



INVESTIGATION OF FLOW DURING INTAKE STROKE OF A SINGLE CYLINDER INTERNAL COMBUSTION ENGINE

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ABSTRACT

This paper deals with experimental investigation of swirling flow in the cylinder of a spark ignited engine. The variations in different non-dimensional parameters such as Flow Coefficient, Swirl Coefficient and Swirl Ratio at various valve lifts and throttle opening was studied using a steady flow bench. The swirl enhancement using valve shrouding, and twisted tape insert was also investigated. The results indicate that a higher swirl coefficient and swirl ratio can be achieved with shrouded valve and twisted tape with penalty on flow coefficient. These experimental results can be utilized to verify the results of modeling using commercial CFD codes and also for increasing the accuracy of mathematical modeling of combustion process in internal combustion engines.

Keywords: internal combustion engine, swirl enhancement, flow coefficient, swirl coefficient.

1. INTRODUCTION

The investigation of in-cylinder flow motion has gained its importance ever since impose of regulatory emission norms. Air motion into the cylinder during the intake stroke of an internal combustion engine is one of the important factors, which governs the performance of an engine. Improvements in engine efficiency can also be attained by enhanced in-cylinder flow motions using optimized cylinder head, port and valve timing. A well-designed intake manifold and cylinder head will reduce the flow resistance and increases the swirl. Swirl is the rotation of charge about cylinder axis and it is used in SI engines to speed up the combustion process and in the diesel engines to control the air-fuel mixing [1]. Two general approaches are used to create swirl during the induction process. In first approach, swirl is created by discharging the flow into the cylinder tangentially towards the cylinder wall (helical port) and in the second approach, the swirl is generated in the manifold runner so that the flow rotates about the valve axis before it enters the cylinder. Several research studies related to swirl enhancement in IC engines reported that swirl facilitates the mixing of the air fuel mixture and increases the combustion rate. The experimental work of Sihun Lee *et al.*, [2] showed that both swirl and tumbling motions enhanced the fuel vaporization and fuel-air mixing and results in better cold start performance. Another advantage that was reported was ability to retard ignition timing as it has faster burning, which gives enough time for fuel vaporization and fuel-air mixing before being ignited. Taehoon Kim *et al.*, [3] improved the lean misfire limit by the introduction of swirl and tumble motion. Three types of ports with an IACV (Intake Air Control Valve) have been developed to obtain sufficient swirl and tumble motion to improve combustion and still keep high volumetric efficiency. Tests showed that the combustion duration was shortened and consequently lean misfire limit and EGR tolerance were improved with considerable reduction in the level of NO_x. J. H. Whitelaw and H. M.

Xu [4] measured the cylinder pressure and flame travel velocity in a single cylinder engine with two arrangements of port geometry and with mixture equivalence ratios from 0.68 to 0.9. The investigation compares the combustion processes in terms of the maximum pressure, flame speed and in cylinder flow velocity without and with an intake valve shroud which increased both the tumble and swirl ratios. The photographic studies confirm the dominant effect of the swirling flow on flame propagation and deviations of the flame kernel from spherical as the air-fuel ratio is increased, with much higher probability of influence of velocity fluctuations. Abdul Rahim Ismail *et al.*, [5] in their experiment investigated air flow and coefficient of discharge desirable for inflow (reverse flow) through the exhaust port using super flow bench. The experimental results show that the air flow and coefficient of discharge in the intake port and exhaust port of the four stroke diesel engine provided the best at 0.25 L / D and in highest test pressure. Increasing the valve lift and test pressure can increase the air flow, valve air flow and coefficient of discharge in intake manifold system or in exhaust manifold system, but after the maximum valve lift per diameter 0.25L / D, the air flow, valve air flow and coefficient of discharge is stable and did not increase. Tomonori Urushihara *et al.*, [6] studied the flow measurements for various types of intake systems that generated several different combinations of swirl and tumble ratios using laser doppler velocimetry and visualization of in-cylinder fuel vapour motion by laser induced fluorescence. It was concluded that a low tumble ratio is a necessary condition for obtaining axial mixture stratification in the cylinder and Strong swirl, which has been considered to be necessary for axial mixture stratification, is not always effective in stratifying the mixture.

