

Review of Thermal Barrier Coatings for Improving the Performance of Internal Combustion Engines

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Abstract

Internal combustion engines operate at very high combustion temperatures, which can cause excessive wear of cylinder liners and significant heat loss through the engine walls. Over time, these effects can reduce engine efficiency and, under continuous operation, may even result in liner damage or failure. At the same time, increasingly strict emission regulations have created a need to improve engine performance while keeping exhaust emissions under control. One promising solution is the use of thermal barrier coatings (TBCs) and wear-resistant coatings on important combustion chamber components. Instead of depending entirely on conventional metallic surfaces, ceramic-based coatings can be applied to components such as piston crowns, cylinder heads, valves, and cylinder walls. These coatings act as a protective layer and reduce the amount of heat transferred to the surrounding engine components. By keeping a greater portion of the combustion heat inside the combustion chamber, TBCs can help improve thermal efficiency and reduce fuel consumption. They can also protect engine components from excessive thermal stresses and wear, thereby improving their service life and reliability. In some cases, the improved combustion conditions may also contribute to a reduction in harmful exhaust emissions. This paper provides an overview of thermal barrier coating technology for internal combustion engines, including commonly used coating materials and coating techniques. It also discusses how these coatings affect engine performance, thermal behaviour, durability, and emission characteristics.

Keywords: Thermal Barrier Coating, Internal Combustion Engine, Ceramic Coating, Thermal Efficiency, Engine Performance.

1. INTRODUCTION

Thermal Barrier Coatings (TBCs) were originally developed to improve the operating performance and thermal protection of aircraft engines [1]. Their use in diesel engines became prominent during the 1980s, particularly in response to the petroleum crisis and the resulting increase in fuel prices. During this period, considerable research efforts were directed toward improving fuel utilization and enhancing the overall efficiency of Internal Combustion (IC) engines. TBCs provide an effective protective layer over metallic engine components, enabling them to withstand elevated temperatures and severe thermal environments. Consequently, these coatings have been extensively investigated for high-temperature and corrosion-resistant applications in gas turbines, diesel engines, and various power-generation systems. The piston is one of the most critical components of an IC engine and is often regarded as the core of the reciprocating engine mechanism. It performs the essential task of transferring the combustion-generated forces to the connecting rod and subsequently to the crankshaft while also participating in the compression process. In conventional petrol engines, a substantial proportion of the energy released during combustion is lost in the form of heat, while only a limited portion is converted into useful mechanical power. Therefore, minimizing heat losses from the engine components is an important approach for improving thermal efficiency [2]. From a theoretical perspective, restricting heat transfer through the engine walls can reduce thermal losses and potentially increase engine efficiency. Since the efficiency of conventional IC engines generally remains around 40–42%, further improvement in thermal performance continues to be a major engineering challenge. The application of TBCs to critical engine components, particularly the piston, has therefore emerged as a potential technique for reducing heat transfer and improving engine performance [3]. A wide range of ceramic materials has been investigated for TBC applications, including Yttria-Stabilized Zirconia (YSZ), Partially Stabilized Zirconia (PSZ), garnets, spinel, mullite, and alumina. These materials are particularly suitable for thermal barrier applications because of their relatively low thermal conductivity, high-temperature resistance, and adequate thermal stability. Their ability to withstand severe thermal conditions makes them suitable for protecting engine components exposed to high combustion temperatures. Applying such coatings to engine pistons can provide several advantages. The coating helps reduce heat transfer and friction losses, which can improve the overall thermal efficiency of the engine. It may

also contribute to lower specific fuel consumption and higher engine power output. In addition, the protective coating can improve the durability of piston surfaces by reducing the effects of high-temperature operation and wear.[4]

The temperature gains achieved have been approximately 200°C through the development of superalloys, 500°C using air-cooling techniques, and 300°C through the application of thermal barrier coatings. Consequently, in the hot sections of modern gas turbine engines, most components are manufactured from superalloys and equipped with air-cooling systems, while an increasing number of components are also equipped with thermal barrier coatings.

