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Proceeding Paper

Three-Dimensional Design and Prediction of Temperature Distribution of a Partially Ceramic Coated Piston Used in Homogeneous Charge Compression Ignition Engine †

C. Sakthi Rajan [1,*], J. Venkatesh [2], K. Jayakumar [3] and G. Prakash Kanna [4]

1 Department of Mechanical Engineering, SBM College of Engineering & Technology, Dindigul 624 005, Tamil Nadu, India
2 Department of Mechanical Engineering, Dr. Mahalingam College of Engineering and Technology, Pollachi 642 003, Tamil Nadu, India; mechanicalmechivenkat@gmail.com
3 Department of Mechanical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Kalavakkam, Chennai 603 110, Tamil Nadu, India; kjayakumar@ssn.edu.in
4 Department of Mechanical Engineering, PSNA College of Engineering & Technology, Dindigul 624 622, Tamil Nadu, India; kanna.gp102@gmail.com
* Correspondence: csrajann@gmail.com
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Abstract: The goal of this research is to analyze the effects of a partial thermal barrier coating on piston temperature distribution in homogeneous charge compression ignition (HCCI) engines, which are investigated using $La_2Zr_2O_7$ nanocoating with 1 mm thickness for numerical analysis. The thermal assessments of both conventional and coated pistons were performed using ANSYS V16. Engine testing was conducted on a single-cylinder, water-cooled CI engine for both the coated and conventional casings. According to the analytical results, the coated piston component's surface temperature increased to 53 °C, which increased the temperature of the air–fuel mixture in the crevice and wall quenching zones. As a result, cold start HC emissions dramatically drop without impacting engine performance compared to normal engines. The maximum HC emission reduction over the standard engine was 43.2%.

Keywords: HCCI engine; thermal analysis; thermal barrier coating; $La_2Zr_2O_7$; ANSYS

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1. Introduction

Pistons that use HCCI are equally as efficient as compression-ignition direct-injection (CIDI) engines while emitting much less pollution in the form of nitrogen oxide (NOx) and particulate matter (PM). The premixed charge in HCCI engines reacts and burns volumetrically throughout the cylinder as the cylinder is compressed by the piston. HCCI combines the benefits of both spark ignition (SI) and compression ignition (CI). A CIDI engine blends the charge properly to reduce particulate matter emissions, whereas an SI engine compresses the charge without throttling losses [1]. Combustion here happens everywhere in the volume, not only at the flame front as in traditional engines. Several studies have proven that computational fluid dynamics (CFD) is one of the most precise methods to predict engine combustion. The utilization of a blend of propane and dimethyl ethanol in an HCCI engine via numerical analysis helps the authors gain a deeper comprehension of the effects that the fuel combination has under a variety of conditions [2]. This experimental study backs up the results from the CFD tool modeling of HCCI combustion. After verifying their hypotheses, the authors use CFD to look at how varying the direct injection rates and timings affect HCCI combustion. The CFD simulation of natural gas-fueled combustion of HCCI evaluated the effectiveness of complete and simplified processes under different conditions of operation [3]. The results showed that CFD modeling approaches could be trusted and investigated the repercussions of diverse processes, both in detail and on a micro scale. Optimizing combustion is crucial for cutting down on fuel use and exhaust pollution [4]. More research on the consistency of these solutions inside the codes is required to allay concerns about the accuracy of findings, constraints, and dependability of codes. Multiple studies have shown that CFD is one of the most accurate methods for modeling engine combustion. Using FEA, the authors compare the effectiveness of pistons made from structural steel and graphite. Graphite, which has superior thermal behavior and is lighter, is the optimum material for pistons, according to their research [5]. The carbon graphite piston was found to be the most efficient in terms of heat transmission. An ANSYS study examined the piston's static structure and thermal behavior under steady-state and transient settings; the piston is forged from the Al-4032 alloy [6]. The impact of the temperature in the engine environment on HCCI combustion may be emphasized with the aid of HCCI engines. Following the lead of data from HCCI trials, this research looked at how the temperature of a coated piston in an HCCI engine was distributed.

2. Materials and Methods

2.1. Temperature Modeling of a Piston

The original piston was a 3D model with a lot of small parts, which made modeling and heat transfer challenging. These elements made the piston difficult to represent. Since it is known that the primary heat-transfer channel runs from the top surface of the piston to the cooling water and lubricating oil, the minor dimensional adjustment did not affect the major heat transfer. In this study, the thermal consequences of the piston are simulated using a reduced 3D axis-symmetric finite element method (FEM) model to reduce the computation time. The FEM model simplified the factors that had a negligible impact on the principal heat transport, such as the chamber's radius and minuscule openings. The FEM model was constructed with PLANE55 components, and a 1 mm element size is depicted in Figure 1.

