Observation of carbon sedimentation effect and soot concentration in diesel engine after intake valve modification

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Abstract

Higher compression ratio is required in diesel engine to ignite the fuel that leads to better efficiency. For complete combustion inside the cylinder it is important to ensure the clean air flow with free of debris and as cool as possible. In this manner, modification of intake valve arrangements is taken in to consideration importantly. In this paper, the intake valve arrangements are modified with newly designed valve mixer. It causes swirl flow of air through the intake port that mixing with the fuel followed by complete combustion. The use of valve mixer reduces the carbon sediment formation on valve fillet and its face area as the carbon particles gradually take place on it after certain running period. It therefore, helps to increase the valve lifetime. And at the same time it reduces the exhaust elements i.e. soot from the automobiles to a significant level.

Key words: Diesel engine, Valve mixer, Carbon sediment, Soot.

1. Introduction

A diesel internal combustion engine burns the air fuel mixture within the cylinders. It is a reciprocating engine that driven by pistons moving laterally in two directions. It is ponderous (compared gasoline engine) due to stronger, heavier materials used to withstand the greater dynamic forces from the higher combustion pressures present in the diesel engine. Diesel engine requires close tolerances to achieve its compression ratio of 14:1 to 24:1. A turbocharged or supercharged diesel engine requires the air entering the engine be clean, free of debris and as cool as possible. The compressed air must be cooled after being compressed to improve a turbocharged or supercharged engine's efficiency. The air intake system is designed to perform these tasks. In dry air intake (filter) system, paper, cloth or a metal screen material is used to catch and trap dirt before it enters the automobile engine. In addition to clean the air, the intake system is usually designed to take fresh air from as far away from the engine as practicable which provides the engine with a supply of air that has not been heated by the engine's own waste heat. Because of high temperature and pressure followed by burning inside the combustion chamber, the valves, cylinder top and intake exhaust port gets carbon sediment. The valves get carbon sediment on valves fillet area mostly and also some onto hardened face. Fig.1 shows the carbon formation area on the valve.

In this study, a design of valve mixer with fin arrangement has been developed that would be mounted around the valve fillet and face area. The arrangement also includes the valve guide, valve mixer guide and case. The attachment helps to moves the air inside the cylinder by causing a swirl flow which creates a good combustion inside the
engine and it also helps to formation of carbon on it rather than on valve fillet and valve face area directly. As a result the valve becomes safe from carbon particles. As the valve mixer absorbs a significant amount of carbon particles, finally it also helps to less emit of soot and other exhaust elements.

2. Design characteristics and computational analysis

Design and computational analysis of valve mixer is important. As the intake air flow through the intake port passes by valve mixer and mixes with the fuel at high pressure, it is necessary to analyze the pressure distribution of fluid over the mixer, velocity vector, streamlines etc.

2-1 Valve mixer and its arrangement

For design of the valve mixer, FLUENT software (version 6.3.26) is used. The geometry is based on the xxx.igs and for mesh analysis the type is Tetrahedron with mesh number of about 0.45 million. Numerical methods followed by the governing equations of mass conversion, momentum conversion, realizable k-ε turbulence model and simple algorithm. Function of wall is standard and with no slaps wall surface boundary condition. Inlet velocity is 58.19 m/s and outlet is pressure. Fig. 2 shows the design of the valve mixer.

Fig. 3 shows the valve mixer arrangement on a valve with other accessories. The other major elements are valve guide, valve mixer guide, case.

2-2 Pressure distribution, velocity vector and streamlines analysis on valve mixer

Pressure distribution is termed as the distribution of pressure at all points around an airfoil at a given angle of attack. The aerodynamic performance of airfoil sections can be studied most easily by reference to the distribution of pressure over the airfoil. This distribution is usually expressed in terms of the pressure coefficient which refers to the difference between local static pressure and free stream static pressure, dimensionless by the free stream dynamic pressure [1]. Summation of the pressure acting on the airfoil results in a total pressure force. Splitting up this total pressure force into a part normal to the flow and another one tangential to the flow direction, results in a lift.
Fig. 4. Pressure distribution on valve mixer

Fig. 5. Velocity vectors across the valve mixer

Fig. 6. Streamlines over the valve mixer

force and a drag force. In some regions, the pressure force acting on the airfoil is of lower pressure than the surrounding pressure and in other regions, it is higher [2]. Typically, graphs of these distributions are drawn so that negative numbers are higher on the graph, as the pressure co-efficient for the upper surface of the airfoil will usually be farther below zero and will hence be the top line on the graph [3]. Fig. 4 shows the pressure distribution on the valve mixer.