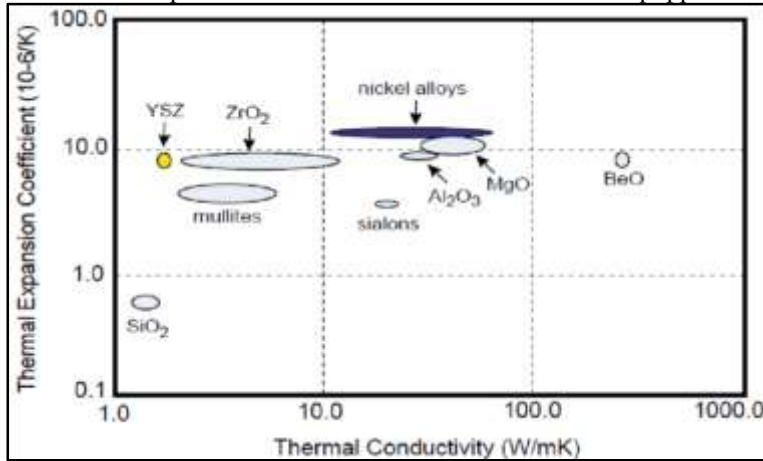


Fig 1. Materials for thermal barrier coating

2. LITERATURE SURVEY

A significant amount of research has been conducted to understand how thermal barrier coatings (TBCs) affect the thermal behaviour, combustion process, efficiency, fuel consumption, and emission characteristics of internal combustion engines. Researchers have used both experimental testing and numerical analysis to study the performance of different coating materials. Various ceramic materials, coating thicknesses, and deposition methods have been investigated to determine their suitability and effectiveness under different engine operating conditions.

A substantial restriction in thermal loss from high-temperature combustion gases to the underlying substrate was observed when ceramic coating thickness was expanded. Finite element modeling of a diesel engine's plasma-sprayed aluminum alloy piston demonstrated center crown temperature escalations of 32.7%, 55.8%, 72.5%, and 84.8% corresponding to layer thicknesses of 0.4 mm, 0.8 mm, 1.2 mm, and 1.6 mm, respectively (Cerit et al., 2014). [2].

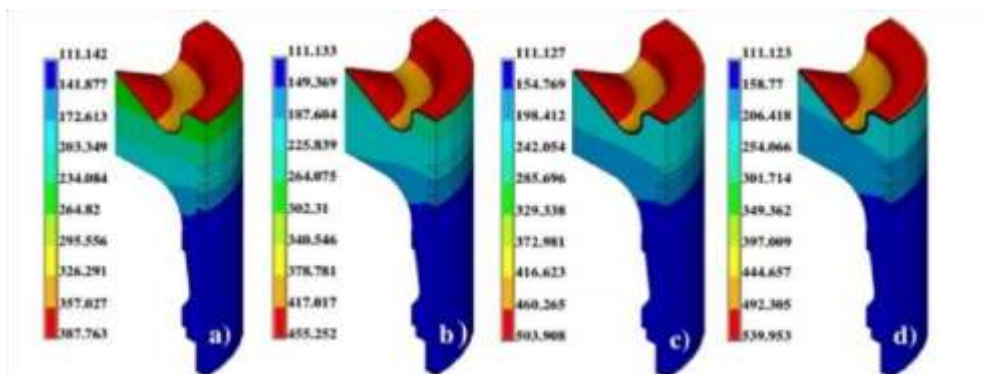


Figure 2. Effect of TBC thickness on temperature distribution: (a) 0.4 mm, (b) 0.8 mm, (c) 1.2 mm, and (d) 1.6 mm

Thermal and structural stress profiles of spark-ignition pistons were heavily modulated by varying the thickness of applied NiCrAl and zirconia coatings. Maximum center temperatures rose to 246.6°C (a 40°C gain over uncoated baselines), while edge thermal values reached 261.8°C and 311.1°C for 0.3 mm and 0.5 mm layers. Furthermore, mechanical stress amplified from an initial 16–24 MPa to 127 MPa with a 0.4 mm deposit, proving that barrier thickness directly alters both internal heat flow and stress concentration (Ng & Gan, 2005) [3].

A 3D finite element simulation of a diesel engine piston revealed that adding a zirconia-based ceramic coating drives a major shift in heat distribution. Surface temperatures at the piston bowl jumped from 285°C up to 424°C once the insulating layer was applied. Thanks to the thermal barrier, heat retention improved by roughly 48% in aluminum-silicon alloy pistons and 35% in steel pistons. The analysis also noted that under identical running conditions, steel pistons consistently ran hotter than the aluminum-silicon ones (Buyukkaya & Muhammet, 2007) [4].