Swirl at the end of compression and beginning of combustion will break into turbulence motion due to upward motion of the piston. Higher level of swirl does not improve the combustion and emission; instead it



reduces the volumetric efficiency as swirl created reduces the kinetic energy of the flowing fluid. The steady state flow analysis helps to find variations in different non-dimensional parameters such as Coefficient of Discharge, Flow Coefficient, Swirl Coefficient and Swirl Ratio for various valve lifts and it also helps in identifying the flow structure within the cylinder. The main objective of this work was to investigate the bulk swirling charge motion inside the cylinder with and without flow modifications in a small utility engine. Flow modification was carried out in two methods, by using a twisted tape in the manifold and shrouding the inlet valve.

2. MATERIALS AND METHODS

Flow benches and particle image velocimetry (PIV) are the two methods commonly utilized to measure the momentum and flow structure of an in-cylinder flow field. Steady flow setups are simple, inexpensive and provide an approximate value of angular momentum. A flow analysis was carried out on a flow bench fitted with flow meter, digital micro-manometer, thermocouples, paddle wheel and angle encoder to measure different non-dimensional parameters such as Flow Coefficient and Swirl Coefficient at various valve lifts using a baseline unmodified cylinder head and cylinder head with shrouded valve attachment, and twisted tape. A test rig with vane type (paddle wheel) swirl flow meter was used for measuring the swirl. An acrylic tube of diameter similar to that of engine cylinder was used. A flow straightener was connected to the intake side of the cylinder head to ensure laminar flow to the cylinder head. An orifice plate was used to measure the air mass flow rate. A blower of 16000 rpm, 600W, and 3.3 m³ / min discharge rate is used to induct air through the intake valve in order to simulate the actual engine operating condition. Air was sucked through the head and intake port configuration. To measure the pressure drop, micro-manometer with selection switch is used. Fixed pressure drop (ΔP) of 0.9 kPa across inlet valve and cylinder was maintained at all valve lifts. The pressure drop is selected to ascertain turbulent flow based on Reynolds number. As the valve lift is increased the supplied air flow rate was increased to maintain the constant pressure drop. The rotation of the vane gives a measure of the swirl inside the cylinder. The paddle wheel used in this work was fabricated using rapid prototyping machine. Engine valves were adjusted with the help of a mechanism using the stock rocker arms and bolts for valve lift and level of lift was measured using a calibrated dial gauge. An Agilent data logger unit, model: 34970A was used to log the data from the sensors. The test parameters were recorded for 60 seconds per valve lift for seven flow rates (by varying throttle) so as to obtain a repeatable time-averaged voltage. The test data acquired using data logger was processed through Microsoft Excel to determine the non-dimensional parameters flow coefficient and swirl coefficient. Following modifications

were made to augment the swirl in the cylinder. In first method, valve was shrouded on the top side for 180°. Shroud height was fixed to 6 mm, which allowed the free closing of the valve without blocking the manifold runner port and at the same time it stayed inside the port. In second method twisted tape was made from stainless steel strip of thickness 1mm and width 25 mm and inserted into the manifold runner. Twisted tape was fabricated by twisting a straight tape about its longitudinal axis. The tape was placed in twist ratio of 0.8. Twist ratio is defined as the ratio of linear distance of the tape for 180° rotation to the width of the tape. Figure-1 shows the photographic view of the experimental setup and Figure-2 shows the schematic of the experimental setup, shrouded valve and twisted tape insert in inlet manifold.

Table-1. Specification of the engine.

Engine parameters	Value
Bore (mm)	79.28
Stroke (mm)	61.67
Displacement (cc)	305
Number of cylinders	1
Maximum intake valve open (mm)	8.1
Intake valve diameter (mm)	31.7
Intake valve stem diameter (mm)	5.97
Intake valve seat diameter (mm)	28.2
Intake valve opening duration (°)	244



Figure-1. Photographic view of the experimental setup.

