DIESEL ENGINE AIR SWIRL MEASUREMENTS USING AVL TEST RIG

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ABSTRACT

Knowledge of air flow in induction port and air motion within the cylinder of High-speed direct – injection diesel engine is of primary importance as it influences fuel – air mixing, combustion and hence fuel economy. To achieve the required optimized swirl with minimum restriction to flow, it is necessary to study the characteristics of inlet ports. Two common induction port shapes used are tangential/directed port and helical port. The methods often used for measuring swirl and other air motion features include steady flow test rig with AVL paddle wheel anemometer.

Keywords: Rig Swirl, AVL paddle anemometer.

I. INTRODUCTION

The importance of proper interaction of air swirl and fuel sprays has been emphasized by a number of researchers. Greaves et al report high speed diesel engine measurements where the engine speeds, injection rate and swirl ratio were varied. Exhaust smoke levels were taken to measure combustion performance i.e. fuel air mixing. They found for high engine speeds, an optimum value of swirl ratio exists below or above which an increase in smoke results, for most fuel injection rates.
The swirl ratio and other characteristics of inlet port system are important design parameters. It has, therefore been made the subject of experimental study in the present work. Inlet port shape may be monitored through the development phase by making a series of silicone rubber casting of the port model. Epoxy resin cores could then be made from the developed flow box shape. Similarly, a thermo plastic vinyl resin could be used to make impression of ports from cast or existing cylinder heads. These shapes are then tested on flow test rigs to obtain the configuration with optimum shape for giving optimum swirl ratio and mean flow coefficient. Traditionally four measuring techniques have been employed for development of port shapes namely AVL paddle wheel an anemometer, Ricardo impulse swirl meter, Hot wire anemometer and Laser Doppler anemometer. Of these, the first two are employed for industrial development and the last two for research analysis.

In view of the above, the following has been attempted in this report:
- Fabrication of steady flow rigs to be used for AVL.
- Experiment set up for measuring the cylinder charge rotation and flow pattern by AVL paddle wheel anemometer at different valve lifts.
- Testing of three inlet ports namely (1) tangential port (2) Directed port (3) Semi – helical port (a modified form of the second for higher swirl and better flow characteristics) of the available engines of the same power range.
- Translation of inlet port cores by Plastering.

II. ENGINE AIR SWIRL AVL PADDLE WHEEL ANEMOMETER MEASUREMENT TECHNIQUE

The development of port design was done on a steady flow rig using vane anemometer by 3\textsuperscript{rd} for the study of effect of cylinder charge motion on combustion. The same method was also used by Rao\textsuperscript{14} for the measurement of swirl and calculation of coefficient of flow in diesel engine.

For measuring the rotation of the cylinder charge, a paddle-wheel anemometer was developed and the method of measurement standardized by AVL using the steady flow test. The principle is shown in figure 2.1.

![Figure: 2.1 AVL Rotational Swirl Measuring Principle](image-url)
For the measurement of swirl generating capacity of inlet ports, the air is sucked in by a test bed blower through the port, over the valve with adjustable lift, the cylinder liner, the large sized tank and finally a connected flow meter. The pressure drop $\Delta p$ between the atmosphere and the tank in this case equals the pressure loss in inlet port and the inlet valve, as there is no significant pressure loss in the cylinder liner. The rotation of the air sucked into the cylinder liner is measured by the paddle wheel speed which is sensed by pulse pick up and is transmitted into an electronic counter. With a given shape of the inlet port having a valve of a particular seat angle and kept at a given position to the cylinder liner, a particular steady flow pattern results for a given valve lift. This pattern only depends on the Reynolds number, the intake conditions and the pressure ratio $Pz/Po$ between cylinder (tank) and the atmosphere. For this range of Reynolds number, intake conditions and $Pz/Po$ of interest in the actual engine flow conditions, this dependence is generally small and may be neglected. For this reason, the pattern of air flowing into the cylinder can be regarded as function of intake port parameters, cylinder liner configuration, their location to one another and the valve lift. This flow pattern may be characterized by the following parameters:

- $m$ - the mass flow rate of air.
- $n_D$ - the speed of paddle wheel of given dimensions, mounted in a fixed distance from the cylinder heads.
- $V_u$ - the mean velocity of the particles of the Air flowing through the circle of diameter $D_m$ drawn by the centre of the paddle in Circumference direction, where the back Lash of the paddle wheel is neglected.
- $V_a$ - the mean air velocity in direction of Cylinder axis.
- $A_c$ - sectional area of cylinder.
- $\rho$ - density of air at experimental conditions.

