EFFECT ON PERFORMANCE AND COMBUSTION CHARACTERISTICS OF DIESEL ENGINE ENRICHED WITH HYDROGEN WITH VARIED PISTON BOWL GEOMETRY

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ABSTRACT

In place of conventional fuels, there is a need to search an alternative fuel as the reserves of conventional fuels are decreasing due to increase in consumption. Hydrogen is considered as one of the best alternative fuels for internal combustion engines due to unique combustion properties. Gas motion inside the engine cylinder, which depends on combustion chamber geometry is highly influences the performance of any internal combustion engine. Hence an attempt is made to study the performance and combustion parameters of hydrogen enriched diesel engine using varied piston bowl geometry. Experiments are conducted on four stroke single cylinder water cooled diesel Engine at constant speed of 1500 rpm at different loads for different flow rates of hydrogen. It is observed that there is knocking tendency for flow rates above 6 lpm due to rise in temperature and peak pressures with addition of hydrogen. The effect of piston bowl geometry on performance parameters viz. brake thermal efficiency (BTE), Brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), heat release rate (HRR) and cylinder pressure have been investigated and presented in this paper. Comparison of performance and combustion characteristics inside the cylinder with modified piston bowl geometry shows that the squish flow effects the turbulence near the TDC during compression stroke. The performance & combustion characteristics for diesel engine enriched with hydrogen are increased by 8.6%, 34%, 17.26%, 13.5% and 7.7% of BTE, BSFC, EGT, HRR and cylinder pressure respectively compared to alone diesel fuel. Further there is an increase of 5%, 3.6%, 10.24%, 6% and 2.9% in BTE, BSFC, EGT, HRR and cylinder pressure respectively is observed with varied piston bowl geometry compared to standard piston.
INTRODUCTION

One of the sources of energy used for electrical power generation, heating and transportation in the world is hydrocarbon fuel. But it has negative side such as polluting emissions, large scale oil spill etc. Due to difficulties in handling alternative fuels the use of hydrocarbon could not be eliminated. In order to eliminate these problems hydrogen gas can be supplemented to reduce the use of hydrocarbon fuel. In combustion process hydrogen enrichment improves the flame speed, lean burn ability and flame quenching distance. Due to scarcity, handling process and production cost it difficult to use hydrogen commercially as an alternative fuel.

Hydrogen has more advantages compared to other fuels as it is non-carbon fuel which results in elimination of emission particulates with complete combustion of fuel [1]. Hydrogen has wider flammability limits, higher flame speed and fast burning velocity compared to diesel, which results in running the engine on very lean mixtures [2-3]. The properties of hydrogen comparing with diesel are shown in Table 1. To meet the ever increasing stringent environmental controls of exhaust emissions from combustion devices including greenhouse gas emissions reduction hydrogen is the best alternative fuel [4].

Table 1 Properties of Hydrogen compared to Diesel

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto-ignition temperature (K)</td>
<td>858</td>
<td>543</td>
</tr>
<tr>
<td>Molecular weight (g)</td>
<td>2.016</td>
<td>170</td>
</tr>
<tr>
<td>Density of gas at NTP (g/cm³)</td>
<td>0.0838</td>
<td>0.86</td>
</tr>
<tr>
<td>Flame velocity (cm/sec)</td>
<td>270</td>
<td>30</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.091</td>
<td>0.83</td>
</tr>
<tr>
<td>Boiling point (K)</td>
<td>20.27</td>
<td>580-640</td>
</tr>
<tr>
<td>Heat of Combustion (kJ/kg)</td>
<td>120</td>
<td>42.4</td>
</tr>
<tr>
<td>Octane number</td>
<td>130</td>
<td>-</td>
</tr>
<tr>
<td>Cetane number</td>
<td>-</td>
<td>40-60</td>
</tr>
<tr>
<td>Stoichiometric air fuel ratio</td>
<td>14.92</td>
<td>34.3</td>
</tr>
</tbody>
</table>

As many physical and chemical processes occur and act on each other in complex geometry, the flow phenomena in reciprocating engines are very complicated. At the end of compression stroke the flow conditions inside the cylinder and near the TDC are critical for fuel-air mixing, wall heat transfer and engine performance improvement [5]. In developing the efficient engine design, a complete understanding of physical properties of fluid motion in combustion chamber is essential [6].
Further it is observed that the geometry of the piston has significant influence the piston approaches to TDC. To obtain a better combustion with lesser emissions in direct-injection diesel engines, it is necessary to achieve a good spatial distribution of the injected fuel throughout the entire space [7]. It is evident that the effect of geometry has a negligible effect on the airflow during the intake stroke and early part of the compression stroke. But when the piston moves towards Top Dead Centre (TDC), the bowl geometry has a significant effect on air flow thereby resulting in better atomization, better mixing and better combustion [8].

In DI diesel engines, swirl can increase the rate of fuel-air mixing, reducing the combustion duration for toroidal chambers at retarded injection timings [9]. Swirl interaction with compression induced squish flow increases turbulence levels in the combustion bowl, promoting mixing [10]. Since the flow in the combustion chamber develops from interaction of the intake flow with the in-cylinder geometry, the goal of this work is to characterize the role of combustion chamber geometry on in-cylinder flow, thus the fuel-air mixing influence on combustion and performance characteristics.