Figure 3. Comparative analysis of coated and uncoated aluminium alloy pistons

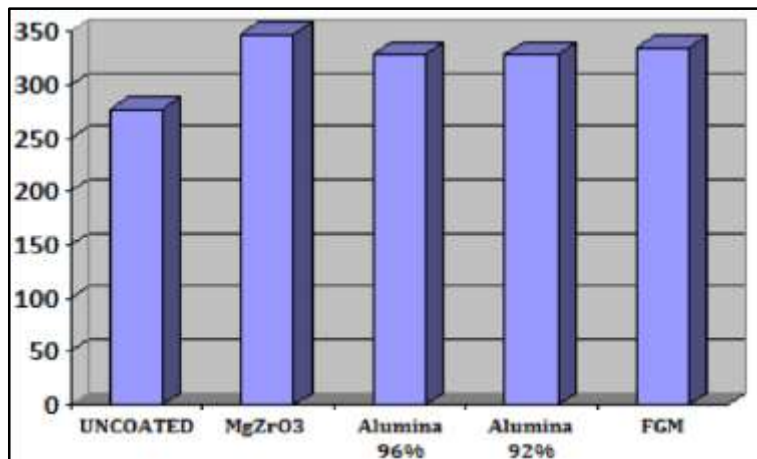
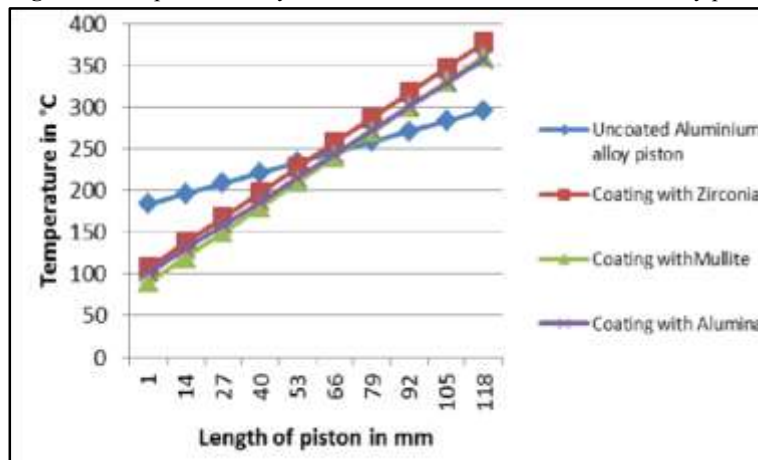


Figure 4. Comparison of temperature distribution for different TBC materials

Thermal simulations of a six-stroke engine showed that ceramic insulation on components like the cylinder block and liner effective traps heat within the combustion zone. Comparing various materials against a 295.86°C baseline for uninsulated pistons, zirconia delivered the strongest thermal barrier, raising peak surface temperatures by 28% to 360.6°C. Comparative gains of 22% for mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) and 21% for alumina (Al_2O_3 , reaching 357.45°C) further prove that ceramic layers significantly cut down heat loss through the piston substrate (Sridhar et al., 2013) [5].

An enhancement of nearly 17.39% in brake thermal efficiency alongside a 13.35% drop in brake-specific fuel consumption was achieved by applying a 200 μm YSZ layer via plasma deposition onto a 3-cylinder, 4-stroke SI engine piston crown. Furthermore, harmful exhaust emissions were noticeably diminished, recording 21.11% and 45.45% reductions for HC and CO levels, respectively (Patil et al., 2017 [6].