Where $V_u$ and $V_a$ can be calculated as:

$$V_u = \Pi.D_m.n_D/60$$

& $$V_a = \frac{m}{\rho.A_c}$$

The flow pattern may also be characterized by a single parameter,

- $\delta$ - the inclination angle of the helical line of diameter $D_m$ where the particles of air move through the cylinder liner.

Which can be calculated as:

$$\cot\delta = \frac{V_u}{V_a} = \left(\Pi.D_m.n_D/60\right) \times \frac{\rho.A_c}{m}$$

$n_D$, $m$, $\rho$ are experimental observations.

$D_m$ & $A_c$ are measurable dimensions.

If the steady flow test with this given device is performed at various valve lifts, the flow pattern in the cylinder liner or respectively its characteristic quantities, do not give any information about the connection between the rotation of the cylinder charge and the engine speed, but it forms the basis of an explanation. The method of representation of flow patterns as swirl ratio $n_D/n$ specified by AVL gives a much better appreciation. Here, the anemometer speed $n_D$ measured by steady flow test is divided by engine speed $n$, which is obtained by equating the mean axial flow velocity $V_a$ with the mean piston speed $V_m = S.n/30$. Hence,
\[ \frac{n_D}{n} = \left( \frac{n_D}{\text{unit}} \right) \times \left( \rho \cdot \frac{\text{Ac}.S}{30} \right) \]

For a given port and engine design and the defined valve of specific weight \( \rho \), the swirl ratio is a function of the quantity \( \frac{n_D}{\text{unit}} \) which characterizes the flow pattern.

In conclusion it could be stated that the parameters which are measured in AVL steady flow test methods are paddle wheel speed \( n_D \), valve lift \( L \), pressure drop \( \Delta p \), differential pressure across the flow meter and intake conditions \( P_o \) & \( T_o \).

The calculated quantities include, axial velocity \( V_a \), circumference velocity \( V_u \), helix angle \( \delta \), mass flow rate \( \dot{m} \), flow coefficient \( C_f \) and AVL swirl ratio. Apart from the measured parameters other inputs include, paddle wheel diameter, cylinder bore, engine speed, density of air at intake conditions.

III. EXPERIMENTAL WORK

Paddle wheel was fabricated out of alloy steel strip as per details indicated in Fig 3.1 and suggested by AVL. The dimensions were incorporated according to inner diameter of cylinder linear. The length of paddle wheel was kept as 0.917 bore whereas height of paddle wheel was 0.167 bore. The thickness of vanes was kept 1.5mm as recommended by AVL. The anemometer vanes were mounted on the SKF ball bearings. AVL had recommended that these bearing have to be used dry and without lubrication and hence calibration measurements have to be carried out every fifth day. The main components of the test rig include:

1. Cylinder head.
2. Cylinder linear.
3. Paddle wheel anemometer.
4. Pulse pick up.
5. Electronic Counter.
6. A large control volume (Tank).
7. Flow meter.
8. Motor driven blower.

Figure: 3.1 Experimental Set up for AVL Swirl Measurement
To test the inlet port at various valve lifts, the following steps were followed:

i. The valve was set at 1mm valve opening by giving a rotation to metric screw and noting the reading on dial gauge mounted upon the valve stem.
ii. Blower was started with control valve partially opened.
iii. The differential pressure across the tank was observed in the U-tube water manometer. It was monitored to 25.4 cm water gauge by operating the control valve.
iv. The final readings were taken after waiting for 15 minutes so that the flow could be maintained steady and when the readings got stabilized. The various reading were noted, namely, lift (L) in mm, discharge (Q) in l/sec., mass flow rate (m) in g/sec. and paddle wheel speed (nD) in rpm.

The readings were taken at each interval of valve lift, starting from 1mm to 10 mm following the same procedure.

Procedure for AVL test calculations
For each valve lift, the important parameters were calculated using a computer program in FORTRAN-77. The simplified flow diagram for the calculation procedure is given in Fig. 3.2

![Flow chart for AVL Calculation](image)

**Figure: 3.2 Flow chart for AVL Calculation**

Essentially the following parameters are calculated:

Circumferential Velocity.

\[ V_u = \pi D_m n D / 60 \]

Where \( D_m \) = diameter of circle drawn by centers of paddle = 80 mm for this case.

