Design and CFD analysis of intake port and exhaust port for a 4 valve cylinder head engine

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Abstract. In cylinder air motion in a compression ignition engine effects mixing of air-fuel, quality of combustion and emission produced. The primary objective is to design and analyze intake and the exhaust port for a four valve cylinder head to meet higher emission norms for a given diesel engine with two valves. In this work, an existing cylinder head designed for two valves was redesigned with 4 valves. The modern trend also confirms this approach. This is being followed in the design and development of new generation engines to meet the stringent environment norms, competition in market and demand for more fuel-efficient engines. The swirl ratio and flow coefficient were measured for different valve lifts using STAR CCM+. CFD results were validated with the two-valve cylinder experimental results. After validation, a comparison between two-valve and four-valve cylinder head was done. The conversion of two valve cylinder head to 4 valves may not support modern high swirl generating port layout and requires a trade-off between many design parameters.

1. Introduction
In the design and development of an IC engine, the cylinder head design is a critical and important part. The details of the in-cylinder flow fields play an important role in the progress and efficiency of combustion. The aim of the study is to develop a four valve cylinder head for an existing 4-cylinder diesel engine with two valve cylinder head, mass produced and used in tractor application. One standard engine available in the Amrita Automotive Technology Center was taken to study, design and analyse in detail with the following preconditions and defined boundaries. There will not be any change to the current cylinder head block, Cam Rod, Crank Shaft, Cylinder head fixing elements, the current engine with push rod type system will be retained, and the new 4 valve cylinder head will facilitate the use of existing child parts as for where ever is possible.

In the combustion of fuel & air the air intake with highest volumetric efficiency can be used with proper air mixing by appropriate swirl, thereby ensuring complete combustion and enables higher performance, better fuel economy and lowest emissions. Therefore, the modern engines are mostly turbocharged. This enables induction of maximum mass of air with the highest possible volumetric efficiency. And by the appropriate port design of air intake, the required swirl levels are achieved for...
better efficiency. Improving the flow conditions by trial and error of prototype in flow bench are time-consuming and costly. Unsteady flow conditions inside the cylinder make it difficult to tune the flow even by using sophisticated techniques [11]. Nowadays, CFD simulations are powerful engineering tools which provide a great contribution to capture the flow conditions that occur in the engines, without needing to perform expensive experimental measurements.

Many research has been performed to improve the flow conditions inside the combustion chamber by utilizing different design of intake ports. Both numerical and experimental methods are observed to be in good agreement for swirl ratio and mean flow coefficient calculation. [1][2][3][8]

Nigel.F.Gale (2003) discusses that the most effective condition for good flow inside the combustion chamber is the combination of tangential and the helical port which gives the highest momentum flux in which the directed component is 30% of the total swirl. The ports may be designed to achieve this. [5]. Rafig Mehdiyev (2006) in their paper discussed developing a 4-valve engine based on theoretical and experimental studies carried on the TUMOSAN engine. The same engine is being used for this study. The studies were made on strategies to be implemented for reducing the emission levels to comply with 2004/26/EC standards requirement. From the comparison of existing two valve designs with the proposed four valves, it was observed that there was an increase in NOx while the specific fuel consumption decreased to a great extent. An increase of volumetric efficiency 0.85 to 0.90 was obtained. It was said that there is no requirement of changing the engine block and the crank shaft as the combustion pressure’s maximum value is lower than 12MPa. A new design for combustion chamber was also proposed considering higher the engine emission at low ambient temperature regions. Although it was said that the CFD analysis is performed, much detailed explanation on the studies was not available. For the studies, they used twin helical ports. [4]

Bharani Dharan R, S S Ramdasi and Neekkanth Marathe (2014) in their paper designed and analyzed a 3 cylinder 4 valve diesel engine Euro-V engine. Detailed studies were made and the prototype was tested in ARAI. Similar design methodology was used for the designing a 4-valve engine. Paddle wheel equipment was utilized to measure the swirl ratio. Swirl ratio of 1.6 was achieved in final design and a good streamline of the flow was observed. Siamese exhaust port with a target flow coefficient of 0.40 was made and analyzed. Valve Proportion layout proposed in this paper was used for the development of new 4 valve cylinder head. [6]

Jun-ichi Kawashima (1999) in their paper did research on variable swirl intake port for four valve diesel engine. Numerical simulations were performed with STAR CD under steady state conditions. Different port configurations were studied to calculate swirl number and the mean flow coefficient. It was not possible to consider all the layout mentioned in the research for our study due to design restriction of utilizing same the existing two valve cylinder head. It is quite evident that the possible design for new 4 valve cylinder head will not outperform best port configuration proposed by them in terms of swirl ratio. No experimental validation was performed. [7]

