

ENERGY-EFFICIENT COMPOSITE MATERIALS FOR I.C. ENGINE COMBUSTION CHAMBERS: APPLICATIONS AND PERFORMANCE REVIEW

Mahesh M. Chudasama

Lecturer, Automobile Engineering Department, Dr J N Mehta Govt. Poly, Amreli, Gujarat, INDIA.

Abstract

Increasing demands for stricter emission norms, rising fuel prices, and the need for greater precision in vehicle emission standards are putting significant pressure on engine manufacturers to adopt technologies that reduce emissions and improve the efficiency of internal combustion engines. One such approach is the use of Thermal Barrier Coatings (TBCs), particularly ceramic coatings, to minimize frictional losses and wear in engine components. This study presents a comprehensive literature review on the application of ceramic TBCs in internal combustion engine chambers, aiming to identify suitable coating materials and evaluate their performance effects. The review highlights the impact of TBCs on brake specific fuel consumption, brake power, emission characteristics, pollutant levels, and the thermal fatigue life of engine components. Plasma thermal spray methods are commonly employed to apply ceramic layers to key engine parts such as pistons, cylinder heads, cylinder blocks, and intake/exhaust valves. The findings are based on an extensive survey of reference books, conference proceedings, and peer-reviewed research papers, with detailed discussions on coating materials, application techniques, and the conclusions drawn by various researchers. This work underscores the potential of ceramic coatings to enhance engine performance and longevity while contributing to emission reduction goals.

Key words: *Low heat Rejection engine, piston head, petrol engine*

Introduction

Modern internal combustion (I.C.) engines face increasingly demanding performance and environmental standards. Achieving high efficiency, durability, and low emissions while maintaining reliability and reducing fuel consumption has become a central focus in engine development. The energy flow and efficiency of a modern automobile are primarily influenced by two factors: vehicle load and power train efficiency. Vehicle load is determined by speed, acceleration, and mass, whereas power train efficiency is closely tied to the thermodynamic performance of the engine. Enhancements in aerodynamics, structural weight reduction, and the integration of hybrid power trains are among the strategies being employed to improve fuel economy.

To meet these objectives, engine manufacturers have continually sought to improve the performance and longevity of engine components. Since the early stages of engine development, protective coating systems have played a crucial role in extending component

Copyright © 2019, Scholarly Research Journal for Interdisciplinary Studies

life and maximizing material properties. Advances in materials science and manufacturing technologies have led to the evolution of sophisticated coating systems, particularly for components exposed to high thermal and mechanical loads.

One significant technological advancement is the use of **Thermal Barrier Coatings (TBCs)**, especially ceramic-based coatings, in the hot sections of the engine, such as the piston crown and combustion chamber. These coatings act as insulators, reducing heat transfer to the underlying metal surfaces and thereby increasing the thermal efficiency of the engine. The application of TBCs also helps protect engine components from high-temperature oxidation, corrosion, and erosion caused by the aggressive gas environment within the combustion chamber.

Modern TBCs are typically applied using advanced techniques such as plasma thermal spraying, enabling uniform deposition and excellent adherence to complex geometries. The effectiveness of these coatings depends not only on their thermal resistance but also on their ability to withstand the combined mechanical and chemical stresses encountered during engine operation. The operating environment of an I.C. engine—governed by fuel type, combustion temperature, and duty cycle adds further complexity to coating design and material selection.

This research focuses on the use of ceramic coatings in internal combustion engine components, particularly within the combustion chamber. It presents a thorough review of current literature, coating materials, application methods, and the performance outcomes of coated engine components. The goal is to assess the potential of thermal barrier coatings in improving engine efficiency, reducing emissions, and enhancing the durability of critical engine parts under high-temperature operating conditions.

Thermal Barrier Coatings (TBCs)

Thermal Barrier Coatings (TBCs) have been extensively used in the automotive and gas turbine industries for over five decades. These coatings are applied to high-temperature engine components such as the combustion chamber, piston crowns, turbine blades, valve seats, inlet guide vanes, stator blades, and afterburners.

