

Study of Swirl and Tumble Motion using CFD

Abhilash M Bharadwaj, K Madhu, Seemanthini J, Vismay K G, Aravind T & Anand M Shivapuji¹,

Dept. of Mechanical Engineering, Atria Institute of Technology, Bangalore

¹Research Scholar, Indian Institute of Science, Bangalore

E-mail : abhilashbharadwaj19@gmail.com, madhuknaidu91@gmail.com, seemanadig@gmail.com, vismay.kg@gmail.com, anandms@cgpl.iisc.ernet.in, aravind.sagar@yahoo.com

Abstract - The call for environmentally compatible and economical vehicles, still satisfying demands for high performance, necessitates immense efforts to develop innovative engine concepts. In an Internal Combustion Engine the performance, efficiency and emission formation depends on the formation of air-fuel mixture inside the engine cylinder. The fluid flow dynamics plays an important role for air-fuel mixture preparation to obtain the better engine combustion, performance and efficiency. Due to the extreme conditions inside a typical IC-engine (high combustion temperatures and pressures, precipitation of soot and other combustion products, etc.) experimental techniques are sometimes limited in approaching the above mentioned problem. Alternatively, computer simulations (Computational Fluid Dynamics, CFD) offer the opportunity to carry out repetitive parameter studies with clearly defined boundary conditions in order to investigate various configurations. We investigate two important, common fluid flow patterns from computational fluid dynamics (CFD) simulations, namely, swirl and tumble motion typical of automotive engines. These two parameters represents the fluid flow behaviors occurred inside combustion chamber which influences the air streams to the cylinder during intake stroke and enhances greatly the mixing of air and fuel to give better mixing during compression stroke. In this study we are concerned on the swirl motion of inducted air during the suction stroke and during compression stroke. The results obtain from the numerical analysis can be employed to examine the homogeneity of air-fuel mixture structure for better combustion process and engine performance.

Index Terms—CFD simulation, Swirl motion, Tumble motion, Swirl and Tumble coefficients.

I. INTRODUCTION

In 1876, Nicolaus A. Otto developed the spark-ignition engine and in 1892 Rudolf Diesel invented the compression-ignition engine. They were the first who studied the internal combustion engines [8]. The in-cylinder flows of internal combustion engine have drawn much attention to automotive researchers and scientist in the present times. An optimal combustion process within an engine block is central to the performance of many motorized vehicles [1]. The in-cylinder charge motion often plays a dominant role in

processes of preparation and conveyance of fuel mixture in the engine [2]. The production of high turbulence intensity is one of the most important factors for stabilizing the ignition process and fast propagation of flame, especially in the case of lean-burn combustion. In the flow within a cylinder, we can distinguish between two types of motion: swirl flow commonly found in diesel engines and tumble flow commonly found in gas engines. In both cases, rotational motion occurs about an axis, though the position of the respective axis is different [4]. Air motion in the combustion chamber is three-dimensional [2]. On a broader perspective, it the in-cylinder motion may be characterized as a combination of swirl, sideways-tumble and normal-tumble [2]-[3]. They contribute to the development of engine performance by accelerating mixing of fuel and induced air. Hence it is indispensable for development of an IC Engine with high compression ratio to realize high turbulence intensity and lean burn combustion. Swirl and tumble flows are always generated during intake and compression stroke of the internal combustion engine due to the high turbulence in the cylinder.

