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The effect of thermal barrier pistons on the performance of insulated DI diesel engine with alcohol as a fuel

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ABSTRACT

The rapidly depleting fossil fuels have simulated the worldwide search for the renewable alternative fuels. Our country is an agriculture based one and the production of sugar cane is more. In the production of sugar from sugar cane, alcohol will be produced as a byproduct. This made alcohol as a perfect replacement because these are derived from indigenous sources and are renewable. But with the low cetane number and high self ignition temperatures, the burning of alcohols in the existing diesel engines is difficult because for the vaporization it absorbs more heat from the engine and makes the engine cool and further more ignition delays. This made the ignition of alcohol in the high temperature combustion chambers. So in our work an insulated diesel engine is developed which retains higher temperatures in the combustion chambers and aids for the combustion. This reduces the ignition delays and leads for the complete combustion and further improves the thermal efficiency and reduces the emissions. The complete experimentation has done on a single cylinder 4-stroke water cooled 3.68 KW Kirloskar diesel engine with alcohol as a fuel. Due to lower viscosity of alcohol the fuel injection pressure is reduced to165 bar for the experimentation. In the experimentation it is observed that maximum heat lost through the piston. So three different piston crowns made up of Nimonic alloy, Copper and Brass are tried on the test engine with an objective to find the best one in terms of performance and emissions with alcohol as fuel and the same is compared with aluminum piston. Among all the pistons the brass piston performed well. Further the efficiency of the engine can be improved by providing turbulence in the combustion chamber. So for the experimentation maximum number of nine grooves is made on the brass piston and is tested. For the comparison the engine is also operated with aluminum piston. Out of all these pistons tested, brass Piston with nine grooves is found to be the best in terms of efficiency and emissions.

Introduction

Due to the high self ignition temperature of the alcohol it requires high compression ratios in the conventional diesel engine [1]. But for the high compression ratios the engine will become bulky. So in order to ignite the alcohols in the combustion chambers, production of high temperatures are necessary. This can be achieved by the insulation of the combustion chamber surfaces [2, 3 and 4]. Kamo and Bryzik [5] have demonstrated the use of partially stabilized Zirconia (PSZ) as the insulating material and also reported reduction in carbon monoxide, carbon particulates and smoke emission levels. Wade et. Al [6] reported the performance of ceramic coated engine with PSZ to 7% improvement in fuel consumption and reduction in HC emissions due to premixed combustion. Wallace et [7] have reported the use of a thermal barrier piston in the adiabatic engine and developed the temperature distribution analysis and reported that the piston top temperature were higher by around 400^0C for the thermal barrier pistons.

The insulated high temperature components include piston, cylinder head, valves and cylinder liner. So the insulating materials used in the combustion chamber should have lower thermal conductivity, good mechanical strength and must capable of withstanding for higher temperatures [8,11]. With the insulation of the engine the exhaust energy is increased compared to that of the conventional engine. Therefore, more technical innovations must be developed to extract useful energy from the exhaust and to derive the maximum benefits from this insulated engine concept. From the experiments (literature) it is observed that much amount of heat will lost through the piston. So in order to retain the heat in the combustion chamber, along with the insulation to the combustion chamber, piston crowns [9,10] are also made with various piston materials like Nimonic alloy, Copper and Brass. These crowns are same in the size of the original piston and can be interchangeable. With the turbulence in the combustion chamber the efficiency of the engine can be further increased. For that different number grooves are made on the piston crown and are tested in the same engine.

Preparation of the insulated engine components

In the present work preparation of the insulated engine with PSZ coating for the combustion chamber components is the most difficult task. The coating material selected must withstand for higher temperature and also have sufficient strength. Among all the coating materials searched the partially stabilized Zirconium (PSZ) is found to be quite useful for adiabatic engine application because of its excellent insulating characteristics,

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adequate strength and thermal expansion characteristics [2, 5, 6]. The insulated engine developed is having an air gap piston and liner, PSZ coated cylinder head and valves. The insulation methodology is explained in detail as follows.