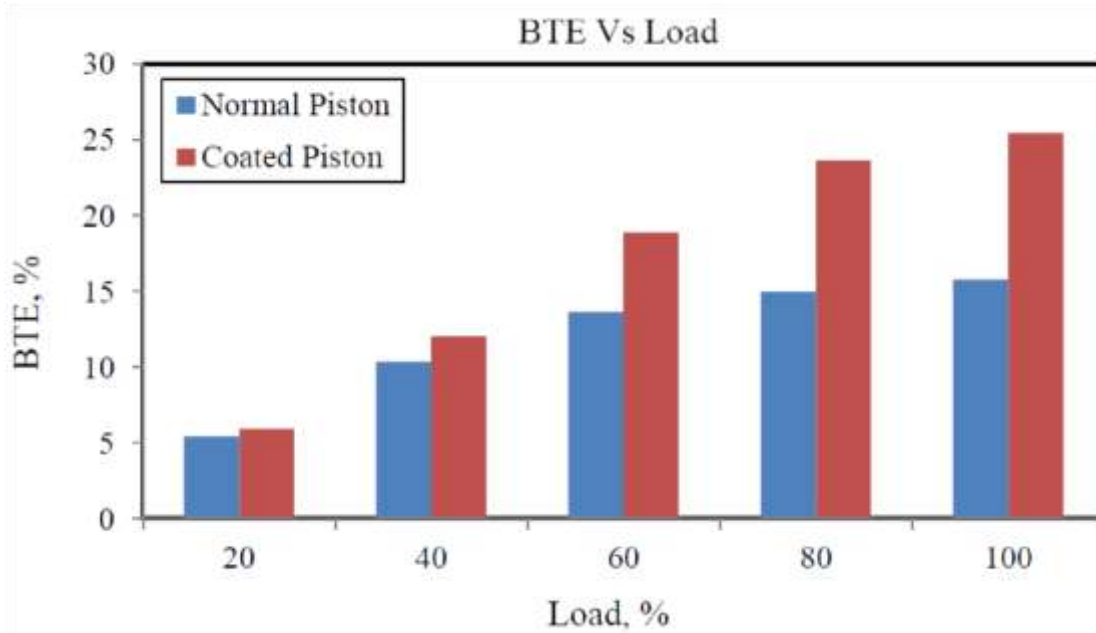


Figure 5. BTE Vs Load

Numerical modeling of an aluminum-silicon alloy piston in ANSYS 16.0 reveals a strong dependency between thermal barrier thickness and engine component behavior. Expanding the ceramic layer directly elevated piston temperatures, yielding a 22% increase at 0.2 mm thickness and jumping to nearly 39.66% when increased to 1.2 mm. However, mechanical stresses showed a non-linear trend under varying layers: recording 56.452 MPa at 0.2 mm, peaking sharply at 146.48 MPa at 0.6 mm, and settling at 104.91 MPa for 0.8 mm coatings. These findings highlight the importance of selecting an optimal coating thickness to strike a practical balance between thermal insulation efficiency and structural durability (Varshney et al., 2018) [7].

Peak cylinder pressure and indicated power (gaining 5–9%) were consistently higher when a 0.25 mm silicon nitride thermal barrier was plasma-sprayed onto a single-cylinder spark-ignition piston crown. Multi-load testing (20–70%) across spark angles of 12°--20° recorded substantial brake thermal efficiency boosts between 5% and 56% depending on operational parameters. These outcomes confirm that restricting heat rejection through the piston head significantly improves overall combustion efficiency (Anser & Jagannath, 2017) [8]

A thermal analysis of a diesel engine piston revealed that applying a 0.4 mm yttria-stabilized zirconia (YSZ) layer raises peak surface temperatures from 291.32°C in the base metal to 362.5°C post-coating. This temperature spike stems directly from the ceramic layer's low thermal conductivity, which impedes heat transfer into the underlying piston substrate. Additionally, the numerical evaluation explored how modifying the coating structure—specifically by incorporating artificial holes—alters overall heat distribution (Gehlot & Brajesh, 2016)[9].

Applying a zirconia thermal barrier to a diesel piston crown enhanced energy conversion efficiency across all tested load settings (20% to full load) following steady-state warm-up. Experimental data showed progressive brake thermal efficiency gains reaching up to 38.02% (with intermediate improvements of 14%, 27.70%, and 36.71%). Additionally, brake-specific energy consumption was consistently reduced by 9.69% to 12.23% across varying loads, demonstrating the energy-saving benefits of restricting piston heat rejection (Balamurugan et al., 2018) [10].

