

Effect of Ceramic Coated Pistons on the Performance of a Compressed Natural Gas Engine

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Abstract. An internal combustion (IC) engine with ceramic wall coating is usually utilized to reduce the heat losses and it is referred to as low heat rejection (LHR) engine. While high fuel price and environment hazard is of major concern for the modern world, LHR engine type is gaining huge importance due to its low emissions and efficient fuel consumption. In this article, the simulation study was conducted using commercial software AVL Boost to analyze the effect of thermal barrier coatings (TBCs) on the performance of a single cylinder, naturally aspirated, compressed natural gas (CNG) engine. The results were carried out on a conventional (uncoated) piston, as well as two different thermal barrier ceramic Titanium dioxide (TiO_2) and Yttria-stabilized zirconia (YSZ) insulated pistons, which were coated with thickness of 0.5 mm. The simulation results were validated against the experimental results. The insulated pistons results showed that better performance at all operating conditions over the uncoated piston. The maximum exhaust gas temperature was increased about 57.35°C , improvement in indicated specific fuel consumption (ISFC) up to 9.1%, and maximum 9.78% improvement in indicated thermal efficiency (ITE) were predicted in the insulated pistons, as compared to the conventional piston.

1. Introduction

An IC engine rejects about two third of fuel energy to the environment either through its walls or through the exhaust valves while merely about one third of it is utilized as a power output. The concept of LHR engine eliminates this heat rejection towards the coolant and improves the energy utilization for work output as well as decreased emissions. The use of ceramic TBCs in engines improves the emissions, high piston surface temperature, efficient fuel consumptions and thermal fatigue protection. It also defends piston from thermal stress, corrosion attack, great heat emissions as well as it decreases heat flux into the piston [1].

Furthermore, a vast number of simulation studies on LHR engines have been carried out by different researchers [2-5]. The researchers have reported enhanced exhaust gas temperatures as well as enhanced performance in certain conditions. Chan et al. [6] used thin YSZ ceramic insulation schemes on a piston crown. When the engine was loaded at lower power, the insulated piston provided a better fuel economy of about 6%, as compared to the uncoated engine. Li et al. developed a one dimensional simulation code for a direct injection (DI), four-stroke, 1.9-liter diesel engine by means of commercial software GT-Power [7]. When the engine cooling temperature was varied from 56.5°C to 100°C , the simulated brake fuel conversion efficiency and brake specific fuel consumption was enhanced by 19.14% and 16.07%, respectively. Moreover, Parker [8] developed an air gap piston and found that the heat reduction was 41%. At the piston crown the maximum temperature of the air gap piston and conventional piston were predicted by 610°C and 222°C , respectively. Morel et. al established a



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thermodynamic cycle code for a four-stroke, 14-litre diesel engine [9]. The piston crowns were coated with 0.5 mm of ceramic partially stabilized zirconia (PSZ). The results showed that the thermal efficiency (TE) increased by 7%, heat losses fell by about 30%, and turbine inlet temperature increased by 30 °K.

Herein, the numerical one dimensional simulation was performed on a single cylinder CNG engine by using a commercial engine simulation software AVL Boost. As piston is the hottest part and mainly it contributes toward heat losses. Piston is coated with two different types of thermal barrier coating (TBC) materials, Titanium dioxide (TiO_2) and Ytria-stabilized zirconia (YSZ) with thickness of 0.5mm of each. The simulation was operated at five different excess air ratios (EARs) from 1 to 1.5 with a step of 0.1, different ignition times, and at a constant engine speed of 1000 rpm. The performance results of coated pistons engine were compared with the uncoated piston engine. With the anticipated performance data, the experimental results are carried out to validate the simulation model, as well as study the potential gains produced by the application of the LHR concept. For this simulation the following assumptions were made.

- 1) A perfect mixture in the combustion chamber
- 2) Start of combustion (degree) taken at 5% of the mass fraction burned
- 3) CNG properties similar to Methane (CH_4)
- 4) In-cylinder heat transfer occurs through forced convection
- 5) Complete combustion befall inside of combustion chamber

The properties of Titanium dioxide (TiO_2) [10] and YSZ [11] that were used as TBC materials for this investigation are given in Table 1.

Table 1. Properties of Titanium dioxide (TiO_2) and YSZ materials.