Piston Insulation

In this a 2 mm air-gap (whose thermal conductivity is low) is provided between a metallic crown and the standard piston made of Aluminium alloy. This air gap is optimized based on the literature available [10]. The metallic crown and standard piston were separated by copper and steel gaskets. Fig.1 shows the air gap insulated piston with brass insert.

Fig1: An air-gap insulated piston with brass insert

Cylinder Liner Insulation

A thin mild steel sleeve is circumscribed over the cast iron liner maintaining a 2mm layer of air in the annular space between the liner and the sleeve [10]. The joints of the sleeve are sealed to prevent seepage of cooling water into the air-gap region.

Cylinder Head and valves Insulation

The combustion chamber area of the cylinder head and the bottom surfaces of the valves are machined to a depth of 0.5 mm and are coated with PSZ material for the same depth [3].The details of cylinder head and valves are as shown in the Fig.2.

Fig 2: PSZ coated cylinder head and valves

Experimental Details

Experiments are conducted on 4-stroke 3.68 KW Kirloskar water cooled DI Diesel engine at various loads. Due to lower viscosity of alcohols the fuel injection pressure is reduced to 165 bar [12] at an injection timing of 27^0 bTDC. If it is operated at normal injection pressures the amount of alcohol injected in to the engine will be more and further it may cool the engine due to its higher latent heat of vaporization. All the tests are conducted at the rated speed of 1500 rpm. The experimental set up used is as shown the following Fig.3.

Fig. 3. Experimental set up of Insulated Engine Test Rig

From the experiments it is observed that maximum heat transfer is through the piston. So in order to retain the heat in the combustion chamber, a piston is designed (similar to that of original piston) which is capable of absorbing heat from the hot combustion gases during the peak cycle temperature conditions and gives out the same to the incoming fresh charge during the suction and compression strokes of the next cycle. For that three thermal barrier piston crowns are designed, such as Nimonic alloy, Copper and Brass piston (BP) to reduce the heat losses from the piston crown to the piston skirt. Further the combustion efficiency can be increased with good turbulence in the combustion chamber. So an attempt is made in this work with different number of grooves on the brass crown piston in an insulated engine. The size of the groove on the piston crown is selected in such away that maximum number of grooves can be generated (BP9). This brass crown is further knurled to increase its surface area thus facilitating better heat transfer rate from the hot gases to the crown. The photographic views of the above piston crowns are as shown in the figures (Fig 4-7). This can be adapted to any engine without any major modifications to the original design.

Fig: 4 Photo Graphic View of Cupper crown

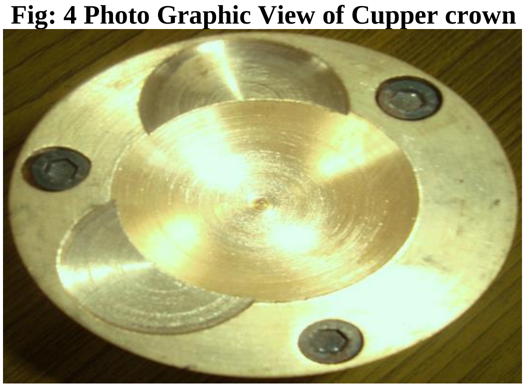

Fig: 5 Photo Graphic View of Nimonic alloy Crown

Fig: 6 Photo Graphic View of Brass Crown

Fig: 7 Photo Graphic View of Brass Crown Piston With 9 grooves

Results and Discussion

A variable load test is conducted on the insulated diesel engine by changing piston crowns. As maximum number of grooves is provided on the piston crown, the clearance volume increases and the compression ratio decrease. With the grooves the poor combustion due to reduction in compression ratio is compensated by better turbulence and insulated conditions. The performance and emission parameters are explained below in detail.

Exhaust Gas Temperature

The study of exhaust gas temperatures for five different pistons is shown in Exhibit: 1. As brass piston acts as a good heat reservoir, at higher loads the insulated engine with brass piston shows maximum temperature and aluminum minimum over a wide range of operations. This increases the combustion efficiency and is further enhanced by the positive ignition of alcohol. The Cupper and Nimonic alloy pistons are found to be good following the brass in the insulated engine. It is observed that the temperature at full load for brass piston is 560^0C and for aluminium it is 510^0C. The temperatures of Cupper and Nimonic alloy lie in between these two extremes. The exhaust temperature is further increased with the turbulence in the combustion chamber and this is 2.32% more temperature for BP9 compared to Brass piston (BP). The high temperature exhaust gas energy can be recovered by turbocompounding.

