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# Cylinder Head Intake Port Design & In-Cylinder Air-flow Patterns, Streamlines formations, Swirl Generation Analysis to Evaluate Performance & Emissions

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## *Abstract*

***On the verge of rapidly increasing threat of global warming; the environmental emission norms are becoming stringent. In-cylinder flow characteristics at the time of injection and subsequent interactions with fuel sprays and combustion are fundamental considerations for the engine performance and exhaust emissions of a diesel engine. Intake ports are designed to provide the optimum balance between air flow and desired in-cylinder air motion characteristics which is governed by the swirl and tumble motion during the intake stroke. The effect of intake port design on swirl generations, flow patterns and streamlines has been analyzed with CFD tool.***

***The results of the CFD simulation will assist to improve understanding of the intake process of internal combustion engine and performance evaluation of intake ports and simulation results can be verified out by prototype testing on swirl test rig.***

***Keywords: Cylinder Head, Intake Port, Swirl, Tumble, Flow Patterns, CFD flow analysis***



## 1. Introduction

The cylinder head of a direct injection diesel engine has to perform many functions. It must provide a mounting for injector, seal the combustion gases and maintain the acceptable temperature of the component. It must bring charge air to the cylinder, with minimum pumping loss and required swirl and other properties of charge motions. Due to increasingly stringent emission limits for heavy duty engines it becomes more challenging to find right compromise between conflicting targets like exhaust emissions, fuel consumption and losses, costs (production as well as development) and customer demand. [1][2]

To meet emission norms set by government there has been a trend among the premium heavy duty direct injection (DI) diesel engines, towards centralized combustion, incorporating a central vertical injector and 4-valves, for improved emissions. The benefits have been attributed to genuine combustion improvements. It is already proved that 4-valves per cylinder configuration provide significant benefits for emissions achieving a superior NOx/particulates trade-off compared to the 2-valves version of the same engine as shown in Figure 1.

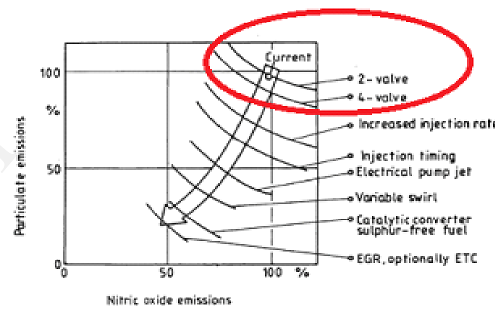


**Figure 1. PM Vs HC + NOx Chart**

It is well known that in DI engine swirl is needed for proper mixing of fuel and air. This is particularly true in case of diesel engines. Moreover the efficiency of diesel engine can be increased by increasing the burn rate of fuel/air mixture. This can be achieved by two ways; one by designing the combustion chamber in order to reduce the contact between the flame and the chamber surface and two by designing the intake system that imparts swirling motion to intake charge. So by designing the intake port for 4-valve system and flow through intake port can be analyzed with CFD in suction condition at different lift conditions but in this paper flow patterns, stream lines and velocity vectors observed at full lift. [1]

Research methodology or work process used in this paper is discussed below:

- Provides the literature to know about flow patterns, designing parameters, types of ports to be used and methodology for design of Intake ports.
- Development efforts are focused while designing intake ports with improvement to

obtain the required swirl and flow patterns.

- Defining the full valve lift 3D model and In-cylinder air flow analysis through CFD package to know swirl, velocity vectors, streamlines formation for full lift model.
- Validation of results by prototype testing.