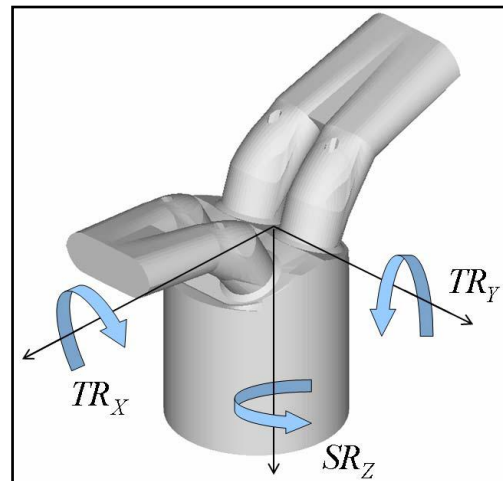


Fig. 1 Definition of in-cylinder flow: sideways tumble TR_x , normal tumble TR_y and swirl SR_z . [2]

II. IN-CYLINDER FLUID MOTION

The resultant influence of swirl and squish coupled with the conservation of angular momentum of swirl gives rise to high swirl velocities inside the piston-bowl and high turbulence levels near the bowl entry plane. To analyze in-cylinder air motion, swirl and tumble ratios, for both- the sideways and nominal directions are calculated for every crank degrees of engine cycle. This is done so as to compute the behavior of fluid flow field characteristic. The in-cylinder fluid motion in internal combustion engines is one of the most important factors controlling the combustion process. The fluid flow prior to combustion in internal combustion engines is generated during the induction process and developed during the compression stroke. Therefore, a better understanding of fluid motion during the induction process is critical for developing engine designs with the most desirable operating and emission characteristics. Matching the combustion chamber geometry, fuel injection and gas flows is the most crucial factor for attaining a better combustion.

III. SWIRL MOTION

Swirl is defined as the large scale vortex in the in-cylinder fluid with the axis of rotation parallel to the piston axis. Swirl, considered as a two-dimensional solid body rotation, persists through the compression and combustion processes [5]. The decay of swirl in an engine cylinder during the compression process is relatively small so that the overall angular momentum of the swirl vortex is almost conserved [3]. For example, Liou and Santavicca (1983) found that turbulence was nearly homogeneous and isotropic near TDC in their engine experiments. They also showed that turbulence intensity near TDC at a given speed was 25-50% greater with swirl than without and then declined continuously with crank angle [5].

IV. TUMBLE MOTION

Another intake-generated large-scale vertical flow pattern is the tumbling motion. The rotation axis of vortex is normal to the cylinder axis, resembling the rotation of a barrel. It is formed about a circumferential axis near the edge of the clearance volume in the piston crown or in the cylinder head, which is caused by squishing of the in-cylinder volume as piston reaches near TDC. Thus, tumbling motion is also called as vertical swirl or barrel swirl. To generate a pure tumbling motion for single intake-valve cylinders, the directional vector of intake jet should be on the plane defined by the cylinder axis and the intake valve axis. A tumbling flow with both the radial and the axial motion is therefore expected in the cylindrical coordinate. If an intake jet has only the tangential and the axial

components in the cylindrical coordinate, a pure swirl flow is produced.

V. SWIRL AND TUMBLE COEFFICIENTS

Both swirl and tumble flows are commonly characterized by a dimensionless parameter employed to quantify rotational and angular motion inside the cylinder, which are known as swirl and tumble ratios, respectively. These values are calculated by the effective angular speed of in-cylinder air motion divided by the engine speed. The effective angular speed is the ratio of the angular momentum to the angular inertia of moment. The mass centre of the charged in-cylinder air is considered as an origin for the calculation. The three variables (swirl, sideways tumble, and normal tumble ratio) investigated in this paper are presented in the non-dimensional form by applying the equations as follows:

$$SR = \frac{60Hz}{2\pi Iz \omega}$$

$$TRx = \frac{60Hx}{2\pi Ix \omega}$$

$$TRY = \frac{60Hy}{2\pi Iy \omega}$$

where, Hx, Hy and Hz are the angular momentum of the in-cylinder gas about the x-axis, y-axis and z-axis, respectively. Ix, Iy and Iz are the moment of inertia about the x axis, y axis and z axis, respectively. In addition, ω is the crankshaft rotation or engine speed in the unit of rotation/minute [6].

VI. TEST RUN

The in-cylinder air motion before fuel injection process is very important to certify a proper air-fuel mixture. This is due to the fact that in-cylinder air motion plays a vital role on the complete combustion in the engine cylinder.