The combustion process depends highly on efficient fuel-air mixture. The mixing process is influenced by the intake swirl, fuel injection system and configuration of combustion chamber [11]. This paper aims to study the effect of piston bowl geometry on performance and combustion characteristics on hydrogen enriched diesel engine at different flow rates of hydrogen.

2. EXPERIMENTAL SET UP

The experiments are conducted on single cylinder, four stroke, water cooled diesel engine. The specifications of the engine are shown in Table 2 and the safety measures required for hydrogen operation, as it associates with Hindenburg or Challenger disasters in its operation. To suppress the explosion inside the hydrogen cylinder a flame arrester is used. The flame arrester consists of partly filled water tank with fine mesh to prevent the flame propagation beyond the wire mesh. In case of backfire the flame gets quenched as it reaches the water surface. Also to prevent the reverse flow of hydrogen into the system a non-return valve is provided. To visualise the flow of hydrogen during the engine operations, a flow indicator is used. To measure the combustion parameters AVL combustion analyser is used. The schematic diagram for experimental set up is shown in Fig 1.

Initially the diesel engine with standard piston of hemispherical piston bowl geometry is operated at no load with rated speed for a duration to reach steady-state condition. The loads are induced to the engine running with diesel for 20%, 40%, 60%, 80% and 100% loads in steps by means of Eddy current dynamometer and performance & combustion related parameters are recorded. Along with air hydrogen is inducted at constant flow rates of 2lpm (litres per minute), 4lpm and 6lpm, the experiments are conducted at different loads. For flow rates above 6lpm of hydrogen it is observed tendency of knocking due to high combustion temperatures with high flame & burning velocities. This is because more heat is being lost through cooling water from hotter walls of combustion chamber and hence results reduction in thermal efficiency. Again, the standard piston is replaced with modified piston with toroidal bowl geometry of same compression ratio. The performance & combustion parameters are measured by conducting experiments initially for diesel fuel alone and then by inducting hydrogen at different flow rates. Finally compared the performance & combustion parameters with all cases.
Effect on Performance and Combustion Characteristics of Diesel Engine Enriched with Hydrogen with Varied Piston Bowl Geometry

Table 2. Specifications of the Engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Power</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>Engine speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Cylinder bore</td>
<td>80mm</td>
</tr>
<tr>
<td>Stroke length</td>
<td>110mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5:1</td>
</tr>
<tr>
<td>Swept volume</td>
<td>550 cc</td>
</tr>
<tr>
<td>Fuel injection timing</td>
<td>21° BTDC</td>
</tr>
</tbody>
</table>

Table 2 Specifications of the Engine

3. RESULTS AND DISCUSSIONS

In this investigation, the performance parameters such as brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature and combustion parameters like cylinder pressure and heat release rate are determined at different flow rates of hydrogen for different piston bowl geometry with different loads.

3.1. Brake thermal efficiency (BTE)

The variations of brake thermal efficiency with brake power for different induced loads at different flow rates of hydrogen induction is shown in Fig 2. It is observed that, maximum increase in efficiency is found at full load with 6lpm flow rate of hydrogen. The BTE for normal engine at rated load is 25.38% with alone diesel and the engine with 6lpm hydrogen has increased to 27.57%. It is observed that there is increase of 8.6 % at rated load. This is because of higher heating value and high flame velocity with hydrogen addition. This improves the rate formation of intermediate compounds and initiates the combustion little later than neat diesel. In turn this delay accumulates oil before combustion results better burning of fuel.

It is observed from Fig 3, the BTE is further increased with varied piston bowl geometry for different flow rates of hydrogen. At 6lpm hydrogen flow rate, it is
observed that the BTE is 28.96% for modified piston and is 26.28% at rated load for diesel alone with modified piston. The BTE at rated load with 6lpm flow rate of hydrogen with modified piston are increased by 5% when compared with standard piston. This is because of improved combustion with better mixture formation due to improved swirl motion of air.

3.2. Brake specific fuel consumption (BSFC)

The brake specific fuel consumption variations with brake power for different flow rates are shown in Fig 4. It is observed that the maximum reduction in BSFC is found at full load with 6 lpm flow rate of hydrogen. The BSFC for normal engine at rated load is 0.411kg/kW-hr with alone diesel and the engine with 6 lpm hydrogen has reduced to 0.271 kg/kW-hr. It is observed that there is a reduction of 34% at rated load. This is because better mixing of hydrogen with air which leads to increase of temperatures in the combustion chamber resulting complete burning of fuel.