Material	Density (g/cm^3)	Melting temperatu re ($^{\circ}\text{C}$)	Thermal conductivi ty (W/mK)	Poisson's ratio	Modulus of elasticity (GPa)	Compressi ve strength (MPa)	Fracture toughness ($\text{MPa}\cdot\text{m}^{1/2}$)
TiO_2	4.0	1870	11.7	0.27	230	680	3.2
YSZ	5.7-6.13	2800	2.0	0.3	205	2200	8

2. Modeling and methodology

Commercially accessible engine simulation AVL Boost software was used, which is based on the one dimensional gas dynamics. It implies that the uniform flow is considered along the cross sections. Built-in templates together engine parts and sub models (such as gas exchange model, combustion model, heat transfer model, scavenging model, and emission models) were used to established the engine simulation model, that describe the physical processes taking place in the engine. In this model, SB is the system boundary, E is the engine, C is the cylinder, I is the injector, PL is the plenum, R is the restriction, MP is the measuring point, and 1-9 numbers is the pipes. Figure 1 shows the single cylinder CNG engine simulation model that was adopted for this analysis.

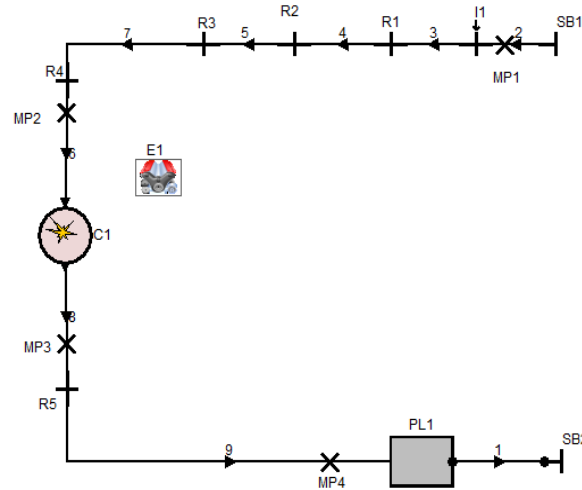


Figure 1. AVL Boost simulation CNG engine model.

2.1 Vibe combustion model

For present study, the Vibe model was selected for the combustion analysis. To calculate the actual mass burning rate and heat release characteristics of an engine the Vibe model is often used. Equation 1 and Equation 2 represent the rate of heat released and mass fraction burned, respectively [12].

$$\frac{dx}{d\alpha} = (m+1) \cdot \frac{a}{\Delta\alpha_c} \cdot y^m \cdot e^{-a \cdot y^{(m+1)}} \quad (1)$$

$$x = \int \frac{dx}{d\alpha} \cdot d\alpha = 1 - e^{-a \cdot y^{(m+1)}} \quad (2)$$

Where $dx = \frac{dQ}{Q}$, $y = \frac{\alpha - \alpha_0}{\Delta\alpha_c}$, Q is the total fuel heat input (J), $\Delta\alpha_c$ is the combustion duration (degree), α_0 is the start of combustion (degree), and α is the crank angle (degree). The Vibe parameter a , it was assumed to be 6.9 for the complete combustion and m is the shape parameter.

2.2 In cylinder heat transfer through Woschni model

From the in-cylinder gas to the walls of the combustion chamber (like cylinder head, cylinder liner, and piston), the heat transfer is computed through Equation 3 [13].

$$Q_{oi} = A_i \cdot \alpha_{oi} \cdot (T_c - T_{oi}) \quad (3)$$

Where Q_{oi} is the convective heat flux to combustion chamber surroundings, α_{oi} is the convective coefficient of heat transfer, A_i is the surface area (piston, cylinder head, and liner), T_{oi} and T_c is the in-cylinder wall temperature and gas temperature, respectively. The Woschni model [14] was published in 1978. Equation 4 is often used to estimate the convective heat transfer coefficient.

$$\alpha_{oi} = 130 \cdot T_c^{-0.53} \cdot p_c^{0.8} \cdot D^{-0.2} \cdot \left[(p_c - p_{c,o}) \cdot \frac{V_D \cdot T_{c,i}}{p_{c,i} - V_{c,i}} \cdot C_2 + C_1 \cdot c_m \right]^{0.8} \quad (4)$$

Where $C_1 = 0.308 (c_u/c_m) + 2.28$, c_u is the circumferential velocity, and c_m is the mean piston speed. For the indirect injection (IDI) engine $C_2 = 0.00622$. While, V_D is the cylinder displacement, D is the bore diameter of cylinder, $p_{c,o}$ is the cylinder pressure of the motored engine, $p_{c,i}$ and $T_{c,i}$ are the pressure and temperature of in-cylinder at inlet valve closing, respectively.