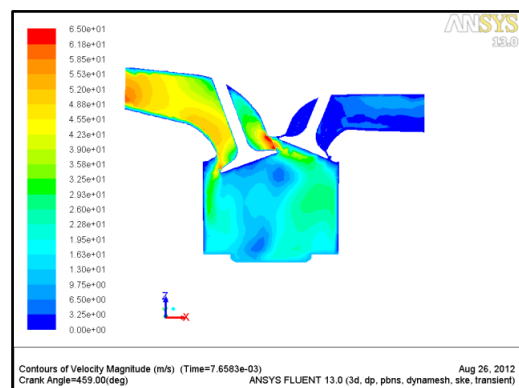


Fig. 2 CFD simulation of air flow in the IC Engine

A test run has been performed to obtain some details of in-cylinder air motion, at the motoring condition, for the suction and compression stroke of an engine. This was done to verify the velocity magnitude in the form of swirl and tumble flow. From fig. 2, it can be seen that there are strong annular jet flows in the combustion chamber near the valve curtains. It because the flow and velocity field in this degree of crank angle reaches to the maximum value where the intake valves almost open at the maximum lift distance [6].

This strong annular jet flows make a clockwise or counter-clockwise swirl on the intake valve. The piston speed is kept constant at 2500 rpm. A clockwise vortex is visible to be formed at the centre of the engine cylinder, under intake valves. This is a due to the jet motion of air which does not strike the cylinder walls but directly flows to the centre of the cylinder. The jet of air which strikes the walls of the cylinder creates an elongated vortex along the wall.

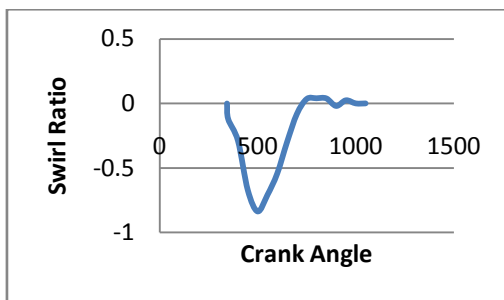


Fig. 3 SR vs Crank Angle - curve

The swirl ratio is observed to begin with a negative tendency. Maximum swirl ratio is achieved around 500°, which is about 160° crank angle after TDC, as the piston reaches the maximum instantaneous speed and the valve opening is at its maximum distance as seen in figure 3. Beyond this point the swirl ratio gradually decreases towards the end of the suction stroke. The trend continues into the compression stroke as well due to the friction at the cylinder wall [6]. During the compression stroke, swirl flow interacts with the tumble flow forming squish air flow motion. The nature and variation of the in-cylinder tumble flow (normal) can be seen in fig. 4.

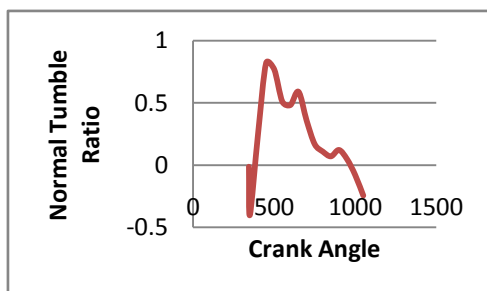


Fig. 4 TRy vs Crank Angle - curve

Tumble about the y-axis becomes negative at the beginning of the suction stroke and falls to minimum at around 10° after TDC. It can be then observed that there is rapid change in the curve and the ratio begins to increase.

