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ADVANCED METHODS FOR ANALYZING COMBUSTION EFFICIENCY IN GAS TURBINES: A COMPREHENSIVE ANALYSIS

Venkata Rama Gautham Devarakonda
Simpsonville, SC, USA
Gautham.rama90@gmail.com

Abstract

Abstract— Gas turbines are essential to many sectors, including aviation and power production, because of their capacity to effectively transform fuel energy into mechanical energy. In order to maximise energy output and save operating expenses, gas turbine performance and efficiency must be improved. Gas turbine technology is still relevant today despite power generating advancements and the introduction of several energy sources because of its dynamic behaviour, flexibility in load demand following, and adaptability to various fuels with few design modifications. But without accurate modelling and simulation, ambitious advancements in gas turbines would not be possible. This paper explores the advancements in gas turbine technology, with a focus on ceramic coating for combustion chambers, which significantly improves thermal and combustion efficiency. Through computational analysis using ANSYS software, we compare the performance of ceramic-coated combustion chambers against conventional chambers. The findings reveal that ceramic-coated chambers exhibit a thermal efficiency of 48.5%, a combustion efficiency of 70%, and a lower heat rate of 0.023, outperforming conventional chambers in all evaluated aspects. These advancements demonstrate the potential of ceramic coatings in boosting turbine performance, paving the way for more sustainable and efficient energy solutions in the future.

Keywords: Combustion efficiency, Ceramic coating, Thermal performance, Inlet air cooling, Technological advancements.

I. INTRODUCTION

An apparatus that transforms the energy in a gas—typically air—into rotating motion is called a gas turbine. The windmill, often known as a wind turbine, is one gadget of this kind that uses wind energy to generate rotational motion. The energy of moving air is used by wind turbines, while gas turbines are powered by gas that is confined inside a casing and is often high in pressure and temperature. The energy collection process may thus be much more precisely controlled[1]. The first "jet engine" was created in 100 BC by Hero, an Alexandrian Egyptian scientist. The "aeolipile" (Figure 1) was comprised of a boiler, two curved, hollow tubes attached to a sphere, and the sphere itself. Using the two hollow tubes that supported the spherical, steam was able to enter from the boiler. The sphere began to rotate as the steam released itself via its twisted tubes. It is stated that the hero utilized this device to unlock the doors of the temple. The first steam engine known to history dates back to the first century AD and is called Hero's Engine or Aeolipile [2]. Greek mathematician, inventor, and writer Hero of Alexandria (c. AD 10–c. AD 70) wrote extensively on mechanical and physical topics.

Fig 1. Hero's Aeolipile

The first successful gas turbine was constructed in Paris in 1903 and consisted of an impulse turbine, a combustion chamber, and a three-cylinder, multistage reciprocating compressor. It operated on the following principle: a compressor sucked air into a combustion chamber, which burned air and liquid fuel. A gases that were produced were subjected to an impulse turbine after being somewhat cooled by water injection. With a thermal efficiency of about 3%, this device proved that gas-turbine engines might be viable for the first time[3].

Gas turbines must be made more energy efficient. Specifically, it concerns the efficient conversion of mechanical energy from fuel energy. This improved performance is dependent on the interplay between the turbine's combustion, airflow, and components. Big gains are achieved via the strategic use of gas turbine technology and a development of gas turbine operations in terms of precision. A step forward for the energy sector is this initiative to increase gas turbine efficiency [4]. It points towards a more efficient and sustainable energy-producing future. Large-scale improvements in turbine performance are facilitated by this. There are tactics that improve operations by using the most recent scientific discoveries. This entails using modern cooling systems and enhancing ventilation. These improvements demonstrate our dedication to consistently raising the bar for gas turbine performance. A new age of excellence in gas power is heralded by the meticulous modifications we make today as we advance towards new possibilities [5].

For a gas turbine to operate with high efficiency, its major components are essential. These consist of the fuel-burning combustion chamber, the turbine (where gas expands and produces power), and the compressor (which maintains air pressure). For the finest result, these components must function flawlessly throughout [6]. Various industrial uses and small to medium-sized high-speed marine boats continue to find these turbine engines appealing.

The motivation to improve gas turbine efficiency stems from several key factors. Economically, enhanced efficiency reduces fuel consumption and operational costs, benefiting both energy providers and consumers. Environmentally, more efficient turbines lower greenhouse gas emissions, supporting global sustainability goals. Technological advancements drive innovation in materials and design, pushing the boundaries of engineering. Enhanced efficiency also strengthens energy security by maximizing the use of available resources, reducing reliance on less stable alternatives. Finally, in a competitive market, improved efficiency offers a significant advantage, allowing companies to achieve better performance and lower costs, thereby gaining a strategic edge. The contribution of this paper discussed as:

- Enhanced gas turbine efficiency lowers fuel consumption and operational expenses, leading to significant cost savings for energy producers and consumers alike.
- By increasing efficiency, gas turbines produce fewer greenhouse gases per unit of energy, contributing to reduced environmental impact and supporting climate change mitigation efforts.

- Innovations in materials, such as super alloys and ceramic coatings, improve turbine performance and durability, driving progress in engineering and materials science.
- Improved efficiency maximizes the utilization of natural gas resources, reducing reliance on less stable energy sources and enhancing overall energy security.
- Higher turbine efficiency provides a competitive edge in the energy market, enabling companies to offer better performance, lower costs, and more reliable energy solutions.