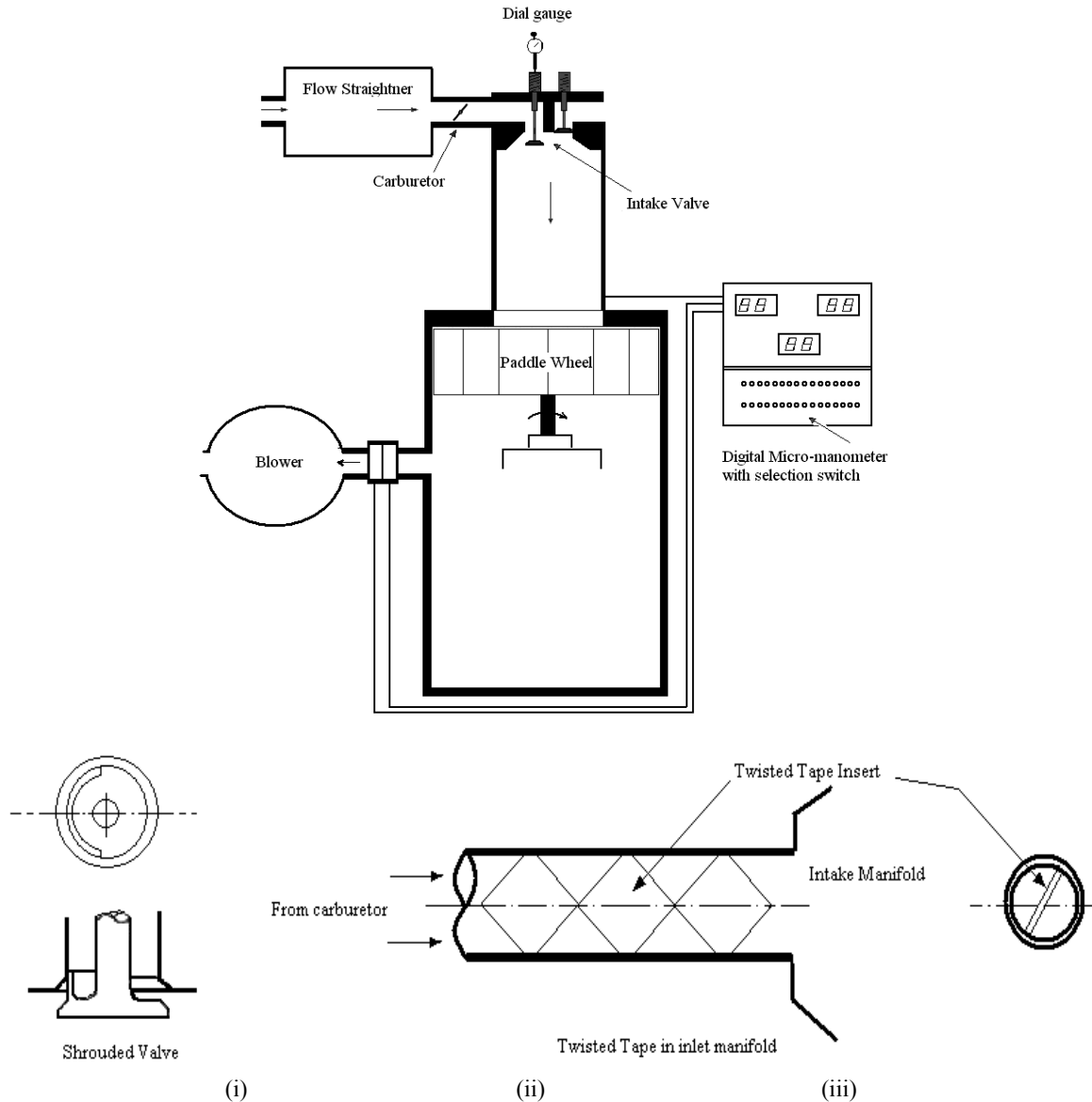


Figure-2. Schematic of (i) Experimental setup (ii) Shrouded valve (iii) Twisted tape insert in inlet manifold.

