mm)	7.6
Intake/Exhaust Port diameter. (mm)	28.5
Engine speed (rev/min)	400
Intake valve open (bTDC-deg)	4.5
Intake valve closed (aBDC)	35
Exhaust valve open (bBDC)	35
Exhaust valve closed (aTDC)	4.5