Many researchers studied the swirl development using the shrouded valve design. B Roy, RD Misra, KM Pandey (2015) studied swirl and the mean flow coefficient using shrouded valve. Both experimental and CFD analysis were performed. It was observed that there is no significant impact on swirl ratio. As the shrouded valve arrangement requires additional mechanism to prevent rotation of valve about its axis and hence was not considered for our study. [8][9][12]

2. Design Methodology
This project has been undertaken on design and development of ports for 4 Valve diesel engine head using an existing cylinder head designed for 2 valves. The engine is a turbocharged with intercooler. The engine is having a displacement of 3.9 liter with 4 cylinders. 2 valve cylinder head will be studied using CFD analysis and will be validated with experiment results before starting new 4 valve cylinder head design. The new design will retain the bolt pattern and push rod holes of existing 2 valve design and the width of cylinder block. Minor change in cylinder head height will be made if required. Centrally placed fuel injector for uniform fuel distribution. The new design will aim at retaining as many sub-components as possible.
Table 1. Engine Specification

| Parameter                  | Specification          |
|----------------------------|------------------------|
| Model                      | 4DT-39T-185C           |
| Emission Regulation        | Tier 3/ Stage 3A       |
| Type                       | Liquid Cooled Diesel   |
| Number of Cylinders        | 4                      |
| Bore                       | 104 mm                 |
| Stroke                     | 115 mm                 |
| Displacement(cu.in)        | 3.9                    |
| Combustion system          | Direct Injection       |
| Intake System              | Turbocharged           |
| Maximum Speed              | 2500 rpm               |
| Output                     | 135kW                  |
| Cooling System             | Liquid                 |
| Flywheel Size              | 12 inches              |

2.1 Valve Proportion layout

Existing 2 valve design and finalized 4 valve proportion layout is shown in figure 1.

![Figure 1. Valve proportion layout of 2 valve and 4 valve cylinder head design](image-url)

Following factors are considered while finalizing the layout:
- Breathing capacity, inlet gas velocity and scavenging are important factors to be considered for selecting valve head diameters
  - The diameter of 104 mm is retained from the existing 2 valve design to support the subsystems i.e. pistons, piston ring, connecting rod etc.
Normally 9-13% of the bore is recommended for valve bridge thickness. Valve Bridge thickness is the space between inlet and exhaust valve seat outer diameters. Less thickness in this area can lead to cracks.

Intake valve is subjected to atmospheric pressure and hence are bigger compared to exhaust port. While the when exhaust valves are open there is high pressure in the cylinder so they can afford to be smaller.

Injector for a 4-valve arrangement is placed centrally to ensure uniform distribution of the air fuel mixture. Sufficient spacing is provided to reduce stress and cracks in that area.

The spacing of 2 mm is provided between the valves and the cylinder outer diameter to facilitate any design change in cylinder head at later design stages.

2.2 Bolt layout
Bolt layout is determined considering the following factors.
- Equally spaced layout for equal transfer of loads
- Complete sealing of forces and gas pressure and
- Port layout and other constraints.

In our project, the number of bolt was decided as 6 per cylinder and dimensions and spacing are retained same as the 2 valve cylinder head.

2.3 Port layout
Port layout, intake port and the exhaust port layout are the important part of cylinder head design. The overall performance of diesel combustion system is determined by the intake flow characteristics. In cylinder flow pattern created during the intake stroke effect fuel-air mixing, bulk charge motion and turbulence. The flow capacity in the port also determines the volumetric efficiency. The combination of helical and tangential port for the intake port is decided for the new 4 valve cylinder head. Manifold opening area was calculated by studying different 4 valve engines and from ARAI database.

![Figure 2. Layout 1 (L1) and Layout 2 (L2)-Helical and Tangential Port arrangement](image)

Two layouts were designed by interchanging the helical and tangential port and swirl ratio and flow coefficient were studied. For the layout 1 the helical port was placed on the left side and for layout 2 it was placed to right side of the cylinder head as shown in figure 2.

2.3.1 Intake Port
The design of 4-cylinder intake port for high performance diesel engine has certain constraints which are to be taken into consideration. The existing 2 valve design is a helical port which is having a swirl ratio of 1.9 at the maximum lift. The decrease in volumetric efficiency due to this has to be expected. Due to stringent emission rules and competitive market, it becomes necessary to improve the volumetric
efficiency and at the same time reduce the emissions. For this reason, the intake port layout was finalized to have one tangential port and one helical port. The helical port will generate adequate swirl in the combustion chamber while the tangential port will ensure better air induction.

Helical port\(^{(H)}\) is design is mainly based on the required mean swirl value, which is decided based on the engine speed, bore, injector details, injection pressure, stroke, bowl diameter etc. Swirl is generated within the helical port before entering the cylinder. Helical port flow coefficient is less compared to tangential port due to high flow restriction.