2.1 Calculation of parameters

Non-dimensional parameters such as discharge coefficient, flow coefficient, swirl coefficient and swirl ratio are defined when characterizing the flow through engine. They are a measure of the breathing performance of an engine. The use of non-dimensional parameters allows experimenters to remove the size effects from the data and compare various design based on geometry [5]. All the parameters are commonly plotted in conjunction with non-dimensional parameter obtained from L / D (Valve Lift / Valve seat diameter). Paddle wheel diameter was bigger than the cylinder diameter in order to prevent air from bypassing the paddle wheel. The ratio, diameter of paddle wheel to bore was set as 1.1. A slight change in pressure due to paddle wheel will change the mass flow rate of air. It was found that the change in mass flow rate

due to the paddle wheel is within 1.3% to 2.7% (10% to full throttle opening). Though fully developed swirl motion was formed at 40 mm from top dead center, results were presented with respect to paddle wheel position at 111 mm which is 1.4 times the bore. Before obtaining the data, calibrations were performed with known swirl reference as explained in [7].

2.2 Flow coefficient

The discharge coefficient, C_d is defined as measured mass flow rate over the ideal mass flow rate. The flow coefficient, C_f , has a similar definition to C_d , but highlights higher valve lift performance. For lower valve lift the minimum area is the valve curtain area (A_{Ci}) and for larger lifts the minimum area is the valve seat area (A_C) [8].



$$C_d = \frac{\dot{m}}{\rho_{air} A_{Ci} V_C} \tag{1}$$

Where,

$$A_{Ci} = \pi D_{Valve} L_i$$

D_{valve} is the inner seat diameter of the valve and L_i is the valve lift. The characteristic velocity V_C , is defined by a compressible flow velocity equation.

$$V_C = \sqrt{\left(\frac{2\gamma}{\gamma-1}\right) \left(\frac{P_{ambient}}{\rho_{mixture}}\right) \left(1 - \left[\frac{P_{ambient} - \Delta P_{head}}{P_{ambient}}\right]^{\frac{\gamma-1}{\gamma}}\right)}$$

$$C_f = \frac{\dot{m}}{\rho_{air} A_C V_C} \tag{2}$$

$$A_C = \frac{\pi}{4} D_{Valve Seat}^2$$

2.3 Swirl coefficient and swirl ratio

Swirl coefficient is defined as the ratio of circumferential air speed in the cylinder to the axial speed of the air flow in the cylinder. The global swirl ratio, R_s , is an integrated value and an estimate of the angular momentum of the total flow field during the entire intake process [9].

$$Swirl\ coefficient\ (C_s) = \frac{Circumferential\ velocity\ (C_u)}{Axial\ Velocity\ (C_a)} = \frac{\omega B}{V_B} \tag{3}$$

Where,

$$\omega = \frac{2\pi N_w D_{pw}}{60}; V_B = \sqrt{\frac{2\Delta P}{\rho}}$$

Where, D_{pw} is diameter of the of the paddle wheel and N_w in the paddle wheel speed

$$Swirl\ ratio\ (R_s) = \frac{B L}{D_{Valve\ Seat}} \frac{\int_{\theta_1}^{\theta_2} C_f C_s d\theta}{\int_{\theta_1}^{\theta_2} C_f d\theta} \tag{4}$$

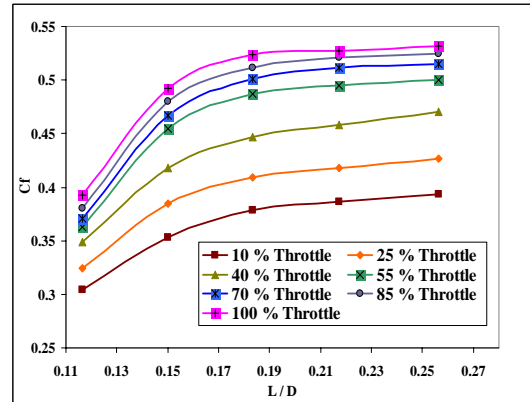
Where θ_1 and θ_2 are valve timings at inlet valve opening and inlet valve closing, B is the bore diameter and L is the stroke length.