### 1.1 Flow Patterns

From a simple point-of-view, there are two types of ideal flow patterns in an engine cylinder as swirl motion and tumble motion, both are rotational motions, however, the axis of rotation is different in each case. In order to facilitate the comparison of the results, the three variables are flow coefficient, swirl and tumble ratio shown in figure 2. [1] [2]

**1.1.1 Flow Coefficient** Flow coefficients are related to the pressure drop of the flow as it passes the port/valve assembly. The definition of the flow coefficient is based on the Bernoulli equation, the recorded static pressure in the dummy cylinder is used to calculate a theoretical velocity (mass flow) based on the total pressure upstream of the flow box. The ratio of actual mass flow and theoretical mass flow is said to be the flow coefficient. Thus the flow coefficient is directly linked to the total pressure loss of the system. [1][2]

**1.1.2 Swirl Ratio Swirl** is angular moment given to air during suction stroke to ensure optimum air fuel mixing combustion for achieve engine performance in terms of power emissions. Intake port performance has significant influence on engine power, fuel economy, and exhaust emissions. Measurement of in-cylinder air motion is becoming increasingly important due to exhaust emissions & efficiency considerations. [1][4]

**1.1.3 Tumble Ratio** Tumble is a rotational motion about circumferential axis near the edge of clearance volume in piston crown or cylinder head, which is caused by squishing of the in cylinder as piston reaches near TDC. Tumble ratio can be defined in X, Y & Z direction. [3]

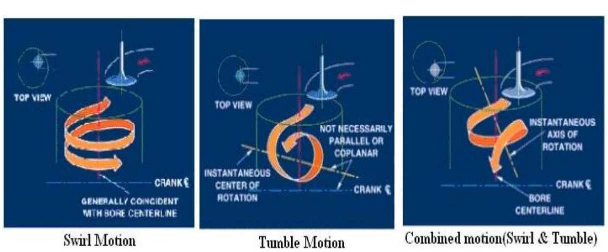


**Figure 2. Shows swirl, tumble and combined motion**

### 1.2 Intake Port Design Parameters

In today's diesel engines two basic intake port designs are widely used as helical port and direct port (tangential port).

**1.2.1 Helical Port** Helical port used for generating the swirl. The different parameters that affect the geometry are studied and considered during designing/modelling as shown in Figure 3. [1][5]

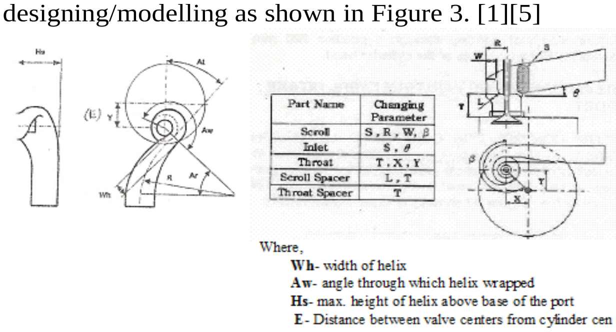


**Figure 3. Helical Port Design Parameter**

**1.2.2 Direct Port** Direct port used for provides more air volume and good breathing qualities with less pressure loss. The different parameters that affect the geometry are studied and considered during designing/modelling as shown in Figure 4. [1][5]

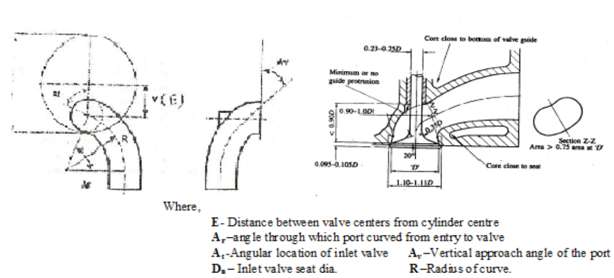


**Figure 4. Direct Port Design Parameter**

To provide the both swirl motion as well as sufficient air volume during air intake and less back pressure during exhaust, 4-Valve configuration is finalized as at Intake ports with one helical port and one direct port.

## 2. Flow Analysis for Intake Port

Steps followed while doing the flow analysis through helical port are as

- Intake Port 3D CAD model for full valve lift condition
- Discretization in Hyper-Mesh and boundary condition at full valve lift during air intake.