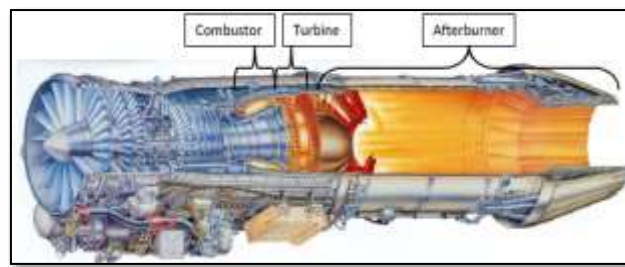


Figure 1: Cross-section of RM-12 engine

Figure 1 illustrates a cross-section of the RM-12 engine, highlighting areas where TBCs are typically applied. The primary function of TBCs is to enable components to withstand higher operating temperatures than would be permissible using base metal alloys alone. This allows for improved thermal efficiency and greater engine performance without compromising component integrity.

Historical Background and Development

TBCs were first developed in the late 1950s for experimental projects at NASA, primarily as protective coatings for ductwork and rocket nozzles. Their initial application was in military aerospace programs, eventually expanding into civilian gas turbines during the 1970s. By the early 21st century, TBCs had become standard in virtually all modern aero and stationary gas turbines.

A typical TBC system consists of at least three layers:

- A **bond coat**, which adheres to the metallic substrate;
- A **thermally grown oxide (TGO)** layer that forms during high-temperature operation;
- A **ceramic topcoat**, which serves as the primary thermal insulation layer.

As shown in Figure 2, TBCs can create a temperature gradient of up to 200 K across the coating.

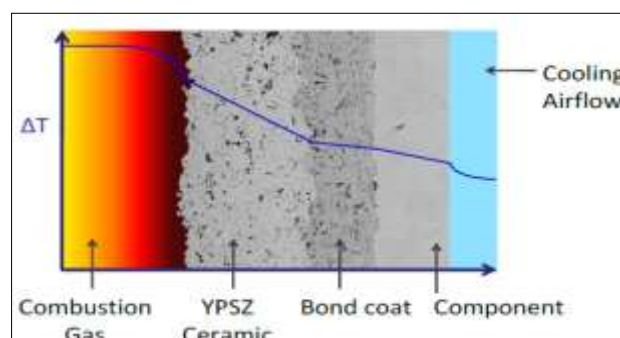


Figure 2: Diagram of a TBC system with temperature drop illustrated across the coating cross-section

The bond coat typically ranges from 100 to 200 μm in thickness, while the ceramic topcoat can vary between 200 μm and 1.5 mm.

Coating Methods and Technologies

Figure 3 provides a classification of different coating techniques, with a focus on catalytic and thermal spray processes.

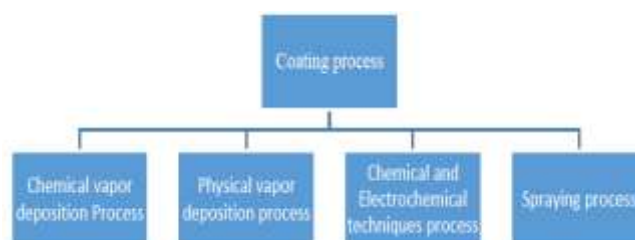


Figure 3 Types of catalytic coating process

Among the various methods, **Air Plasma Spray (APS)** and **Electron Beam Physical Vapor Deposition (EBPVD)** are the most widely used in industry. Less common methods include **High-Velocity Oxygen Fuel (HVOF)**, **Electrostatic Spray-Assisted Vapor Deposition (ESAVD)**, and **Direct Vapor Deposition (DVD)**.

Air Plasma Spray (APS)

The APS method is a widely adopted and cost-effective technique for depositing TBCs. As shown in Figure 4, the process involves injecting powdered material into a high-temperature plasma jet.

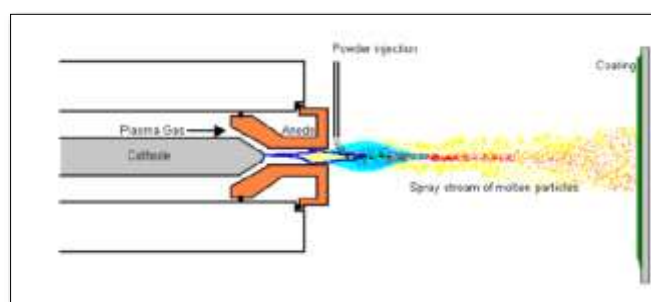


Figure 4 Show diagram of the plasma spray Process

The material melts and accelerates toward the target surface, forming a dense, adherent coating upon impact and rapid cooling.