3. RESULTS AND DISCUSSIONS

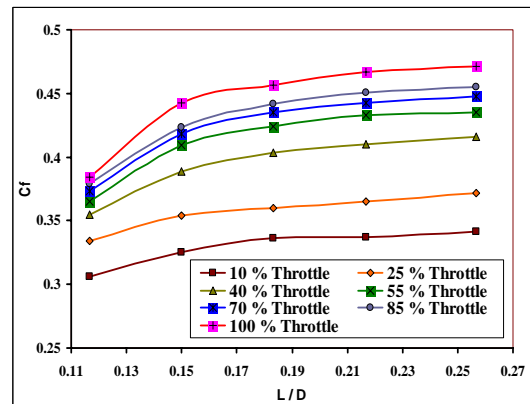
3.1 Flow coefficient (C_f)

The flow coefficients (C_f) of the base head, head with shrouded valve, and twisted tape with respect to L / D ratio are shown in Figure-3. It is noted that at constant pressure drop, increasing the inlet valve lift, and throttle opening resulted in increasing the flow coefficient in all three configurations of the head. Due to increase in mass flow rate with respect to valve lift and throttle, increased

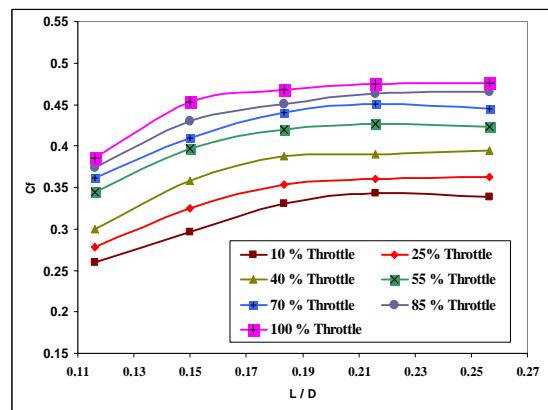
friction in the flow region leads to drop in the flow capacity. The flow coefficient of base head at 10%, 50% and 100% throttle opening increases by 29%, 35% and 36% when the valve lift is increased from 3.7 mm to 8.1mm.



(a)



(b)

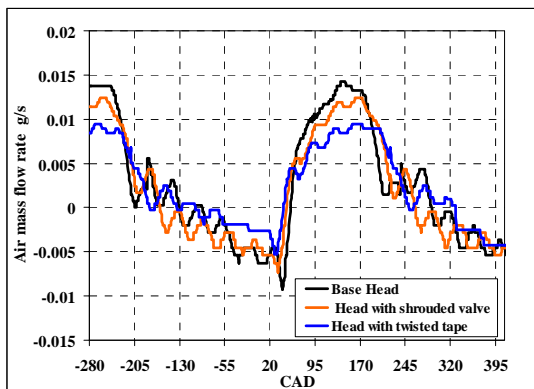


(c)

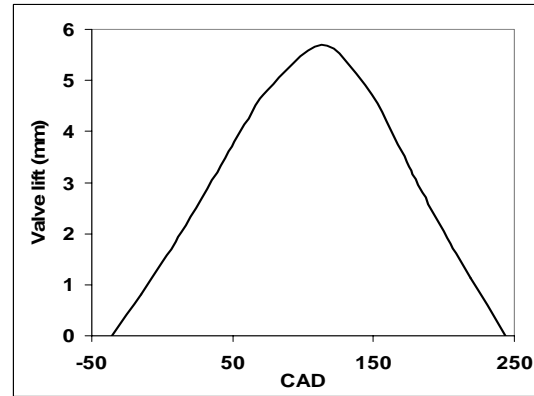
Figure-3. Variation of flow coefficient with respect to L / D for (a) base head (b) shrouded valve (c) twisted tape.