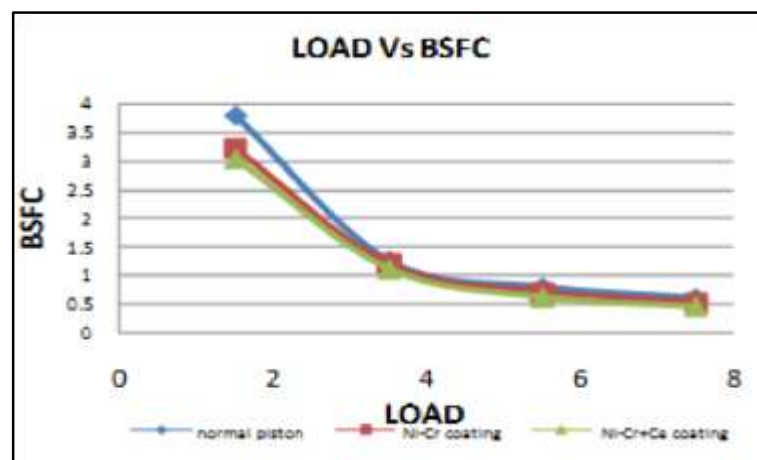


Figure 7. Load Vs BSFC

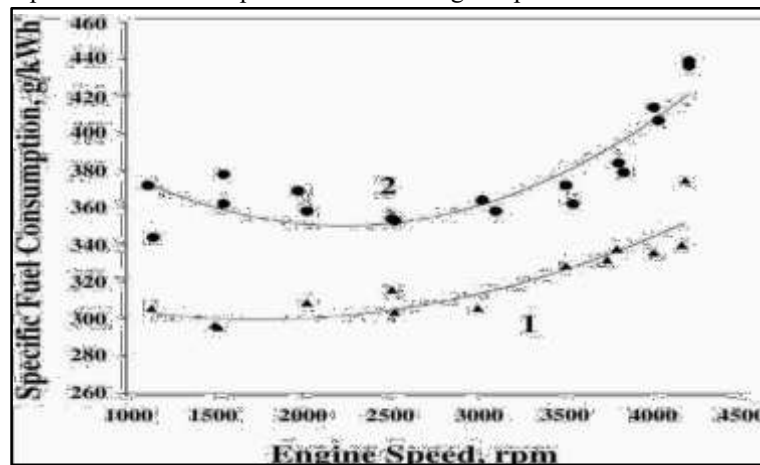
A coupled static and thermal analysis performed in CREO and ANSYS showed that applying a silicon dioxide (SiO₂) layer onto a piston crown effectively mitigates structural stress while retaining heat in the combustion zone. Incorporating convective heat

transfer boundary conditions across the crown and skirt revealed a reduction in maximum thermal stress from 180.73 MPa in the uninsulated substrate to 164.49 MPa post-coating. Conversely, peak piston surface temperatures elevated from 305.82°C to 370.72°C, confirming that SiO₂ insulation substantially reshapes both the thermal gradient and mechanical stress field of the component (Satyanarayana & Rajyalaxmi, 2016) [11].

Comparing various 300 μm ceramic coating formulations on a 4-stroke direct-injection diesel engine revealed that material selection significantly dictates performance gains. Molybdenum combined with alumina (Mo + Al₂O₃) achieved the highest improvement, boosting brake thermal efficiency by 3.26% and cutting brake-specific fuel consumption by 10.34%. In comparison, YPSZ (Zr₂O₃ + Y₂O₃) and titania-blend (Al₂O₃ + TiO₂) coatings yielded efficiency increases of 2.09% and 1.98%, respectively, while both reduced fuel consumption by 6.89%. These findings confirm that optimizing thermal barrier compositions is essential for maximizing engine economy (Dhileepan et al., 2016) [12].

Experimental testing of a low-heat-rejection, three-cylinder engine (76 mm bore × 73 mm stroke) demonstrated that applying a dual-layer ceramic system—comprising a 0.15 mm bond coat beneath a 0.45 mm YSZ crown coating—significantly enhances thermal utilization. Under low-power operating conditions, the insulated setup yielded a 6% boost in fuel economy alongside an elevation of 8–10 bar in peak cylinder pressure, confirming that restricting piston heat dissipation optimizes internal combustion energy (Gopikrishna et al., 2015) [13].

Figure 8. Comparison of specific fuel consumption at different engine speeds for conventional (2) and modified (1) engines.