2.3 Model calibration strategy and validation

This section describes the developed simulation model calibration strategy and validation process. The general model calibration strategy for the present investigation is depicted in Figure 2.

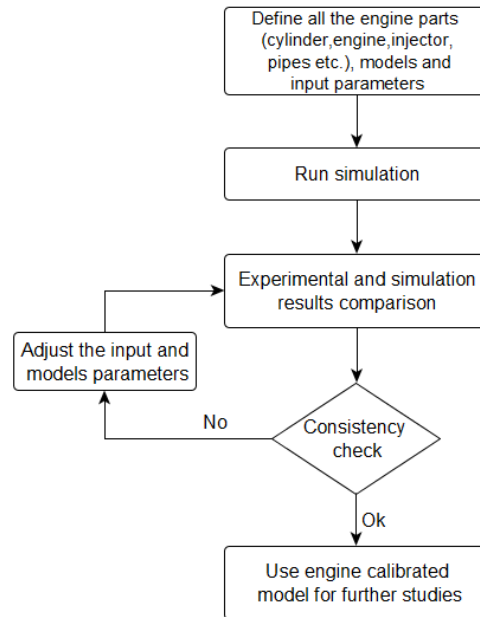


Figure 2. Model calibration strategy.

The simulation results are validated against the experimental data at 4.11 bar and 8.42 bar of indicated mean effective pressure (IMEP). The pressure trace at different engine loads with constant engine speed of 1000 rpm and it compared with the experimental data is illustrated in Figure 3. The results comparison between simulation and experiment show a good agreement because of minor deviation.

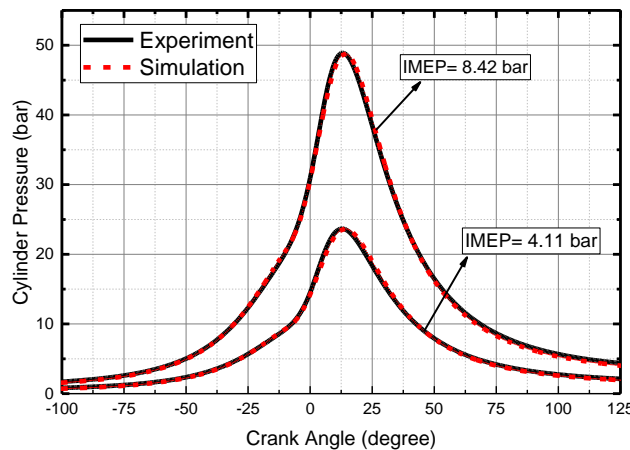


Figure 3. Validation of simulation results using in-cylinder pressure.

2.4 Experimental setup and operating conditions

A four stroke, single cylinder, indirect injection (IDI), naturally aspirated, water-cooled CNG engine is used for the present analysis. The schematic diagram of the single cylinder CNG engine test bench is illustrated in Figure 4. The engine was operated at different engine loads (4 bar, 8 bar and 12 bar), ignition times (21, 24 and 27-degree crank angle before top dead centre), excess air ratios (1 to 1.5) and at a constant engine speed of 1000 rpm. To reduce the intake and exhaust pressure variations two 100L surge tanks are used. The intake air mass flow rate is measured and control by using a six-channel sonic nozzle system. The back pressure valve is used to control the exhaust pressure. Kistler

6125C pressure transducer in combination with a Kistler charge amplifier is used to measure the cylinder pressure of the engine. The general CNG engine specifications are shown in Table 2.

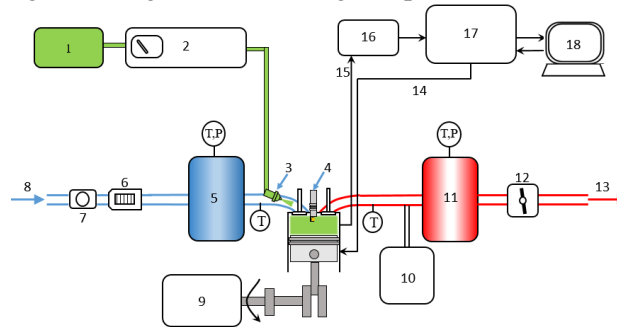


Figure 4. Schematic diagram of CNG engine test bench.