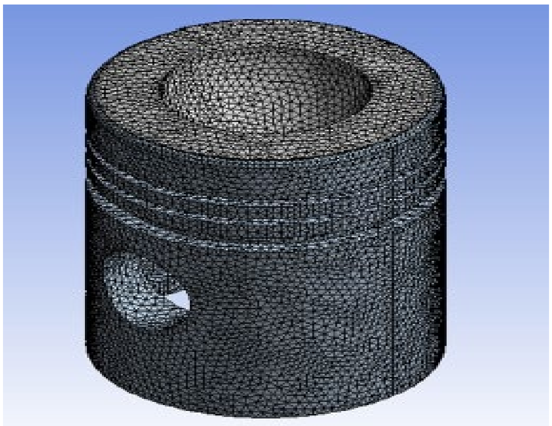


Figure 1. FEM model of the piston.

2.2. Steady-State Heat Transfer

Using the computer design software Ansys V16, the Al-Si piston of a diesel engine was studied. Both coated and uncoated pistons were subjected to a three-dimensional finite element thermal analysis. This model demonstrates the way the surface of the piston ring contacts the ring gap. The computer code depicts these interactions as a network of sites of contact. The stages for conducting the temperature study are shown as a flowchart in Figure 2. The geometry model of the Al-Si piston used in Ansys V16 is illustrated in Figure 3.

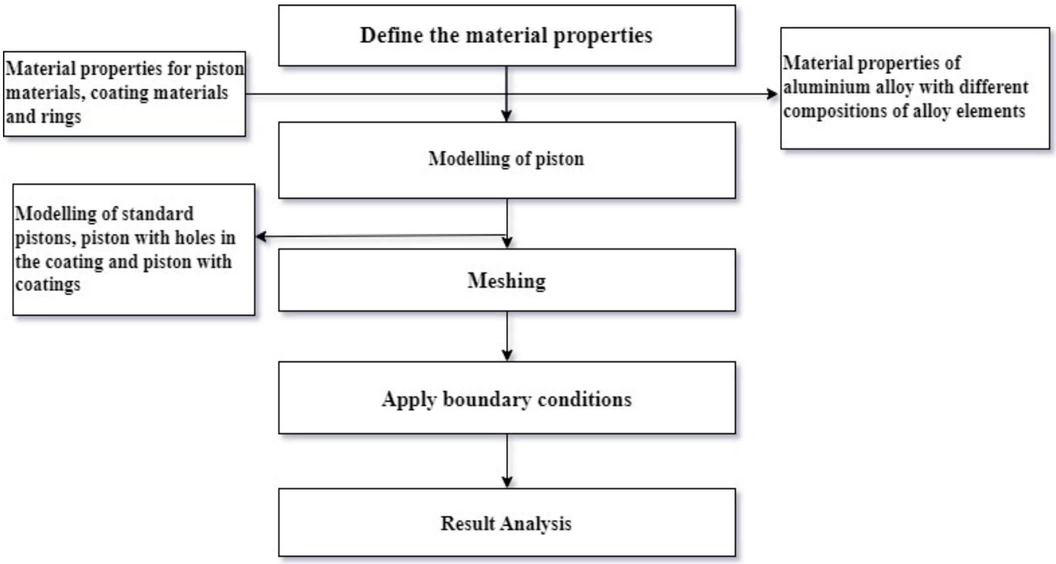


Figure 2. Methodology.

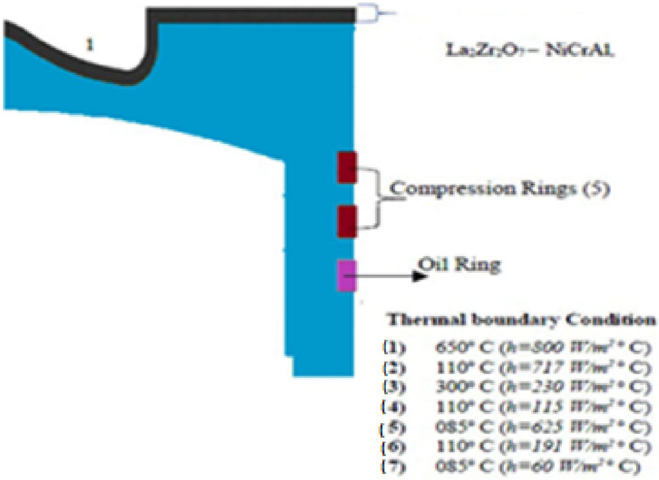


Figure 3. Boundary conditions.