Brake Thermal Efficiency

The variation of brake thermal efficiency with power output for five different types of piston is shown in Exhibit: 2. As the brass crown piston acts as a good heat reservoir, the combustion process in the chamber is complete. So the brake thermal efficiency of the brass crown piston about 4% higher than the aluminium crown piston over a wide range of operation. Compared to aluminium piston the efficiency increased by 2.3% and 3 % for Nimonic alloy and Copper alloy respectively. The turbulence in the combustion chamber makes the charge in to homogeneous and increases the brake thermal efficiency of the engine with BP9 and is 2.53% higher than BP.

Volumetric efficiency

The effect of different piston materials on the volumetric efficiency depicts in Exhibit: 3. Since the combustion chamber temperatures are high with brass piston than any other pistons, heat transfer to the incoming air is high during the intake stroke which results in the drop in volumetric efficiency. This further affects the combustion by reducing the amount of air available for combustion and thus reduces the power output. This reduction of power can be compensated by supercharging.

The volumetric efficiency of the aluminium piston crown is varying from 85% at no load to about 82% at full load. For brass crown piston in the insulated engine, it is found that the drop in volumetric efficiency is more. The absolute drop in the volumetric efficiency is about 5% as compared to the aluminium crown piston at rated speed. The volumetric efficiencies of engine with Nimonic and copper alloys vary in between these two extremes. For BP9 of the insulated engine the drop in volumetric efficiency is more and is about 1.2% as compared to BP.

Ignition Delay

The variation in ignition delay with power output is illustrated in Exhibit: 4. The brass crown piston shows the lowest ignition delay due to the hotter combustion chamber among all the pistons tested and highest ignition delay is for aluminium piston. It is observed that the ignition delay of an insulated engine with aluminium piston varies from 22^0CA at no load to about 19^0CA at full load. The performance of brass crown piston with respect to delay period is commendable and this record a reduction of 10% and 13% at no load and rated load respectively compared to aluminium piston. The ignition delays of Cupper and Nimonic alloy varies in between these two extremes. With the groves on the brass piston, it reduced the time lag for initiating the combustion and this further brings down the ignition delays. The reduction in the ignition delay of BP9 is 6.25% at rated load compared to BP.

Smoke Density

The variation of exhaust smoke emissions for different piston crown materials is as shown in Exhibit: 5. The higher prevailing operating temperatures in the insulated combustion chamber result better combustion and oxidation to the soot particles which further reduce the smoke emissions. The brass crown piston in the insulated engine gives the lowest smoke emission over the entire operating range and the reduction is to be 16.67% compared to aluminum piston. It is seen that due to variation in the temperatures generated in the combustion chamber the reduction in smoke levels with Nimonic alloy and cupper pistons is about 7.7% and 12% respectively to aluminium piston. Due to the oxidation of the soot particles with the excess air in alcohol the smoke emissions are marginal. At the rated load, the smoke emissions of BP9 in the insulated engine are reduced by about 9% compared to BP.

Hydrocarbon (HC) Emissions

Exhibit: 6. depicts the amount of unburnt hydrocarbons present in the exhaust as function of load for different piston crown materials. It can be seen that in spite of rich air-fuel mixture due to lower volumetric efficiency, the HC emission are considerably reduced. The reduction in the HC emissions can be explained in terms of reduced flame quenching near the combustion chamber wall. Because of higher wall temperatures in the insulated engine, the flame quenching near the walls is reduced. This in turns reduces the formation of hydrocarbon emissions. At the rated load with brass crown piston a maximum reduction of hydrocarbon emission level is observed and is about 17.3% compared to aluminium piston. Due to the variation in the thermal conductivity and specific heat of materials the storing and rejecting capacity heat varies and further the temperatures will also vary. The reduction in the smoke levels of Nimonic alloy and cupper pistons is about 12% and 15.5% respectively to aluminium piston. With the turbulence in the combustion chamber the reduction of HC emission for BP9 is about 9.26% compared to BP.