The tangential port\(^{(T)}\) offers less restriction to flow thus have high flow coefficient but low swirl ratio. The flow is directed tangentially to the cylinder. Intake area should gradually decrease and it should have higher manifold opening area compared to helical port.

2.3.2 Exhaust Port
The function of exhaust port\(^{(E)}\) is to carry the burnt gases from the cylinder to the atmosphere with minimum backpressure. Siamese port design was chosen for exhaust port due to design restrictions created by bolt and push rod holes.

2.3.3 Valves for 4 Valve Cylinder Head
It is recommended to have minimum valve stem size of 8mm for heavy duty vehicles as per ARAI standards hence the stem size was retained from existing valve design(8mm) and modified according to new port design. Valve seat angle was taken as 60\(^{\circ}\).

2.4 Calculation of Swirl Ratio
Simulations were performed using STAR CCM+. Swirl is defined as rotational motion with its axis aligned with the cylinder axis. Swirl can be used as a parameter to measure the intensity of flow inside the cylinder. To quantify swirl inside the cylinder swirl ratio is used. Swirl ratio definition is based on paddle wheel swirl rig. It is the ratio of angular velocity of paddle wheel to engine speed.

Swirl Ratio \(S_w\) is defined as

\[
S_w = \text{Axis}_x.S_x + \text{Axis}_y.S_y + \text{Axis}_z.S_z
\]  

(1)

Where:
\[
S_x = \frac{M_x}{I_x} = \frac{\sum_{cells} \rho_i V_i [(Y_i - Y_m)w_i - (Z_i - Z_m)v_i]}{2\pi \frac{N}{60} \sum_{cells} \rho_i V_i [(Y_i - Y_m)^2 + (Z_i - Z_m)^2]}
\]

(2)

\[
S_y = \frac{M_y}{I_y} = \frac{\sum_{cells} \rho_i V_i [(Z_i - Z_m)u_i - (X_i - X_m)w_i]}{2\pi \frac{N}{60} \sum_{cells} \rho_i V_i [(X_i - X_m)^2 + (Z_i - Z_m)^2]}
\]

(3)

\[
S_z = \frac{M_z}{I_z} = \frac{\sum_{cells} \rho_i V_i [(X_i - X_m)w_i - (Y_i - Y_m)u_i]}{2\pi \frac{N}{60} \sum_{cells} \rho_i V_i [(Y_i - Y_m)^2 + (X_i - X_m)^2]}
\]

(4)

Rotational speed was taken as 2500 rpm. For all the simulations cylinder axis is z axis hence \( S_w = S_z \).

2.5 Flow Coefficient
The \( C_d \) coefficient provides useful details regarding the valve’s behavior during the intake, and it typically is analyzed for a set of different valve lifts. There are various methods in order to assess it. For the simulations of this study, it was chosen to define this value as a ratio between calculated mass flow rate and a theoretical mass flow rate which would pass through the valves of the engine.

\[
C_d = \frac{m_v}{m_{th}}
\]

(5)

Theoretical mass flow rate is defined as

\[
m_{th} = \rho A_{va} V_b
\]

(6)

Where \( V_b \) is defined as Bernoulli velocity

\[
V_b = \sqrt{\frac{2AP}{\rho}}
\]

(7)

And \( A_{va} \) is the effective valve open area

\[
A_{va} = \frac{\pi d^2}{4} h
\]

(8)

Where \( h \) is valve lift.

3. Mesh Optimization
Polyhedral mesh was used to for the CFD analysis. The meshes were generated within the STAR CCM+ software.

**Table 2. Variations of swirl ratio with mesh count & time taken to finish simulation**

| Test No | Valve Lift (mm) | Mesh Count | Swirl Ratio | Time Taken (hr) |
|---------|-----------------|------------|-------------|-----------------|
| 1       | 6               | 82620      | 1.4230      | 0.1667          |
| 2       | 6               | 139540     | 1.6300      | 0.5000          |
| 3       | 6               | 342320     | 1.5930      | 2.0000          |
| 4       | 6               | 625521     | 1.5907      | 7.0000          |
| 5       | 6               | 1200283    | 1.5875      | 18.0000         |
| 6       | 6               | 3500255    | 1.5875      | 48.0000         |
It was noted that there is no considerable deviation in swirl ratio for 3rd test and it takes less time hence all the simulations were conducted with mesh count in between 300000-400000.