1. CNG 2. CNG flow meter 3. CNG injector 4. Spark plug 5. Intake surge tank 6. Sonic nozzle 7. Pressure regulator 8. Compressed air 9. Horiba LI250 10. Horiba MEXA-7200 11. Exhaust surge tank 12. Exhaust pressure valve 13. Exhaust gas 14. Control signal 15. Pressure signal 16. Charge amplifier 17. NI Control/combustion analysis system 18. PC

Table 2. CNG engine specifications.

Engine type	CNG Engine
Number of cylinders	1
Displacement volume	1.85 (liter)
Stroke	156 (mm)
Bore	123 (mm)
Connecting rod	228 (mm)
Compression ratio	10.5:1
Maximum speed	2300 (rev/min)
Maximum torque	360 (N.m)
Number of strokes and valves	4

3. Results and discussion

The numerical investigation of a conventional piston engine and two ceramic thermal barrier (YSZ and TiO_2) coated piston engines were conducted, as well as the performance results were compared. The conventional and insulated engines performance characteristics are measured and compared in terms of thermal efficiency, volumetric efficiency, indicated specific fuel consumption, and exhaust gas temperature at different excess air ratios. These results are denoted in the Figure 5 to 8. The results and observation of present numerical investigation of the effects of ceramic coated pistons on the performance of a CNG engine are discussed.

3.1 Thermal efficiency

Thermal efficiency (TE) is the type of efficiency through which the chemical energy input in the mode of fuel is transformed to valuable work. The in-cylinder reduction of heat losses is the main intention of LHR engine investigation which has potential be enhanced TE. With increase in EAR the ITE increases for both conventional and insulated (YSZ and TiO_2) pistons. The comparison of the ITE results of uncoated and insulated pistons is shown in Figure 5. In case of improving ITE, the YSZ coated piston have more effect than the TiO_2 coated piston. The increase in ITE of TiO_2 coated piston

(40.79 %) and YSZ coated piston (41.56%) is higher than that of the conventional piston (37.85%). The maximum improvement in ITE was predicted by 9.78% (YSZ coated piston) and 7.75% (TiO_2 coated piston). This may occur in the engine due to larger accessibility of heat in combustion chamber and reduced loss of heat to the coolant.

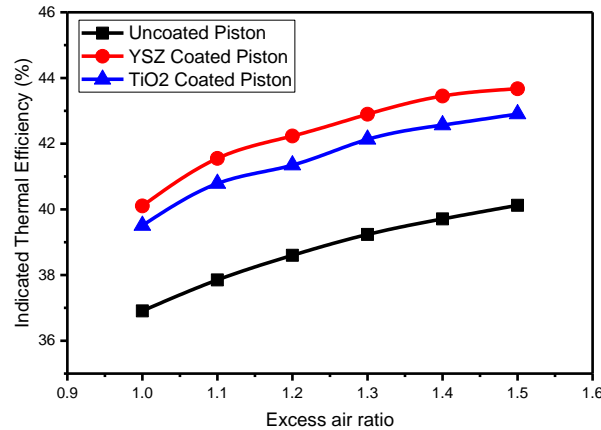


Figure 5. Indicated thermal efficiency against the EAR.

3.2 Volumetric efficiency

Volumetric efficiency is a sign of an engine's breathing capacity. It depends on an engine's operating and ambient conditions. Figure 6 shows the variation in volumetric efficiency with increasing excess air ratio (EAR) for conventional and insulated pistons. For all the cases the volumetric efficiency is lower for thermal barrier insulated piston engines. With increase in EAR, the volumetric efficiency increases for both the conventional and insulated pistons. It is found that the volumetric efficiency of insulated pistons (TiO_2 and YSZ) is 4.32% to 8 % less than the uncoated piston. Because the coated engines operating under high temperature, which cause of rise the piston speed and as a result of smaller amount of air was imbibed in the combustion chamber. This deficiency of air can be accomplished by using the turbocharger.

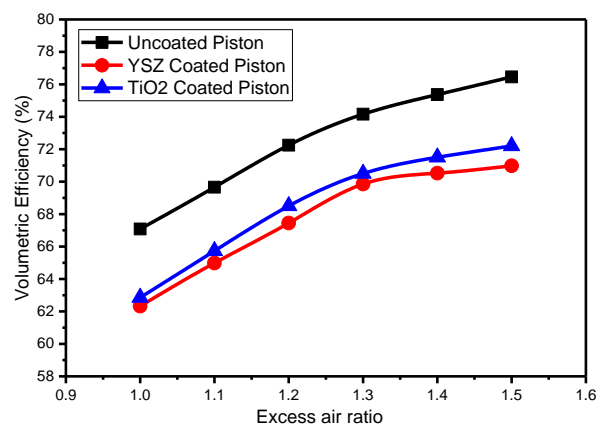


Figure 6. Volumetric efficiency against the EAR.