Electron Beam Physical Vapor Deposition (EBPVD)

EBPVD is a specialized technique used for high-performance applications such as aerospace and semiconductor industries. The process, illustrated in Figure 5,

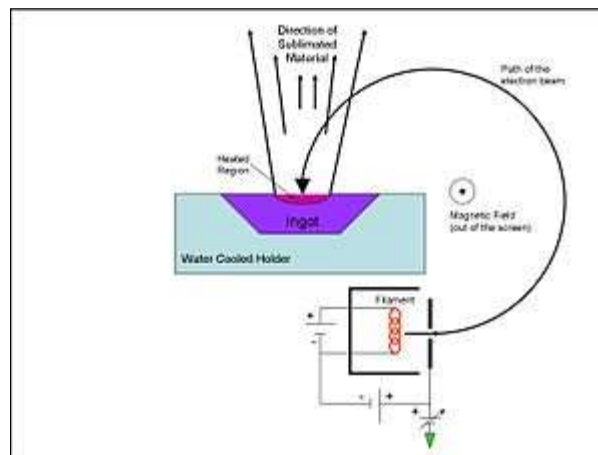


Figure 5 shows the schematic diagram of an EBPVD system involves vaporizing a ceramic material using an electron beam in a vacuum chamber. The vapor condenses onto the heated substrate, forming a thin and uniform coating. EBPVD offers high deposition rates (up to 100 $\mu\text{m}/\text{min}$) at relatively low substrate temperatures, with excellent material utilization and coating quality.

Advanced Ceramic Materials for TBCs

The choice of ceramic material and deposition method depends on desired coating properties, component geometry, application environment, and cost considerations.

Common materials used in TBCs include:

- **Oxides:** Alumina (Al_2O_3), Zirconia (ZrO_2), Yttria (Y_2O_3), Magnesia (MgO), Mullite, Garnets, Spinel
- **Non-Oxides:** Beryllia (BeO)
- **Composites:** MCrAlY alloys, Cermets, Carbides, Abradables, and Polymer Fillers

Each material has specific properties related to thermal conductivity, phase stability, thermal expansion, and resistance to oxidation, corrosion, or erosion under high-temperature conditions.

Benefits of Ceramic-Coated Engine Components

Applying ceramic coatings to internal combustion engine components yields several advantages, as demonstrated by both experimental studies and finite element simulations for compression ignition (C.I.) and spark ignition (S.I.) engines:

- **Enhanced Thermal Efficiency:** Retains more heat within the combustion chamber.
- **Reduced Fuel Consumption:** Lower heat losses improve energy conversion.
- **Higher Combustion Temperatures:** Promotes more complete fuel combustion.
- **Lower Emissions:** Decreased formation of unburned hydrocarbons and NO_x .

- **Improved Engine Performance:** Higher power output and better fuel economy.
- **Extended Component Lifespan:** Reduces wear, corrosion, and oxidation.
- **Reduced Friction and Noise:** Minimizes mechanical losses and combustion knock.
- **Compatibility with Low-Quality Fuels:** Increases fuel flexibility and ignition stability.
- **Improved Cold Start Performance:** Less heat is lost to the cooling system.
- **Lower Specific Fuel Consumption:** Increased effective engine efficiency.

II. EXISTING LITERATURE

Gosai D.C., Nagarsheth H.^[1] claimed that I. C. Engine component such Piston top surface, cylinder head and liners are ceramic coated with Partially Stabilized Zirconia and compared with base line engine. They concludes that fuel economy was improved at certain level and partial reduction in emission parameter for the Thermal Barrier Coated engine.

Y. , Lei J. , Deng X. , Liu Y., Sun, D., Zhang Y^[2] The thermal insulation capability effect was illustrated by Liu , they reported in a simulation that applying a ceramic layer with a thickness of 370 μm to the top face of a piston results in a temperature decrease of over 50° C in the throat of the piston.

Karthickeyan V. Balamurugan P^[3] carried out experimental investigation on a biodiesel engine, which involved altering the ratio of pumpkin seed oil and diesel, revealed that applying a 400 μm coating of air plasma-sprayed PSZ/Al₂TiO₅ on the piston head, cylinder head and valves resulted in a notable increase in NO_x emissions, along with a reduction in HC and smoke when compared to a combustion chamber with standard baseline engine(without coating).