A maximum tumble is achieved at about 120° after TDC. It may be due to the jet air flow during the valve opening that the normal tumble decreases in the beginning and increases into the early part of the compression stroke. Thereafter, the normal tumble ratio would decrease, with a small increase in between, during the further crank angles

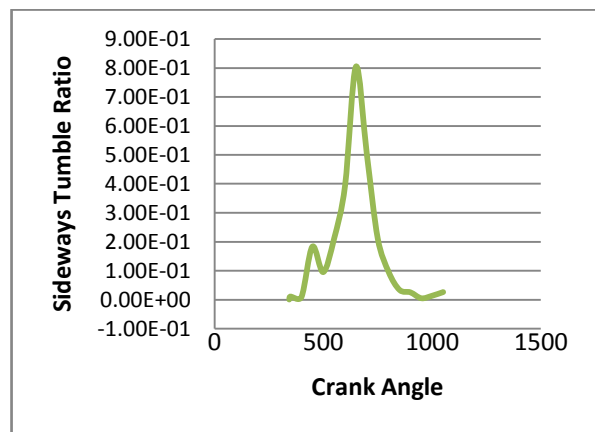


Fig. 5 TRx vs Crank Angle – curve

The tumble ratio in the sideways direction can be seen in figure 5. The graph shows the sideways tumble ratio and its variation inside engine cylinder. Tumble affect about the x-axis is very low in the beginning of the suction stroke. It then increases gradually and reaches a peak value in the compression stroke. A dominant tumbling motion has been developed at this stage due to the sideways tumbling action as well. The curve gradually decreases as the compression stroke ends.

VII. TURBULENCE DUE TO SWIRL

Creating a swirling vortex in the cylinder has been recognized as a way of enhancing turbulence levels during the compression stroke since the early days of IC Engines [7]. Swirl enhances turbulence during the compression stroke through the following methods: Turbulence generated by the shear at the wall is transported throughout the bulk of the flow by diffusion and swirl generated secondary flows or any protruding objects not on the axis of rotation of the swirl vortex will create turbulence through shear and vortex shedding or a swirl vortex in combination with the squish flow will cause an acceleration of the rotational speed of the vortex as the piston approached TDC to conserve the

angular momentum. This will increase the turbulence late in the compression stroke.

VIII. TURBULENCE DUE TO TUMBLE

The exact process as to how tumble enhances turbulence is not yet understood, however the fundamental mechanism has been identified. During the intake stroke a tumble vortex is established. This vortex is compressed during compression stroke and it increases its rate of rotation to conserve angular momentum. With increase in compression, the vortex becomes more non-circular. The vortex reaches a critical point beyond which the vortex breaks down into smaller vortices. These vortices decay into similar turbulent structures, thereby enhancing the turbulent levels [7].

IX. CONCLUSION

A well known feature inherent in the swirl flows is that they require energy to generate the vortex during suction stroke. This energy comes primarily from the kinetic energy of the gases entering the cylinder through the inlet valve. So to increase the swirl intensity, the gas velocities must be high at the inlet valve, thereby, requiring a smaller cross-sectional area of the inlet valve [7]. This is one of the major compromises of the swirl flows, that is, the requirement of large inlet valve for larger suction of air flow during high engine rpm and the requirement of smaller inlet valve for better swirl intensity generation. A similar situation exists in the tumble flow scenario as well. So there exists an optimal ratio for both swirl and tumble flows. The performance of the engine falls beyond the optimal ratios due to the decrease in volumetric efficiency, even though, the swirl and tumble intensities are very high. This study shows that in-cylinder CFD predictions yield a reasonable result that allows improving the knowledge of the in-cylinder flow pattern and characteristics during intake and compression strokes instead of using the experimental test by Particle Image Velocimetry (PIV) or laser Doppler anemometry (LDA). At this moment, this CFD in-cylinder analysis result has not been validated with the experimental result of flow visualization due to the requirement of high experimental equipments, devices and measurement tools. Three dimensional simulation and then visualization techniques, using streamlines, may also prove to be very useful because the in-cylinder flow motions inside the cylinder are difficult to visualize in the absence of performing technical equipment. It is possible to reveal and communicate different visualizing characteristic of the flow using 2D approach but in order to bring more light to the very complex in-cylinder flow phenomena, the using of the three dimensional CFD simulation is necessary [5].

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