Flow coefficient of base head registered a maximum value of 0.53 at maximum valve lift and throttle opening. Flow coefficients of shrouded valve head showed significant drop in flow coefficient when compared to base head. Around 3 to 13.5% drop was observed with shrouded valve at different throttle openings. This is most likely due to the presence of shroud on the valve top which reduces the kinetic energy of the flowing air as it shears the flow around it and changes its direction. At 10%, 50% and 100% throttle opening, flow coefficient increases by 30%, 22% and 23% when the valve lift is increased from 3.7 mm to 8.1mm. Flow coefficient of shrouded valve head registered a maximum value of 0.475 at maximum valve lift and throttle opening. The flow coefficient of twisted tape insert head registered lower values at different throttle opening when compared to other two configurations. With the twisted tape inserted head, at smaller throttle opening (10 to 25%), a marginal difference was noticed and with increase in throttle opening the difference increased. Around 4 to 27% drop in flow coefficient was observed at different throttle opening when compared to base head results. This is most likely due to more flow restrictive area (when twisted tape is introduced in the head) and the rotation of air in the runner which increases the friction and as a result the kinetic energy of the flowing air is reduced. Increased runner length with twisted tape may further reduce the value of flow coefficient. At 10%, 50% and 100% throttle opening, flow coefficient increases by 11%, 19% and 22.5% when the valve lift is increased from 3.7 mm to 8.1mm. Flow coefficient of twisted tape inserted head registered a maximum value of 0.44 at maximum valve lift and throttle opening. Compared to twisted tape head and shrouded valve head base head performs better from the point of flow coefficient. The results clearly state that after reaching 6.9 mm valve lift (0.22 L / D) flow gets almost saturated irrespective of the throttle opening in all three configurations of the head. It is also noted that the difference in flow coefficient between different throttle openings after part throttle (55%) is reducing irrespective of the configurations. Figure-4 shows the output of Mass Air Flow sensor (MAF) and valve lift profile with respect to crank angle.



(a)



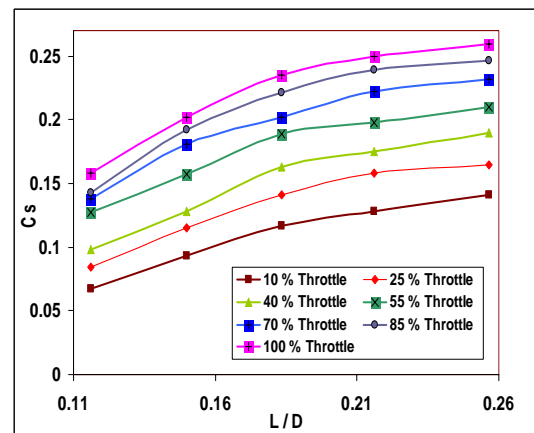
(b)

Figure-4. (a) Variation of air mass flow with respect to CAD (b) Variation of valve lift with respect to CAD.

MAF sensor values are acquired from motored engine at 3000 rpm with throttle being held at wide open position. MAF sensor output shows significant drop in mass flow rate of air when the engine is operated with shrouded valve head, and twisted tape insert head.

3.2 Swirl Coefficient (C_s)

During induction stroke air flows around the inlet valve and gets into the cylinder through the gap between the valve and the valve seat. Air expands into the cylinder and impinges directly on the cylinder wall creating a large angular momentum. As the air flows only through the inlet valve, the momentum of the air just below the exhaust valve is small. The large angular momentum on one side of the cylinder moves through the other side of the cylinder as the flow develops downstream [9] and it becomes uniform there after having center of the swirl near the center of the cylinder. This organized swirl motion appears at 40 mm from the TDC. The Swirl coefficient curves obtained from the steady flow bench were presented in Figure-5.