Axial Velocity

\[ V_a = \frac{\rho n D}{A_c} \]

Helix Angle

\[ \delta = \cot^{-1} \left( \frac{V_u}{V_a} \right) \]

AVL Swirl ratio

\[ n_D / n = n_D - p A_c S / (30 \cdot n D) \]

Flow Coefficient

\[ C_f = Q / (A V_o) \]

Mean Flow Coefficient

\[ C_f (\text{Mean}) = \int_{a_1}^{a_2} C_f \, d\alpha \]

Where \( \alpha_1, \alpha_2 \) were taken corresponding to lift from lift – crank angle diagram.

Gulp factor

\[ Z = [B / D]^2 \cdot (2S \cdot W / a C_f (\text{Mean})) \]
IV. RESULT & DISCUSSION

The basis of the study is a characterization of the air motion using steady flow rigs and application of empirical models to predict the in-cylinder conditions which affect engine performance. Fig 4.1 shows three cylinder heads of Engines namely Engine ‘A’ with tangential port, Engine ‘B’ with directed port and Engine ‘C’ with semi-Helical Port. All these heads were taken from the engines with same power range.

![Figure 4.1 Cylinder Heads Tested for Flow and Swirl Characteristics](image)

**AVL TEST RESULTS**

AVL tests were performed with suction configuration i.e. air flow was induced through inlet port without manifold by sucking the air through drum as already shown in fig 3.1.

Tests were conducted separately for three ports A, B & C and the results are tabulated in tables 4.1-4.3. These tables give the measured values, i.e. valve lift, discharge, mass flow rate and paddle wheel speed, as also the calculated values i.e. lift to dia ratio for valves, circumferential velocity, axial swirl ratio and flow coefficients. These results have been further plotted with non-dimensional lift/diameter ratio for inlet valve as the basis. Figs. 4.2-4.9 show the comparison of the flow and swirl characteristics of the three ports i.e., A, B and C.
### Table 4.1 AVL Test Results of Engine A having Mean Flow Coefficient 0.3126 & Gulp factor 0.3415.

<table>
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<tr>
<th>S No.</th>
<th>Lift (mm)</th>
<th>Lift/Dia.</th>
<th>Mass Flow Rate (gm/s)</th>
<th>Paddle Wheel Speed (rpm)</th>
<th>Circumferential Velocity (mm/s)</th>
<th>Axial Velocity (mm/s)</th>
<th>Helix Angle (Deg.)</th>
<th>Avl Swirl Rating</th>
<th>Flow Coefficient</th>
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<td>0.02</td>
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<td>25.2</td>
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### Table 4.2 AVL Test Results of Engine B having Mean Flow Coefficient 0.3129 & Gulp factor 0.3411.

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<tr>
<th>S No.</th>
<th>Lift (mm)</th>
<th>Lift/Dia.</th>
<th>Mass Flow Rate (gm/s)</th>
<th>Paddle Wheel Speed (rpm)</th>
<th>Circumferential Velocity (mm/s)</th>
<th>Axial Velocity (mm/s)</th>
<th>Helix Angle (Deg.)</th>
<th>Avl Swirl Rating</th>
<th>Flow Coefficient</th>
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85
Table 4.3 AVL Test Results of Engine C having Mean Flow Coefficient 0.3121 & Gulp factor 0.3420

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<tr>
<th>S No.</th>
<th>Lift (mm)</th>
<th>Lift/Dia.</th>
<th>Discharge (L/s)</th>
<th>Mass Flow Rate (gm/s)</th>
<th>Paddle Wheel Speed (rpm)</th>
<th>Circular Velocity (mm/s)</th>
<th>Axial Velocity (mm/s)</th>
<th>Helix Angle (Deg.)</th>
<th>Avl Swirl Rating</th>
<th>Flow Coefficient</th>
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<td>1.62</td>
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Figs. 4.2 and 4.3 show the same trend for discharge (L/S) and mass flow rate (g/s) versus non-dimensional lift (L/D) ratio. It may be noted that all these ports allow the flow from 10 l/s to 40 l/s for the L/D ratio ranging from 0.024 to 0.244. For initial half range of L/D ratio, the flow increases linearly and for the remaining half the increase is moderate and then it becomes asymptotic. It is because at the higher lifts, the resistance offered by the ports is more and skin friction comes into play with the flow. Further, it may be noted that the port B offers less resistance for low lifts and more resistance at higher lifts.
Figs 4.4 and 4.5 show the same trend of variation of paddle wheel speed (rpm) and circumferential velocity (mm/sec). Port C produce more swirl (2479 rpm) at maximum valve lift as compared to port B (2138 rpm) and Port a (1894 rpm) it is because helical port develops swirl inside the port, producing a spiral outflow from the valve. Whereas ports B and A develop swirl by producing a directional airflow which is forced to rotate by impingement on the cylinder wall. Further it may be noted that paddle wheel anemometer is less sensitive to detect the swirl at low lifts up to 4mm. It is because the mode of operation of paddle wheel is to impose a circumferential velocity in terms of 10.384 m/sec whereas port B produces 8.958 m/sec and port A 7.933 m/sec respectively. Circumferential velocities determine the paddle wheel speed.
Fig 4.6 shows the variation of axial flow velocity versus L/D ratio. The axial flow velocity has the same trend as the mass flow rate. It varies from 1 m/sec to 4.5 m/sec for L/D ratio range from 0.024 to 0.244. Axial flow velocity determines the mass flow rate. Thus for the same mass flow rate, different swirl speeds could be generated as seen above. However, excessive emphasis on increase in one adversely affects the other especially at higher valve lifts and maximum flow conditions.