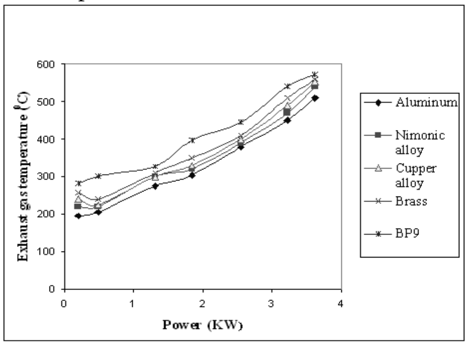

Exhibit 1.Comparison of Exhaust Gas Temperature with Power Outputs for Different Piston Inserts

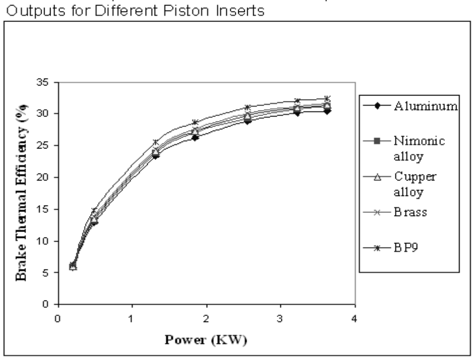

Exhibit 2. Comparison of Brake Thermal Efficiency with Power Output for Different Piston Inserts

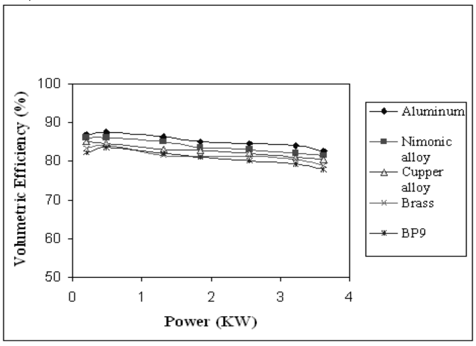

Exhibit 3. Comparison of Volumetric Efficiency with Power Output for Different Piston Inserts

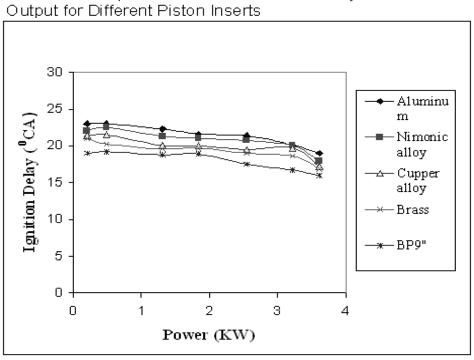

Exhibit 4. Comparison of Ignition delay with Power Output for Different Piston Inserts

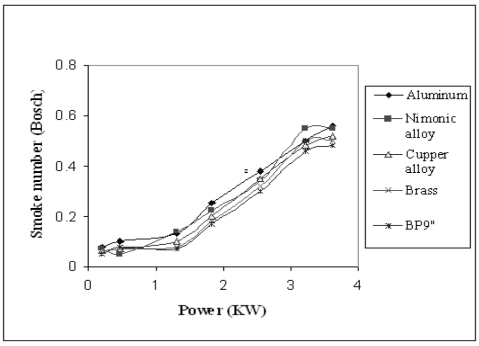

Exhibit 5 Comparison of Smoke Densities with Power Output for Different Piston Inserts

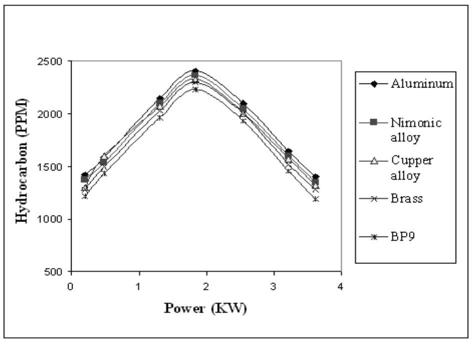

Exhibit 6.Comparison of Hydrocarbon Emissions with Power Output for Different Piston Inserts