Gosai D.C., Nagarsheth H^[4] determined test with engine coating materials MgZrO₃ and YSZ engine combustion chamber components like piston's top surface, engine heads, valves and liners valves and it is reported that better combustion is occurs with MgZrO₃ coated diesel engine.

Raghu , Girishkumar G.S., Chandrashekara K. ^[5] based on their research reported, they demonstrated that coating a diesel engine's piston with Air plasma sprayed YSZ/NiFeCoCrAlY coating led to a 16% reduction in fuel consumption, a 7% increase in brake thermal efficiency and its shows over 10% improvement in mechanical efficiency.

Das D. ,Majumdar, G., Sen R.S., Ghosh B. B.^[6] conducted on a diesel engine, it was found that a plasma-sprayed partially stabilized zirconia Thermal barrier coating applied to piston

crowns of 250, 350 and 450 μm thicknesses can lower fuel consumption by up to 10%, significantly reduce smoke emissions by nearly 50% and reduce HC and CO emissions by up to 40%. However, NO_x emissions experienced an higher ranging from 7 to 11%.

Kunal Mondal, Calvin M. Downey^[7] investigated that Application of thermal barrier coatings (TBCs) on components such as high-pressure turbine blades, and combustors is uncompromisingly growing in commercial and military related applications and allows higher working temperatures and reduces the cost of cooling systems, thus refining overall component efficiency. Energy-generation sectors, like turbine engines and reactors, are also progressively using thermal barrier coatings, and industries like nuclear and defense are accepting this coating method quickly.

Selman Aydin^[8] claimed that engine coating materials such as 88% ZrO₂, 4% MgO and 8% Al₂O₃ deposited for 400 μm on piston bowl, cylinder head and valves from reading he declared that partial reduction in Brake specific fuel consumption, brake thermal efficiency, CO, HC and smoke emission.

M. Mohamed Musthafa^[9] Development of performance and emission characteristics on partially stabilized zirconia (PSZ) coated diesel engine fuelled by biodiesel with cetane number enhancing additive of Di-tertiary-butyl peroxide (DTBP) partially stabilized zirconia (PSZ) coated diesel engine fuelled by biodiesel with cetane number Biodiesel with additive and petroleum diesel were used as the test fuels. There was no significant improvement on performance and emissions (except HC and CO) of uncoated engine running on biodiesel with additive fuel

B. Dhinesha, R. KrishnaMoorthy^[10] Effectively utilize the biofuel along with nano additive)powered with a coated and uncoated diesel engine YSZ was coated on the engine piston, valves and cylinder head by plasma spray coating technique, simulation study using FEA, Thermal Analysis thermal efficiency of the engine was enhanced by 1.75%fuel-based emissions such as hydrocarbon; carbon monoxide and smoke were reduced with a penalty of increased oxides of nitrogen emission.

Dhiren Patel & A.J. Modi^[11] investigated the performance and emission characteristics of a twin-cylinder, water-cooled diesel engine equipped with ceramic thermal barrier coatings. In their experiment, the engine ran on blends of conventional diesel fuel and biodiesel derived from non-edible neem (*Azadirachta indica*) oil. The neem biodiesel was synthesized in the laboratory by transesterification of the vegetable oil with methanol, using potassium

hydroxide (KOH) as a catalyst. To create a low-heat-rejection (LHR) configuration, magnesium zirconate (MgZrO_3) coatings were applied to the combustion chamber inner walls, the piston crown, and the valve faces using an air plasma spray (APS) technique.

Patel and Modi reported that the LHR engine showed substantial improvements in thermal performance compared to an uncoated conventional engine. Specifically, under full-load conditions the ceramic-coated engine exhibited an approximately 11–13% higher brake thermal efficiency (BTE) and a 7–12% lower brake specific fuel consumption (BSFC) than the uncoated baseline engine. These quantitative results indicate that applying ceramic insulation to critical engine components, in combination with neem-based biodiesel blends, can significantly enhance diesel engine efficiency.