![Figure: 4.6 AVL Axial Flow Velocity versus Lift](image)

Fig. 4.7 shows the variation of helix angle (degrees) versus L/D ratio. Helix angle is the inclination of helical line of D_m where particles of air move through the cylinder liner. It may be noted that port C gives minimum range of helix angles over valve lift as compared to port B & A. It can be reasoned out that helical port produces a spiral out flow from valve, thus contributing more circumferential velocity component than axial component and hence smaller helix angle. Helix angle is minimum at higher lifts. Port C has a helix angle of the value 23.91°, port B gives 26.27° and ports a, 29.67° at the maximum valve lift of 10 mm.

![Figure: 4.7 AVL Helix Angle versus Lift](image)

Fig. 4.8 illustrates the variation of AVL Swirl ratio versus L/D ratio. It is the ratio of paddle wheel speed to engine speed. It increases as the valve lift is increased. It ranges from 0.1 to 2.0 corresponding to the valve lift of 1 mm to 10 mm for the port C, which has more value as compared to other two for the same value of L/D ratio.

![Figure: 4.8 AVL Swirl Ratio versus Lift](image)
Fig 4.9 shows the variation of flow coefficient versus L/D ratio. All the three ports show the same trend of variation of flow coefficient. Its value ranges from 0.1 to 0.45 corresponding to the lift of 1 mm to 10 mm. These values remain same for geometrically similar ports.

Using this data the calculated quantities indicated are discharge coefficient, flow coefficient, flow coefficient based on lift, non-dimensional rig swirl, Reynolds nos., coefficient of performance, swirl angle, swirl ratio and gulp factor.

V. CONCLUSION

The objective set forth for present work include familiarization of flow characteristics of the port shapes mentioned above while using AVL and therefore getting an insight into their relative merits and demerits. Some of the conclusions obtained from above study are as follows:

It could be concluded from the above studies, that the port A which is a tangential port has the lowest swirl speed at the maximum valve lift. As this swirl speed further affects the compression swirl, it could be stated that the fuel air mixing will be at a slower rate, thereby giving larger ignition delays and lower rate of combustion resulting in a moderate speed. It is however possible to improve upon the performance with this port, in case squish is used properly along with the swirl.
Port B is also tangential port but with directed lip. Hence, it produces a higher swirl speed at a maximum valve lift. Thus, it could be used effectively for an engine which is optimized to run at a given speed and power. Port B has higher flow coefficients at low lifts. Helical port C generates more swirls as compared to tangential or directed port. Swirl speed is more (2479 rpm, $n_D/n = 2.08$) for helical port as compared to directed (2138 rpm, $n_D/n = 1.87$) and tangential (1894 rpm, $n_D/n = 1.62$) port corresponding to the maximum lift of 10 mm. Thus, modifying tangential port to directed port by providing a lip, a swirl speed can be increased by 12.8% and further modifying this directed port to semi-helical port, it could be increased to 30.8%.

VI. SCOPE FOR FURTHER WORK

1. A three dimensional computer simulation of flow field in inlet ports investigated in the present work can be formulated.

2. This data could be used to predicting compression swirl and could further connected by computer simulation of diesel engine to the engine performance. Thus by predicting the effect of swirl related parameters on the engine performance, fuel – economy and pollutant formation.

VII. REFERENCE

17. AVL, Austria, “Paddle wheel anemometer”, Operational manual.

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