A 6% boost in fuel economy under low-power operating conditions was observed after applying a plasma-arc deposited zirconia ceramic layer to the piston crown of a single-cylinder, 4-stroke diesel engine (95 mm bore and stroke). The coating process was executed under controlled electrical parameters utilizing a 230 V potential with current settings ranging between 2 A and 12 A. The resulting thermal barrier effectively restricted heat loss, demonstrating the practical energy-saving potential of crown insulation (Chan & Khor, 2000) [14].

A thermal efficiency increase of 3.5% alongside a 5.4% drop in high-load fuel consumption was achieved by plasma-spraying a 250 μm YSZ coating onto a diesel engine piston crown. The thermal deposition process was executed under extreme jet conditions, reaching temperatures of nearly 10,000 K and gas velocities above 1000 m/s. Beyond improving energy conversion, the ceramic layer reduced heat loss to the cooling jacket by 5.10% while significantly lowering exhaust pollutants, recording reductions of 35.17% in unburnt hydrocarbons and 2.72% in carbon monoxide emissions (Garud et al., 2017) [15].

Specific fuel consumption was lowered by 4.5–9% alongside a significant elevation in exhaust-gas temperatures (150–200°C) when key combustion chamber components—including piston crowns, valves, and cylinder heads—were insulated with a 0.5 mm zirconia layer. This thermal modification reduced ignition delay and yielded concurrent decreases of roughly 12% in CO emissions and 20% in NO_x output (Ciniviz & Mustafa, 2012) [18].

Peak surface temperatures rose by 55% (390.8°C) for Mg-PSZ and by 30% (330.8°C) for PSZ when atmospheric plasma spraying was utilized to deposit ceramic layers over aluminum pistons using optimized carrier gas parameters (Durat et al., 2012) [31].

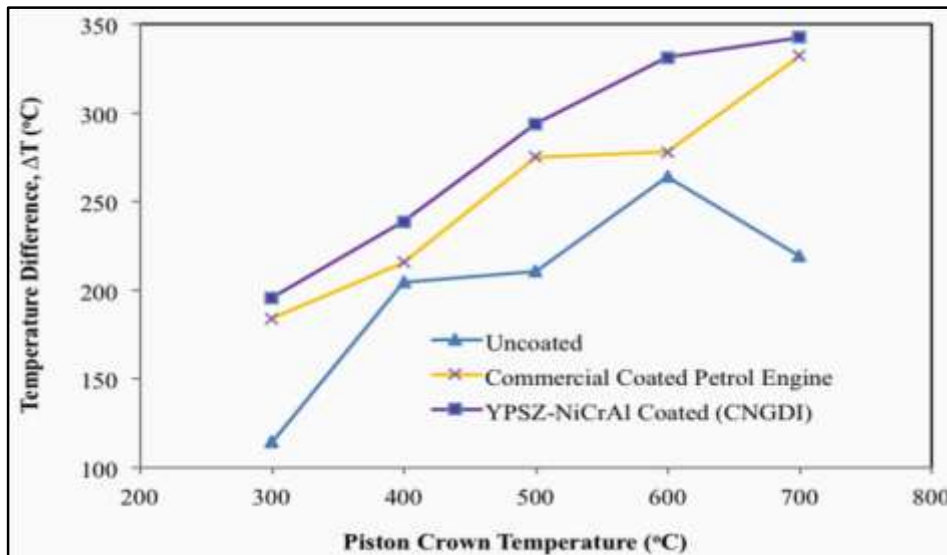


Figure 9. Temperature differences of several types of piston crowns

A thermal evaluation of plasma-sprayed partially stabilized zirconia (PSZ) on an aluminum piston demonstrated a marked reduction in substrate thermal conductivity across operational temperatures ranging from 300°C to 900°C. Ytria-stabilized PSZ (YPSZ) crown coatings generated significantly higher surface temperature differentials compared to baseline uncoated configurations, confirming the enhanced insulating capability of the ceramic barrier (Helmisyah et al., 2012) .[32]