3.3 Specific fuel consumption

The results comparison of indicated specific fuel consumption (ISFC) of the uncoated and insulated pistons at different excess air ratios is illustrated in Figure 7. For all the cases the specific fuel consumption is lower for thermal barrier insulated piston engines. With increase in EAR, the ISFC decreases for both insulated (TiO_2 and YSZ) and conventional piston engines. The improvement in fuel economy for an LHR engines within the range of 11.2 g/kW h to 16.8 g/kW h were predicted over the conventional engine.

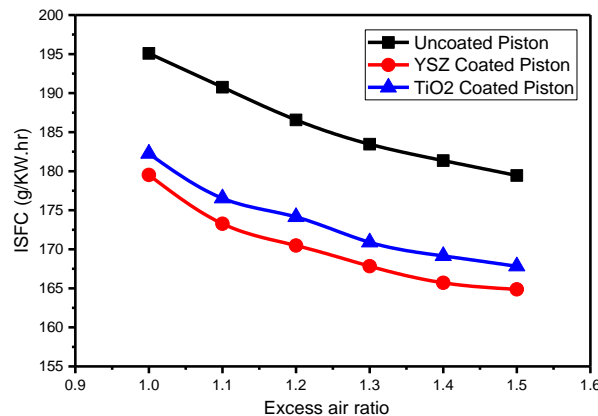


Figure 7. Indicated specific fuel consumption against the EAR.

3.4 Exhaust gas temperature

The comparison of the exhaust gas temperature results of conventional piston and thermal barrier coated (TiO_2 and YSZ) pistons is illustrated in Figure 8. In general, the insulated pistons engine shows higher exhaust gas temperature. The exhaust gas temperature decreases as the EAR increases for both uncoated and coated pistons. The maximum exhaust gas temperature of ceramic YSZ and TiO_2 insulated pistons was enlarged about 57.35°C and 41.98°C respectively over the uncoated piston. As the insulated pistons hamper the heat losses inside the combustion chamber in that way rising the exhaust gas temperature is a considerable.

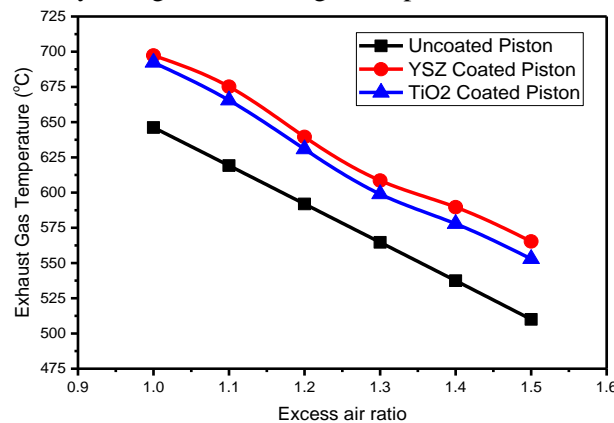


Figure 8. Exhaust gas temperature against the EAR.

4. Conclusion

The numerical investigation was carried out to analyze the effects of ceramic thermal barrier coatings on the performance of a water-cooled, four stroke, single cylinder CNG engine. One conventional (uncoated) piston and two thermal barrier (TiO_2 and YSZ) coated pistons (with thickness of 0.5 mm) were used for the present investigation. Simulations of uncoated piston and insulated pistons were operated under the similar conditions. The conventional engine as well as insulated engines were run at diverse excess air ratios from 1 to 1.5 through a step of 0.1. The following conclusions are drawn.

- 1) There is maximum about 9.78 % increase in the ITE was predicted with coated pistons (TiO_2 and YSZ) over the conventional (uncoated) piston.
- 2) The ISFC in case of insulated pistons (TiO_2 and YSZ) is reduced up to 16.8 g/kW h (9.1%) than the uncoated piston under the same operating conditions.
- 3) Volumetric efficiency decreased about 4.32 % to 8% in coated pistons over the conventional piston.
- 4) For ceramic insulated pistons TiO_2 and YSZ, the maximum exhaust gas temperature was increased around 41.98°C and 57.35°C respectively, as compared to the conventional piston.

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