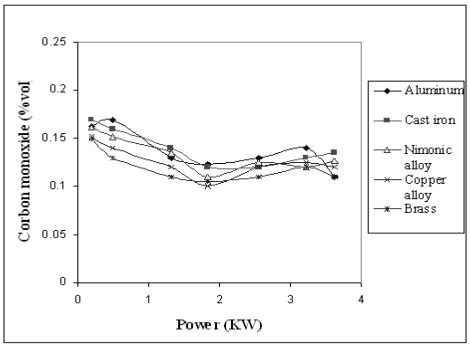

Exhibit 7.Comparison of Carbon Monoxide Emissions with Power Output for Different Piston Inserts

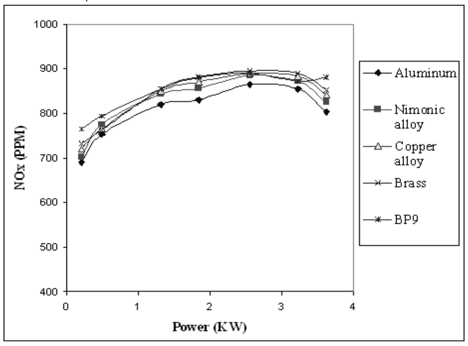

Exhibit 8. Comparison of NOx Emissions with Power Output for Different Piston Inserts

Carbon monoxide (CO) Emissions

The amount of CO present in the exhaust for various piston materials with respect to load is illustrated in Exhibit: 7. As the brass crown piston acts as a good heat reservoir the temperatures generated in the combustion chamber is higher. This further improves the oxidation of carbon monoxide and this reduces the CO emissions. The lowest carbon monoxide emission is given by the brass crown piston and the reduction is about 17.27% by volume at rated load. Due to lower temperatures in the combustion chamber compared to brass piston, the reduction in CO levels with Nimonic alloy and cupper pistons is about 10.23% and 16.67% compared to aluminium piston at rated load. These CO levels are further decreased with grooves on the piston. So the lowest CO emissions is with BP9 configuration compared to BP and is about 8% by volume.

Nitrogen Oxide (Nox) Emissions

The variation of NOx emissions with various configurations of the insulated engine is illustrated in Exhibit: 8. The formation of NOx depends on the heat transfer and evaporation rate of the fuel. The temperature with brass crown piston is more in the combustion chamber, so the heat transfer between the fuel and crown increases, which further increases the evaporation rate of the fuel. This increases the combustion phenomenon and due to the availability of oxygen with alcohol, the NOx formation also increases. But the amount of NOx formation is slightly reduced by the latent heat of vaporization of alcohol.

So the increase in NOx emissions with brass crown piston is more compared to aluminium piston. The increase in NOx emissions with brass crown piston is about 6.1% compared to aluminium piston at rated load. The NOx emissions of Nimonic alloy lie and cupper pistons lies in between brass and Aluminum pistons. Due to higher turbulence in the combustion chamber with grooves, the fuel and air mixing is proper which further increases heat transfer and evaporation rate of the fuel and further increases the formation of NOx 3.4% more for BP9 to BP at rated load.

Conclusions

Based on the above results and discussions, the following conclusions are drawn:

- With the groves on the brass piston, the generation of turbulence is more and this increases the temperatures inside the combustion chamber. This further increases the exhaust gas temperature. The high exhaust energy can be recovered by turbocharging.
- The higher temperatures in the combustion chamber increase the brake thermal efficiency of BP9 by 2.53% compared to BP.
- The turbulence in the combustion chamber provides the homogeneous mixture and this increases the temperatures in side the combustion chamber. This further reduces the volumetric efficiency and ignition delay.
- The oxidation of alcohol fuel increases with the oxygen present in it. With this the emissions are drastically reduced.
- But with the higher prevailing temperatures in the combustion chamber the NOx emissions increases. This is due to the reaction of nitrogen with oxygen at higher temperatures.

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