- Post processing in CFD tool. [4]

### 2.1 Intake Port 3D-CAD Model

By considering the design parameters enlisted above, Intake port model has been modelled in I-deas and full valve lift (valve lift=9.69mm) position decided on the basis of piston bowl position when intake valve is fully open. [5] [8]

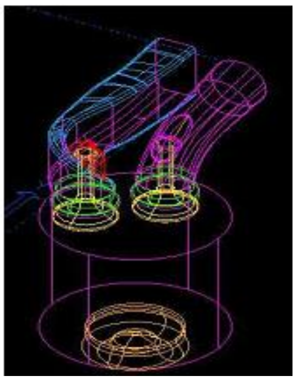

**Figure 5. Full Valve Lift Wireframe Model**

### 2.2 Discretization

Taking into consideration the complexity of geometry for helical port, the assembled 3D model is imported to hyper-mesh for discretization.

Volumetric mesh is done with tetrahedron elements as tetra mesh panel allows filling an enclosed volume with first/second order tetra hedral elements. The computational domain considered for CFD calculation covers intake ports, intake valves, the cylinder liners and piston bowl. [7]

**Figure 6. Discretized Full Lift Model**

The Inlet boundary condition is given as air mass flow rate (kg/sec) and Outlet boundary condition is given as suction pressure at piston bowl end.

### 2.3 Post Processing Results & Discussion

With the fully open valve, the intake flow enters the cylinder at a high speed as an annular jet forming a recirculation centre below the valve tip and pattern shown in figure 7.

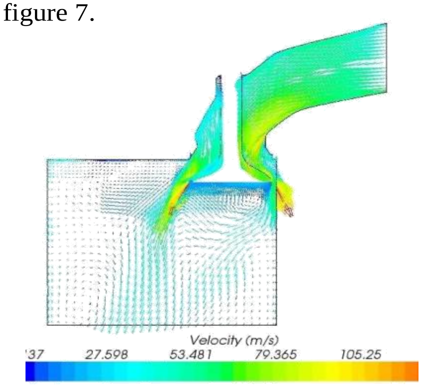


**Figure 7. Flow Pattern at the entry In-cylinder**

The horizontal velocity distribution at the port entrance shows that angular momentum is generated in the helical port before the flow enters the cylinder and pattern shown in figure 8.

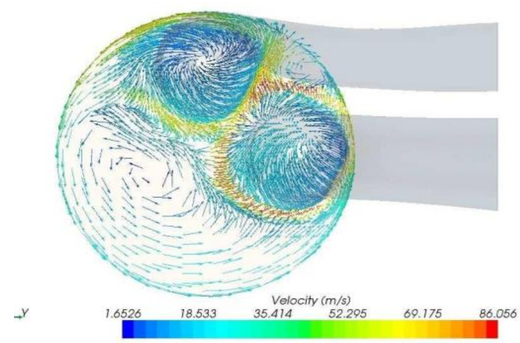


**Figure 8. Horizontal velocity Pattern In-cylinder**

This angular momentum is combined with the angular momentum generated in the cylinder by the intake flow hitting the cylinder wall, changing the direction tangentially along the circumference. Due to this interaction with the cylinder wall two opposite swirl motion are generated with some complications. At the bottom exit the two opposite swirl motions merge into single swirl with the minor swirl zone attached to the wall as shown in figure 9.

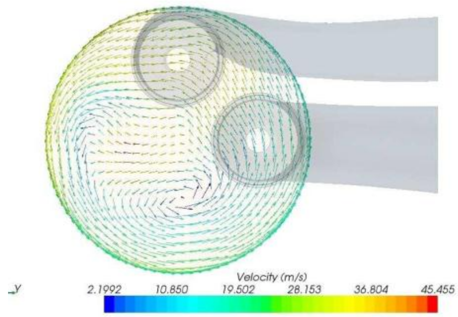


**Figure 9. Horizontal Velocity Pattern at bottom cylinder**

It is clearly shown that the flow in the far intake port is forced to rotate about the valve axis before it enters the cylinder and swirl is generated within the inlet port shown in Figure 10. And illustration of formation process of swirl flow in the cylinder shown in Figure 11 and formation process of tumble flow during the induction process is shown in figure 12.