4. Boundary Conditions
Before running a CFD simulation, it is necessary to set specific boundary conditions for the computational domain. K-epsilon turbulence model was used for the simulation. The boundary conditions were chosen from earlier research conducted on the same engine. The inlet velocity is taken as 83.28m/s for 2 valve cylinder head intake port and velocity of 65 m/s was assumed for the 4 valve cylinder head intake port which comes close to the experimental results done for twin helical port. The drop-in velocity can be accounted for increase in the total cross-section area. It is a turbo charged engine with intercooler. The intercooler outlet or cylinder intake temperature is taken as 333K as per the experiment results. The outlet condition is taken as atmospheric. The engine rpm was considered for swirl calculation is 2500.

Due to the high velocities involved the flow is turbulent. For the simulations turbulence intensity was assumed to be 5% and the length scale is taken as 7% of inlet port area. For exhaust gas simulations, it is important to prevent large variation in the exhaust gas velocity and temperature. For simulations, the exhaust inlet is given with an inlet boundary condition of 0.01kg/s as mass flow rate and 600K temperature.

4.1. Properties of the fluid
The fluid used for all the simulation is air with the following properties

| Property               | Value   |
|------------------------|---------|
| Density                | 1.18415 kg/m³ |
| Dynamic Viscosity      | 1.85508e-5 Pas |
| Specific Heat          | 1003.62 J/kg-K |
| Molecular Weight       | 28.9664 kg/kmol |
| Thermal Conductivity   | 0.0260305 W/mK |
| Turbulent Prandtl Number | 0.9    |

4.2. Convergence Criteria
The convergence criteria is set as 4000 iterations or residuals for pressure, momentum, turbulent dissipation rate and turbulent kinetic energy as 0.001.

5. Results
A 4 valve cylinder head design meeting the minimum swirl requirement for tractor application as per ARAI standards was designed. Design and placement of ports affects the flow pattern developed inside the cylinder. An existing 4 valve engine with similar port configuration was studied to develop new ports. The position of existing 2 valve cylinder head bolts and push rod holes limits the space available for new ports. It also restricts directing the ports in a specific direction. New design ensured sufficient spacing between the port walls and bolt holes to avoid crack development due to high combustion pressure.

Acceptable results were achieved regarding the evaluation of swirl ratio with STAR CCM+ software. After validation, it can be used as a good tool to quickly modify the design parameters and perform the analysis. Usage of polyhedral mesh reduces the mesh count as well convergence time for the simulation compared conventional tetrahedral mesh.

Swirl and flow coefficient for different valves were studied using CFD techniques. Experimental swirl ratio values were taken from ARAI test rig results for the same engine. Figure 3 shows the variation of swirl with different valve lift for both experimental and CFD analysis. It reveals a minor variation in swirl ratio and follows the same trend. Swirl ratio of 1.6 was observed at maximum valve lift of 6mm. The decrease in swirl for low valve lifts due to reduced valve flow area is observed
The CFD result (figure 4) shows that layout 2 offers more swirl and a slight increase in flow coefficient compared to layout 1. There is a reduction in swirl due to the flow mixing between two ports. The new four valve cylinder port configuration is having less swirl ratio compared to two valve design but offers sufficient swirl as well as increased flow coefficient. Swirl ratio for the tangential port is less as the function of this port is to increase the flow condition rather than generating swirl motion. There is a reduction of swirl ratio when flow through both port is active.

The flow mixing occurs when flow through both helical and tangential port is active and results in a reduction of swirl. For layout 1, even though the individual ports show similar performance as layout 2 there is a significant drop in swirl for the combined port. The reason being the influence of interference between flow streams from the tangential and helical port is more. Significant reduction in swirl at lower valve lifts was observed for new 4-valve design.
Flow coefficient for the helical port is lower than tangential for due to the higher flow restriction and the simulation results shows the same. Helical port shows higher density accumulation in the port compared to the tangential port. It is observed that the mean flow coefficient of new 4 valve design for both layout 1 and layout 2 is higher than the existing 2-valve design (figure 8).

Table 4: Exhaust manifold outlet velocity and temperature for valve lift 4mm and 6mm

| Valve lift | 4 mm | 6 mm |
|------------|------|------|
| 2 Valve E  | 13.58| 598  |
| 4 Valve E  | 14.52| 601  |
| 2 Valve E  | 13.252| 587  |
| 4 Valve E  | 14.32| 599  |

The exhaust port design ensured that there is no significant drop in velocity and temperature (table 4) at the outlet to retain the existing turbocharger assembly. There is a reduction in flow coefficient for new 4-valve design due to the combined port design of the exhaust port.
6. Conclusion

1. The experimental results were found to be in accordance with simulation results. The CFD method can be used as a good tool for evaluating ports.
2. After validation, it was clear that CFD software helps to reduce the number of real time experiments to be conducted to achieve the optimal port design.
3. Position of tangential and helical port influence the swirl motion generated inside the cylinder.
4. Conversion of existing 2 valve cylinder head to 4 valve requires a tradeoff between a lot of design parameters and may not support modern high swirl generating port layouts.

7. References

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