Further observed from Fig 5, the BSFC is further reduced by changing the piston bowl geometry for different flow rates of hydrogen. At 6 lpm hydrogen flow rate, it is observed BSFC is 0.264 kg/kW-hr for modified piston and 0.40 kg/kW-hr at rated load for diesel alone with modified piston. The BSFC at rated load with 6 lpm flow rate of hydrogen with modified piston are reduced by 3.6% when compared with standard piston. This is because the inducement of enhanced air swirl in the combustion chamber leads to the complete combustion of charge in the combustion chamber with liberation of maximum energy.
3.3. Exhaust gas temperature (EGT)

The variations of exhaust gas temperature with brake power for different flow rates are shown in Fig 6. It is observed that the maximum increase in temperature is found at full load with 6 lpm flow rate of hydrogen. The EGT for normal engine at rated load is 365°C with alone diesel and the engine with 6 lpm hydrogen has increased to 428°C. It is observed that there is an increase of 17.26% at rated load with hydrogen enrichment. This is due to shorter duration in burning heavy fuel molecules than neat diesel which in turn increases the combustion temperature.

Further observed from Fig 7, the EGT is increased further with modified piston bowl geometry for different flow rates of hydrogen. At 6 lpm hydrogen flow rate, it is observed EGT is 452°C for modified piston and for diesel alone with modified piston is 410°C at rated load. The EGT at rated load with 6lpm flow rate of hydrogen with modified piston is increased by 10.24% when compared with standard piston. This is due to the inducement of enhanced air swirl in the combustion chamber enhances the temperature of the combustion.

![Graph showing EGT vs BP](image)

3.4. Heat release rate (HRR)

It is observed in Fig 8, the heat release rate is higher with hydrogen addition compared to that of neat diesel. The maximum increase in HRR at rated load with 6 lpm flow rate of hydrogen is 121.1 kJ/m³·deg at 9° before TDC when compared with neat diesel at rated load it is 106.62 kJ/m³·deg at 10° before TDC. At rated load an increase of 13.5% is noticed with hydrogen enrichment compared to neat diesel. This is due to changes in fuel combustion phenomena with sufficient ignition delay and small quenching distance.

It is noticed from the Fig 9, the HRR is further increased with modified piston at different flow rates of hydrogen compared to that of neat diesel. It is observed, the maximum HRR increase at 6lpm flow rate of hydrogen is 128.33 kJ/m³·deg at 9° before TDC and 110 kJ/m³·deg at 11° before TDC with neat diesel at rated load. There is an increase of 6% HRR is noticed with hydrogen addition with modified piston compared standard piston at rated load. This is because of better mixing of fuel and air mixture results efficient burning of the fuel.

![Graph showing HRR vs BP](image)
3.5. Cylinder Pressure

The variation of cylinder pressure with crank angle is shown in Fig 10, which is higher with hydrogen addition compared to that of neat diesel. The maximum increase in cylinder pressure is found at rated load with 6 lpm flow rate of hydrogen is 50.86 bar at 1° after TDC and it is 47.21bar at 1° after TDC when compared with neat diesel at rated load. At rated load an increase of 7.7% is noticed with hydrogen enrichment compared to standard piston. This is because of highest combustion temperature of the hydrogen apart from high calorific value & high burning speed.

There is further increase in cylinder pressure observed with modified piston at different flow rates of hydrogen compared to that of neat diesel as shown in the Fig 11. It is observed, the maximum cylinder pressure at 6 lpm flow rate of hydrogen is 56.3 bar and with neat diesel at rated load it is 48.6 bar at 1° after TDC. There is an increase of 2.9% cylinder pressure is noticed with hydrogen addition with modified piston compared standard piston at rated load. This is due to better air motion the release of more breakdown products at rapid rate during the combustion process.
4. CONCLUSIONS

This paper reports the role of hydrogen enrichment at different flow rates in existing diesel engine by changing the piston bowl geometry in analysing the performance and combustion characteristics emission characteristics with the objective of improving the engine performance & combustion characteristics at different loads. The main conclusions of the present study are summarized as follows:

- The Brake Thermal Efficiency is increased about 8.6% for hydrogen enrichment with 6lpm compared to base diesel at rated load operation. This is due to high heating value and high flame velocity of hydrogen compared to neat diesel.
- It is observed that the Brake specific fuel consumption is reduced with hydrogen enrichment when compared to diesel operation due to increase of temperature in combustion chamber with better mixing of hydrogen & air, which results in reduction is about 34%.
- There is a growth of 17.26% in exhaust gas temperature is noticed with addition of hydrogen at 6lpm compared to alone diesel operation due to shorter duration in burning heavy fuel molecules with liberation of high energy.
- The combustion parameters such as heat release rate and cylinder pressure are increased by 13.5% and 7.7% respectively at rated load and 6lpm flow rate of hydrogen due to sufficient ignition delay, high burning speed and small quenching distance compared to base line diesel operation.
- It is found that, a further increase of 5%, 3.6%, 10.24%, 6% and 2.9% in BTE, BSFC, EGT, HRR & cylinder pressure respectively with hydrogen enrichment by modified piston bowl geometry against standard piston. This is because of improved swirl motion of air, high turbulence behaviour in the combustion.
- Further, at higher flow rates above 6lpm of hydrogen admission the combustion becomes uncontrolled due to high cylinder temperatures leads to tendency of knock.

REFERENCES