In case of velocity vector, for motion with constant velocity is the vector points in the direction of the motion (v) and dividing it by the scalar (l) that only changes its length, not its direction. It means the velocity vector points in motion towards same direction. If the velocity is not constant, the use of slope of tangent line approach is good for defining the components from which it is possible to assemble the velocity vector [4]. Fig. 5 shows the velocity vector of the moving components over the valve mixture and the corresponding graphical presentation [5].

Finally, stream lines are the family of curves that are instantaneously tangent to the velocity vector of the air flow.

For the components of the velocity, curves are parallel to the velocity vector and there is no time dependence. This is because they are calculated instantaneously, meaning that at one instance of time they are calculated throughout the fluid [6]. Fig. 6 shows the streamlines over the valve mixer.

### Table 1. Test engine Specification

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore x Stroke</td>
<td>89 mm x 92.4 mm</td>
</tr>
<tr>
<td>Displacement volume</td>
<td>2784 cc</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>22.1</td>
</tr>
<tr>
<td>Number of cylinder</td>
<td>5 (five)</td>
</tr>
<tr>
<td>Cooling type</td>
<td>Water cooling type</td>
</tr>
<tr>
<td>Valve system</td>
<td>Single overhead cam</td>
</tr>
</tbody>
</table>

### 3. Experimental analysis:

For the experimental analysis, SsungYong motor engine used. Table-1 refers the specifications of the test engine. For measuring soot concentration percentage the experiment carried out at three different RPM at 4020, 3600 and 3200. RPM 4020 followed between 41 to 51 seconds, RPM 3600 followed between 61 to 71 seconds and RPM 3200 followed between 81 to 91 seconds respectively.

### 4. Findings and discussion

4-1 Carbon particle effect on valve
combustion engine. In case of conventional intake system, the result of sedimentation that caused by the carbons, pollutants (toxic gases) occurs and affects engine's durability. That's why after running a period the valve material wears away and the valves become unable to use further. As a result the durability of valve reduced. Adaptation of the valve mixer with necessary auxiliary attachments on the valve fillet helps to minimize the formation of carbons on the valve upper surface. The carbons are formed on the mixer and after certain period it is possible to change the mixer. As a result the life time and durability of the valve increases. Fig. 8 shows the core areas (arrow marked) of carbon formation on the valve mixer.

4-2 Soot concentration

With increasing environmental and health awareness and new legislations on particulate emission, there is a need to reduce the soot emissions from practical combustion systems. As most of the combustion occurs at high pressures, it is of interest to understand how pressure influences the combustion phenomena, in particular soot formation pathways [7]. Soot formation is a complex process that involves many chemical and physical steps. Fig. 9 shows the flowchart of soot formation that includes: (a) decomposition of the

Fig. 7. Carbon sedimentation on valve, cylinder top and intake port

Fig. 8. Carbon formation area on valve mixer

Because of internal combustion inside diesel occurs at high pressure and temperature, valves, top of the cylinder and intake port are seriously affected by the carbons. Fig. 7 shows the carbon sedimentations valve, top of the cylinder and intake port.

These are the general symptoms of an internal

![Flowchart of Soot Formation](image_url)

Fig. 9. SFlow chart of soot formation

![Schematic Diagram of Soot Formation Steps](image_url)