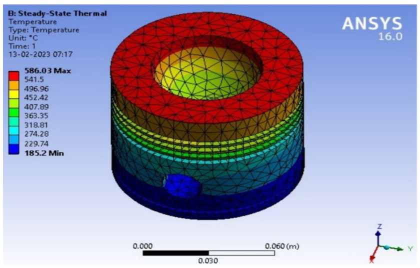
3. Results and Discussion

3.1. Thermal–Stress Investigation of Piston

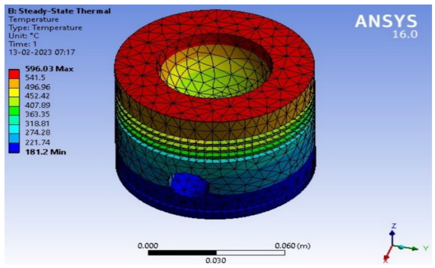
Figure 4a–c shows the $La_2Zr_2O_7$-coated piston, which has much less heat transfer than an untreated aluminum alloy piston. Due to the lower heat conductivity of $La_2Zr_2O_7$ compared to stainless steel, there was a temperature gradient along the piston. The average surface temperature of a coated piston is 586 °C, whereas the average surface temperature of an uncoated piston is 639 °C compared to an uncoated piston. As a result of the coating, the maximum temperature of the piston is slightly greater. When zirconia was used for the coating, the piston became hotter towards the lip of the combustion bowl.

3.2. HC Emissions

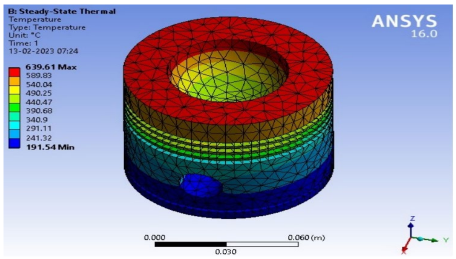
Figure 5 shows the difference between the standard engine and the engine with a coated piston. At 1200 rpm, HC emissions were drastically cut for the piston with coatings. The first 20 s period has a decrease in HC emission of 43.2 to 8.1%, whereas the subsequent 20 s period sees a decrease of 26.4 to 10.8%. As previously mentioned, the air–fuel mixture temperature increased by as much as 53 °C in the partially coated section of the piston, leading to an increase in unburned charge oxidation near the entrance of the clearance between the piston and liner. This raises the temperature of the mixture in the wall quenching zone, which, in turn, reduces the HC emissions caused by wall quenching.



(**a**)



(**b**)



(**c**)

Figure 4. (**a**). Temperature distribution for uncoated piston. (**b**). Temperature distribution for coated piston $MgZrO_2$. (**c**). Temperature distribution for coated piston $La_2Zr_2O_7$.

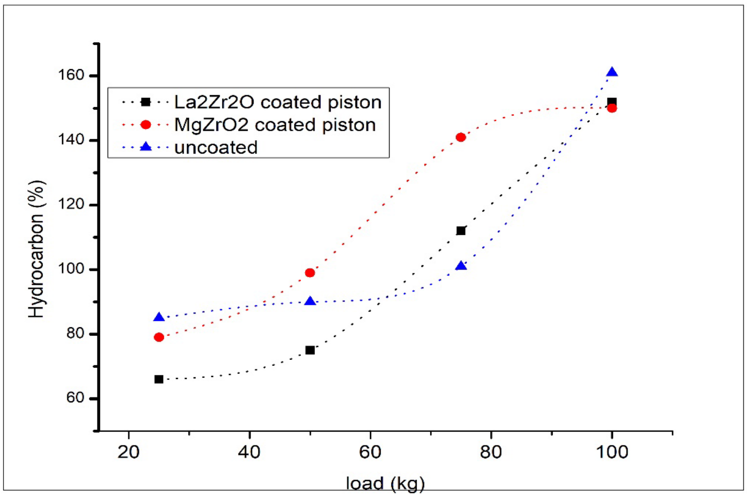


Figure 5. Variations in HC emissions.

4. Conclusions

In this work, the impact of a thermal barrier coating on the temperature of crevice and wall quenching areas was examined using a thermal analysis. According to the findings of the thermal investigation, the piston's covered area, which is adjacent to the crack and wall quenching zones, causes a rise of up to 53 °C. $La_2Zr_2O_7$ material produced better results. The thermal analysis results indicate that the coated section of the piston, which is close to the crevice and crown regions, causes an increase in the temperature. It is, therefore, concluded that a 639 °C temperature increase leads to an increase in air–fuel mixture temperature in these sections, and thus, unburned charge oxidation near the entrance of the clearance increases. The oxidation of the unburned charge at the clearance entry increased, leading researchers to believe that this temperature rise is responsible. In addition to a considerable reduction in HC emissions during cold starts, the experimental findings also reveal that the engine torque is unaffected by the partial coating.

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