Ekrem Buyukkaya and Cerit^[12] conducted a comprehensive thermal analysis of a ceramic-coated diesel engine piston using a three-dimensional finite element method. Their study compared the thermal behavior of uncoated pistons made from aluminum-silicon alloy and steel with that of a piston coated with a thermal barrier layer. Specifically, the coated piston featured a 350 μm layer of magnesium zirconate (MgZrO_3) applied over a 150 μm NiCrAl bond coat. The results demonstrated that ceramic coatings significantly enhanced thermal efficiency by reducing heat loss through the piston crown. The coated configuration exhibited lower thermal conductivity and improved thermal insulation compared to traditional metallic materials. Additionally, the ceramic coating contributed to improved combustion characteristics and emission reduction, indicating its potential for improving engine performance and durability. The study highlighted the superior thermal durability and wear resistance of ceramics, reinforcing their suitability for high-temperature applications in internal combustion engines.

Das et al.^[13] investigated the performance of thermal barrier coatings applied to internal combustion engine pistons using the plasma spray technique. In their study, three piston crowns were coated with a 100 μm thick aluminum oxide (Al_2O_3) bond coat, overlaid with varying thicknesses (250 μm , 350 μm , and 450 μm) of partially stabilized zirconia (PSZ) as the top coat. Their results indicated that the application of PSZ enhanced oxidation, which led to an increased generation of CO_2 emissions. However, the ceramic-coated pistons demonstrated improved engine performance, with higher cylinder pressures and more efficient heat release rates. This was attributed to more complete combustion processes, facilitated by the insulating properties of PSZ, which effectively reduced heat loss from the

combustion chamber. Found up to 10% decrease in fuel consumption and 50% reduction in smoke with PSZ-coated pistons.

Helmisyah Ahmad Jalaludin, Shahrir Abdullah, Mariyam Jameelah Ghazali, Bulan Abdullah, and Nik Rosli Abdullah^[14] conducted an experimental investigation into the thermal performance of ceramic-coated piston crowns in a compressed natural gas direct injection (CNG DI) engine. In their study, a bonding layer of nickel-chromium-aluminum (NiCrAl) and a ceramic top coat of yttria partially stabilized zirconia (YPSZ) were applied via air plasma spraying onto AC8A aluminum alloy CNG DI piston crowns and standard CamPro piston crowns. The aim was to reduce thermal distortion under high-temperature engine conditions. The thermal behavior of the coatings was evaluated using a burner rig, with temperature measurements taken from both the piston crown surface and the underside. The results indicated that the YPSZ/NiCrAl-coated piston crowns experienced significantly lower heat flux compared to uncoated pistons, suggesting enhanced thermal barrier performance of the ceramic coating system.

Liu et al. ^[15] demonstrated the effectiveness of ceramic coatings in enhancing the thermal insulation performance of engine components through simulation analysis. In their study, they applied a ceramic layer with a thickness of 370 μm to the top surface of a piston and observed a significant thermal reduction. Specifically, the simulation revealed a temperature decrease of over 50°C in the throat region of the piston. This result underscores the potential of ceramic thermal barrier coatings (TBCs) to mitigate heat transfer in high-temperature environments, contributing to improved component durability and thermal efficiency in internal combustion engines.

Summary of Literature Review and Research Scope

Research and innovation in any technical domain can only progress through a thorough understanding of prior work conducted in the same field. The contributions of earlier researchers form the foundation upon which new discoveries are built. Accordingly, a comprehensive review of the existing literature is critical to identify current trends, gaps, and opportunities in the subject area.

In the context of internal combustion engines, the application of advanced coating materials—especially Thermal Barrier Coatings (TBCs)—has been extensively explored in both aerospace and industrial gas turbine (IGT) sectors. These coatings continue to demonstrate success due to their material reliability and process adaptability. Materials such

as partially stabilized zirconia and magnesium zirconate (MgZrO_3) have been effectively applied using Air Plasma Spray (APS) technology. It has been shown that by adjusting deposition parameters—such as flow control and spray distance—the microstructure and performance of coatings can be tuned to meet specific engine requirements.

This chapter presented a detailed literature review focused on:

- The mechanical and thermal analysis of the combustion chamber,
- The impact of ceramic coatings—especially on the piston crown—on engine performance and efficiency.