Fig. 10. Schematic diagram of soot formation steps

Table 2. Characteristics of soot particles emitted at different engine load

<table>
<thead>
<tr>
<th>Engine equivalence ratio</th>
<th>Exhaust molecular weight (kg/kmol)</th>
<th>Exhaust temp. at exit (°C)</th>
<th>Volume mean diameter (μm)</th>
<th>Gravimetric soot mass concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean (mg/m³) Std. Dev.</td>
</tr>
<tr>
<td>0.238</td>
<td>28.98</td>
<td>144</td>
<td>0.058</td>
<td>2.2  0.65</td>
</tr>
<tr>
<td>0.312</td>
<td>28.99</td>
<td>173</td>
<td>0.098</td>
<td>2.8  1.27</td>
</tr>
<tr>
<td>0.411</td>
<td>29.00</td>
<td>205</td>
<td>0.115</td>
<td>4.0  1.17</td>
</tr>
<tr>
<td>0.515</td>
<td>29.01</td>
<td>252</td>
<td>0.114</td>
<td>11.4  1.01</td>
</tr>
<tr>
<td>0.582</td>
<td>29.02</td>
<td>278</td>
<td>0.106</td>
<td>25.6  3.61</td>
</tr>
</tbody>
</table>

Fig. 11. Soot concentration as a function of crank angle

Fig. 12. Evolution of the soot size distribution with respect to crank angle

hydrocarbons in the fuel [chemical consumption of the fuel by any chemical process, including either unimolecular or bimolecular reactions], (b) formation of small aromatic hydrocarbons from the decomposition products, (c) growth of the small aromatics to compounds containing larger numbers of rings, (d) inception of small soot particles from the large aromatic hydrocarbons and (e) growth of the small particles to particles with larger masses [8].

Diesel particulate emissions are complex aerosols consisting primarily of soot (solid carbon) and volatile organics (mostly hydrocarbons). Typical soot particles are agglomerates of 10-30 nm diameter spheroids joined together into clumps or chains. Characteristic dimensions range from 0.01 to 1.0 μm, but most of the mass is log normally distributed with mass median diameters on the order of 0.1 to 0.3 μm [9]. Fig. 10 shows the schematic diagram of different steps of soot formation [10].

The soot mass concentration in a diesel engine is investigated by Mark and David. The soot mass concentration values are listed in the table-2 [9]. Here, exhaust molecular weight calculated from chemical balance assuming of C₅₂H₁₀ and products of CO₂, H₂O, O₂ and N₂. Exhaust temperature at exit measured at optical measurement volume, volume mean diameter measured at filter sampling site with Electrostatic Aerosol Analyzer (EAA) and gravimetric soot mass concentration refer to non-volatile mass concentration as measured by gravimetric method, volume is referenced to density of exhaust at standard conditions of 1 atm and 25°C.

High temperatures in combustion with the low oxygen content are ideal conditions for the formation of soot. Fig. 11 shows the overall soot concentration inside a combustion chamber as a function of crank angle. Most of the large amount of soot produced at early crank angles is consumed again at later crank angles and the remaining mass
of soot which is finally detected in the exhaust gases, is only a very small fraction of the initial one.

Fig. 12 shows the evolution of the soot size distribution with respect to crank angle. The soot size distribution evolves during the combustion cycle, with the larger particles forming later in the combustion event and into the exhaust stroke [12].

From the experimental analysis it is observed that, incorporation of valve mixer with fins cause a swirl flow of air through intake valve that mixes with the fuel inside the cylinder leads good combustion. Fig. 13 shows the graph between percentages of soot concentration with respect to time (at different RPM). In conventional systems, at the starting stage the soot concentration is about 10% and at RPM 4020, it increases about 50% whereas after using the valve mixer it results soot concentration at starting stage lies below 10% and at all three RPM's it remain in an average of 10%. Therefore, compared to the existing engine system, new system reduces soot concentration more than two times and improves the combustion rate to a significant level.

5. Conclusions

The technology highlights the increase of valve life time and durability by reduction of carbons over the valve and on the other hand it reduces the exhaust soot percentage through complete combustion (excellent ignition) by smooth swirl airflow across the valve mixer. This system is also related to its technical and commercial applications. Finally the system follows the advantages that related to the cost efficient solution for intake valve and also environmentally viable in terms of exhaust emission.

References

2. Information of velocity distribution at Wikipedia. [http://www.mh-aerotools.de/airfoils/velocitydistributions.htm]
7.
12. "Examining soot emissions from boosted diesel engines at high EGR", sources of the larger soot particles and solutions for "clean"/ "dirty" re-circulated soot particles, SAE 2010 World Congress.