(a)

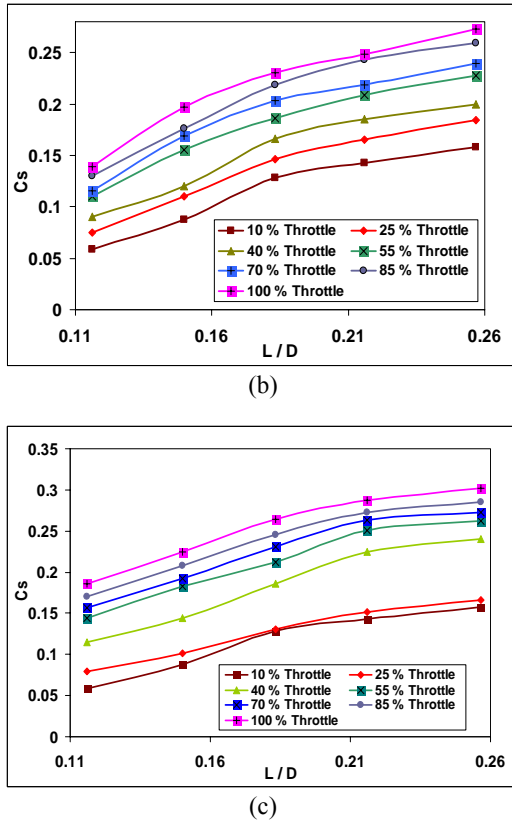


Figure-5. Variation of swirl coefficient with respect to L/D for (a) base head (b) shrouded valve (c) twisted tape.

Table-2. Swirl ratio of base head, shrouded valve head and twisted tape inserted head at different throttle opening.

Throttle opening	10 %	25 %	40 %	55 %	70 %	85 %	100 %
Base head	0.33	0.43	0.52	0.60	0.65	0.70	0.75
Shroud head	0.36	0.45	0.52	0.61	0.67	0.71	0.76
Twisted tape head	0.39	0.46	0.62	0.72	0.77	0.81	0.87

4. CONCLUSIONS

The aim of the present work was to investigate the in-cylinder flow and swirl on a 10 hp, single cylinder, four stroke engine cylinder head. The flow coefficient, swirl coefficient and swirl ratio provided information about the air flow and swirl in the cylinder. The effects of introduction of modifications to valve, and port (valve shrouding and twisted tape insert) are analyzed and compared with the base cylinder flow performance. From the experimental results the major conclusions that can be drawn are:

- The maximum value of the mass flow rate and flow coefficient was obtained with base head. Though increasing the valve lift can increase the air flow, increased friction reduces the flow capacity of the in intake manifold. Flow coefficient of base head

registered a maximum value of 0.53 at maximum valve lift and wide open throttle. Lower values of swirl coefficient and swirl ratio were noticed with base head

In all three configurations swirl coefficient increases with increase in valve lift, reflecting increased air flow through the increased gap between the valve head and seat. Base head registered lower swirl coefficient when compared to other two configurations. About 6 to 11% increase in swirl coefficient was noticed with shrouded valve head and 6 to 28% increase in swirl coefficient was noticed with twisted tape insert head when compared to the swirl coefficient of base head.

The maximum value of swirl coefficients registered by base, shrouded valve and twisted tape insert head at maximum valve lift and 100 % throttle opening are 0.26, 0.27 and 0.3. The effect shrouded valve and twisted tape insert on swirl ratio (R_s) at various throttle opening is summarized in Table-2. Swirl ratio of shrouded valve head and twisted tape insert head registered higher swirl ratio values when compared to base head. At 10, 55 and 100% throttle opening swirl ratio of shrouded valve head was calculated to be 4, 3.2 and 3% more than base head. Similarly at 10, 55 and 100% throttle opening swirl ratio of twisted tape insert head was calculated to be 18, 20 and 16% more than base head. It is clear from the results that flow modifications in inlet manifold to increase the in-cylinder swirl results in drop in flow coefficient as a part of kinetic energy of the flowing air is utilized to increase swirl.

registered a maximum value of 0.53 at maximum valve lift and wide open throttle. Lower values of swirl coefficient and swirl ratio were noticed with base head

- Flow coefficient of Shrouded valve head and Twisted tape insert head were lower than base head by around 3 to 13.5% and 4 to 27% at different throttle openings
- It was found that the swirl coefficient and swirl ratio of the shroud valve head and twisted tape insert head is greater than the base head by 6 to 11% and 6 to 27% at different throttle openings. The maximum value of swirl coefficient and swirl ratio is achieved in twisted tape insert head.

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