Based on the reviewed studies, the following key conclusions can be drawn:

- **Coating materials with low thermal conductivity** (e.g., abradables, polymer fillers, MCrAlY alloys, carbides, and cermets) applied to engine pistons and combustion chambers significantly improve thermal efficiency and contribute to reduced engine emissions.
- **Nickel-chromium-based coatings** demonstrate high resistance to hot oxidizing and corrosive gases, offering protection against scaling on carbon and low-alloy steel surfaces.
- **Inconel alloys** are especially valuable for repairing superalloy components and protecting less noble substrates. Their excellent resistance to high-temperature oxidation and corrosion makes them ideal for demanding engine environments.

Scope for Future Research

Despite extensive advancements, several promising research areas remain underexplored.

Future work may focus on:

- **Nanostructured APS coatings**, which may further enhance thermal insulation and durability;
- **Oxidation behavior under real engine operating conditions**, to assess long-term coating stability;
- **Optimization of coating thickness and piston crown profiles**, to achieve maximal thermal efficiency and combustion performance.

References

- D. C. Gosai and H. J. Nagarsheth, "Diesel engine cycle analysis of two different TBC combustion chambers," *Procedia Technology*, vol. 23, pp. 504–512, 2016.
- Y. Liu, J. Lei, X. Deng, Y. Liu, D. Sun, and Y. Zhang, "Research and analysis of a thermal optimization design method for aluminium alloy pistons in diesel engines," *Case Studies in Thermal Engineering*, vol. 52, p. 103667, 2023.
- V. Karthickeyan and P. Balamurugan, "Effect of thermal barrier coating with various blends of pumpkin seed oil methyl ester in DI diesel engine," *Heat and Mass Transfer*, vol. 53, pp. 3141–3154, 2017.
- Raghu, G. S. Girishkumar, and K. Chandrashekara, "Experimental study of the effect of thermal barrier coating on diesel engine performance," *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, pp. 2051–2054, 2018.
- D. Das, G. Majumdar, R. S. Sen, and B. B. Ghosh, "The effects of thermal barrier coatings on diesel engine performance and emission," *Journal of the Institution of Engineers (India): Series C*, vol. 95, pp. 63–68, 2014.
- K. Mondal and C. M. Downey, "Recent advances in the thermal barrier coatings for extreme environments," *Materials Science for Energy Technologies*, pp. 208–210, 2021.
- S. Aydin, C. Sayin, and H. Aydin, "Investigation of the usability of biodiesel obtained from residual frying oil in a diesel engine with thermal barrier coating," *Applied Thermal Engineering*, vol. 80, pp. 212–219, 2015.
- M. M. Musthafa, "Development of performance and emission characteristics on coated diesel engine fuelled by biodiesel with cetane number enhancing additive," *Energy*, vol. 134(C), pp. 234–239, 2017.
- B. Dhinesha and R. Krishnamoorthy, "A numerical and experimental assessment of a coated diesel engine powered by high-performance nano biofuel," *Energy Conversion and Management*, vol. 171, pp. 815–824, 2018.
- A. J. Modi and D. Patel, "Experimental study on diesel engine performance with blends of diesel and neem biodiesel," *SAE Technical Paper*, SAE International, Jan. 2015, pp. 1–8.
- E. Buyukkaya, "Thermal analysis of functionally graded coating AlSi alloy and steel pistons," *Surface and Coatings Technology*, vol. 202, no. 12, pp. 1–6, 2007.
- H. A. Jalaludin, S. Abdullah, M. J. Ghazali, B. Abdullah, and N. R. Abdullah, "Experimental study of ceramic coated piston crown for compressed natural gas direct injection engines," *Arabian Journal for Science and Technology for Mechanical Engineering (AIJSTPME)*, pp. 73–77, 2012.
- Das, D.; Majumdar, G. ; Sen, R.S.; Ghosh, B.B. *The Effects of Thermal Barrier Coatings on Diesel Engine Performance and Emission. J. Inst. Eng. India Ser. C* 2014, 95, 63–68.
- Helmisyah Ahmad Jalaludin, Shahrir Abdullah, Mariyam Jameelah Ghazali, Bulan Abdullah, Nik Rosli Abdullah "Experimental Study of Ceramic Coated Piston Crown For Compressed Natural Gas Direct Injection Engines" *AIJSTPME* ,2012,pp 73-77
- Liu, Y.; Lei, J.; Deng, X.; Liu, Y.; Sun, D.; Zhang, Y. *Research and analysis of a thermal optimization design method for aluminium alloy pistons in diesel engines. Case Stud. Therm. Eng.* 2023, 52, 103667.