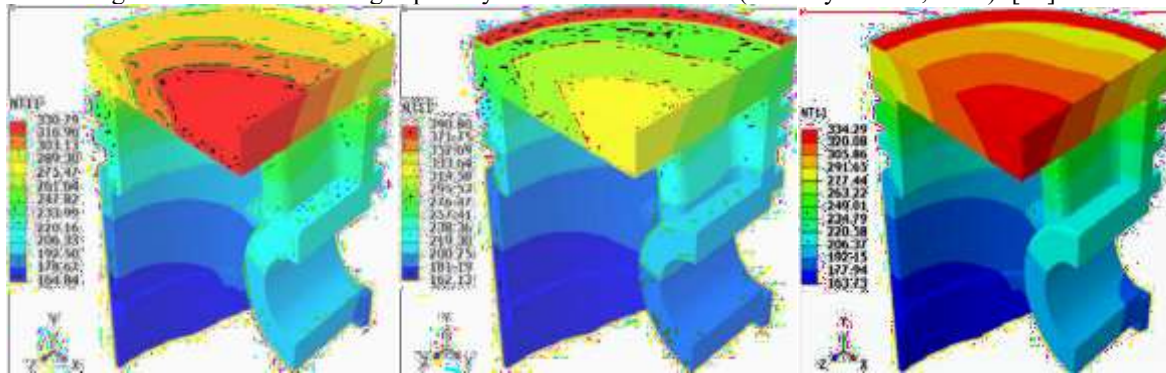


Figure 10. (a) uncoated piston (b) Mg-PSZcoated piston (c)Y-PSZ coated piston

A finite element study in ANSYS 15.1 evaluating aluminum pistons under varying yttria-stabilized zirconia (YSZ) coating thicknesses (0.2 mm, 0.4 mm, and 0.6 mm) confirmed a direct correlation between barrier layer depth and thermal insulation performance. Increasing the YSZ thickness progressively lowered both thermal flux and surface temperature at the top land, with the 0.6 mm configuration achieving the minimum values. These results demonstrate that thicker ceramic deposits are more effective at restricting heat dissipation into critical piston regions (Attar & Bhongade, 2017) [33]

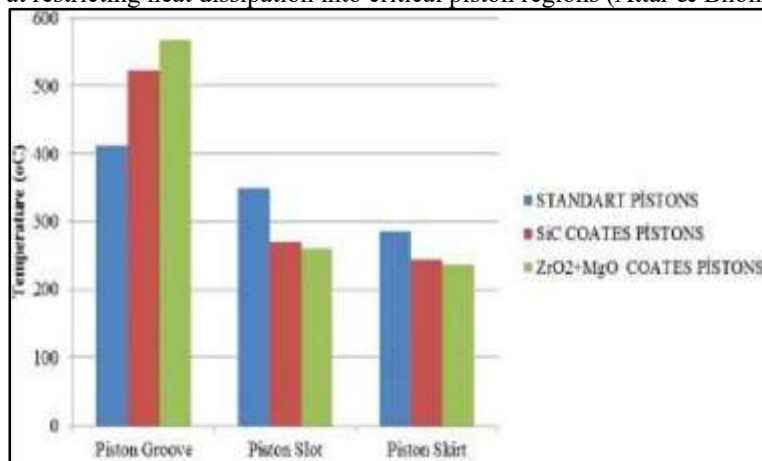


Figure 11. Temperature influencing the piston surface

3. CONCLUSION

The literature indicates that **YSZ, YPSZ, Mg-PSZ, alumina, mullite, MgO-ZrO₂, SiC and other ceramic materials** have been widely investigated as thermal barrier materials for IC-engine components. Most studies have concentrated on the **piston crown**, although coatings have also been applied to cylinder heads, cylinder liners, valves and piston rings. Plasma spraying remains one of the most frequently reported deposition techniques because it can produce relatively thick ceramic layers with good thermal-insulation characteristics.

Across the reviewed investigations, the application of TBCs generally results in **higher piston/crown surface temperatures, reduced heat transfer to the piston substrate, improved brake thermal efficiency and reduced specific fuel consumption**. Several studies have also reported reductions in HC and CO emissions. However, the increase in combustion-zone temperature can potentially promote NO_x formation and increase thermal stresses if the coating thickness and material are not appropriately selected.

Therefore, the effectiveness of a TBC system depends strongly on **coating material, thickness, bond-coat selection, deposition technique, substrate material, engine operating condition and thermal-stress behaviour**. These factors indicate the need for further optimisation and experimental validation before TBCs can be reliably implemented in practical IC-engine applications.

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