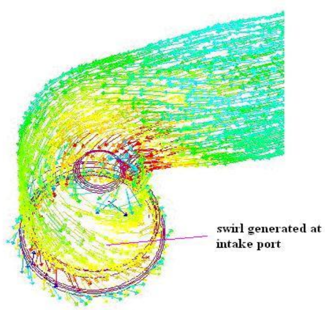


**Figure 10. Velocity Vectors near Port Neck**

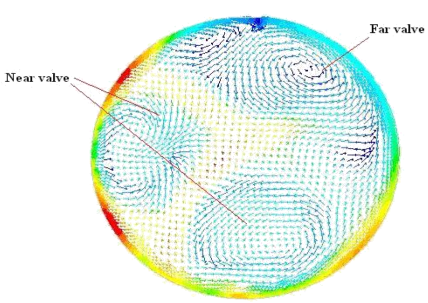


**Figure 11. Illustration of Swirl Formation Process**

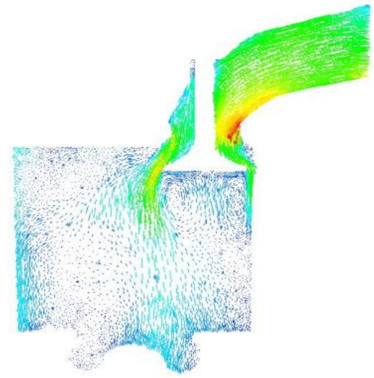

**Figure 12. Tumble Formation Process**

The swirl number is obtained from CFD by summing the values of angular momentum along z axis over the entire cylinder from top to bottom & is found to be 0.19.

## 3. Prototype Development and Validation

With reference to CFD simulation and with minor modification, a prototype has been made (cast prototype shown in figure 13.) and tested on swirl test rig.



This consists of a light aluminium foil honeycomb which is freely suspended on precision ball races with its periphery sealed by an oil filled trap. The suspended by a light torque arm bearing on a fixed spring at its outer end. The movement of the restraining spring is measured by an electronic transducer. Thus with a swirling air charge moving up the cylinder, the axial holes in the honeycomb, through which the air must pass to escape, destroy the swirl causing the destroyed total angular momentum flux to produce a torque reaction on the suspended honeycomb. Measurement of this reaction torque is a direct measure of the swirl angular momentum.

**Figure 13. Cast Prototype Cylinder Head Model**

To perform swirl testing several other components other than prototype is needed. Components like

Intake valve, inner valve seat, valve bridges, valve guide, cup valve spring retainer; helical coil spring (each quantity two) then assembled the cast model with two intake valves, springs, valve guide, bridge plate, spring washer, spring nut and valve insert.
Mount the cast model of 4-valve cylinder head on AVL adapter plates on the conveyors; the cylinder must be fixed securely on dowel provided on fixture.
Mount the AVL cylinder liner in measuring station according to measurement requirements. Select Intake swirl data, record for AVL cylinder head type and requirements in the window measuring setup.
Edit data such as: Valve lifts in small step: 1 mm to 9.69 mm.
Reading has been taken for combined ports and swirl number found to be 0.25. Dismount the measured cast cylinder head model.

## 4. Conclusion & Future Scope

In this paper, I have given more focus on developing intake port geometry to meet the swirl ratio required to meet emission and intake ports were simulated on CFD to know velocity vectors, different flow patterns and is used to predict/improve performance.
CFD simulation of intake ports and prototype testing results compared to know the compatibility of CFD tool results.
The arrangement and orientation of helical and directed port have an important effect on swirl ratio and intake flow interference and different swirl value can be optimized with different valve location and layout on cylinder head further.



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