1.1 Structure of the paper

The paper is structured as follows: Section II covers the overview of Gas Turbine. Section III details about the Fundamentals of Gas Turbine Efficiency. Section IV provides technological innovations enhancing turbine efficiency. Section V presents some challenges. Section VI gives us literature review. Section VII offers Conclusion and future work and lastly section VIII has all the reference used in the paper.

II. OVERVIEW OF GAS TURBINE

An internal combustion engine known as a gas turbine uses gas as its working fluid to transform mechanical energy inherent in fluid motion into chemical energy by means of an impulse or reaction. An assortment of equipment, including industrial pumps, maritime propulsion, train propulsion, and automobile propulsion, may be primarily moved by the converted mechanical energy, which can also be utilized for power production[7]. Reviewing the fundamental components of a gas turbine is essential for a comprehensive understanding of these Gas Turbines.

2.1 Basic Components of a Gas Turbine

Typically, all gas turbines have three main sections that enable them to function.

- **Compressor:** A compressor is an integral part of any gas turbine; it sucks in air, presses it down, and then rushes it to the combustion chamber. Most industrial setups utilize a series of compressors to satisfy pressure and flow rate requirements. The basic categories of compressors used are axial and centrifugal compressors, with the former usually delivering higher efficiency values.
- **Combustion Chamber:** This chamber contains multiple injectors that introduce fuel to mix with the air prior to combustion. When temperatures rise beyond 2,000°F, combustion takes place, releasing a gas stream that is both hot and pressurised. This stream grows as it passes through the turbine portion.
- **Turbine:** This section has a complex arrangement of blades mounted on a shaft that spin as an outcome of a high-pressure, high-temperature gas stream. The shaft then transfers the torque from the blades to a generator, which converts it into energy. Turbine blade rotation also increases air pressure within the combustion chamber.

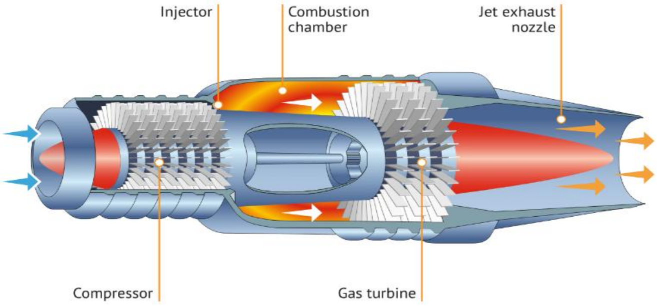

Fig 2. Components of a Gas turbine

After a compressor compresses an intake air, fuel is fed into a combustion chamber. Figure 2 depicts a gas turbine's component parts. The turbine is powered by the hot gas produced when this is consumed. A portion of the turbine's energy powers the compressor; the remaining portion may power an aero plane (if the gas turbine is mounted there, for example) or spin a generator to produce electricity [3]. Gas turbine power plants run on syngas, biogas or natural gas derived from biomass. A combined-cycle power plant uses gas turbines to increase efficiency in addition to steam turbines.

2.2 Classification of Gas Turbine

We may classify gas turbines into 2 broad categories: open cycle and closed cycle [5]. It is possible to compare the closed and open cycle gas turbines' operations by looking at factors including installation cost, fuel type, efficiency, operating cycle, and heat input quality.

1. Open cycle Gas Turbine

A centrifugal or axial-flow compressor is used to compress the room temperature air that is drawn into an open cycle gas turbine. When activated, the compressor raises the air temperature and pressure to levels specified by the OEM. A combustion chamber is used to burn fuel at a relatively constant pressure using a compressed air at a higher-pressure. The turbine is propelled by high-pressure, heated gases, and the power generated as a result of the shaft's rotation may be used for several purposes, including power production and as prime movers in industrial machinery. Exhaust gases are emitted into the environment as seen in Figure 3. An open cycle mechanism describes this cycle as it does not recycle the exhaust gases but instead releases them into the atmosphere [7].

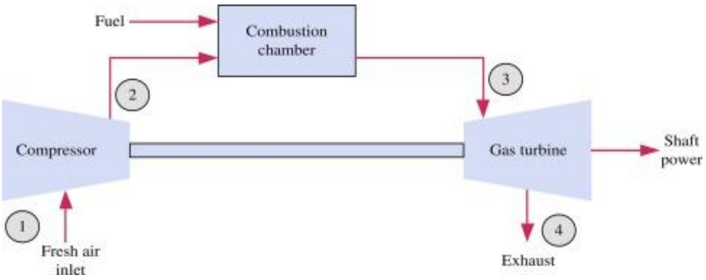

Fig 3. Open Cycle Gas turbine.

2. Close cycle gas turbine

Compressors in closed-cycle gas turbines heat and pressurize the air that enters them. The air is heated to a high temperature and pressure before entering the heat exchanger, which is heated by an outside. The turbine is fed air that is both hot and under pressure in order for expansion to occur. In a closed cycle gas turbine, power is produced as the working fluid's pressure increases throughout the turbine. A cooling chamber cools an exhaust working fluid instead of releasing it into the environment. This allows the system to operate continuously[7].

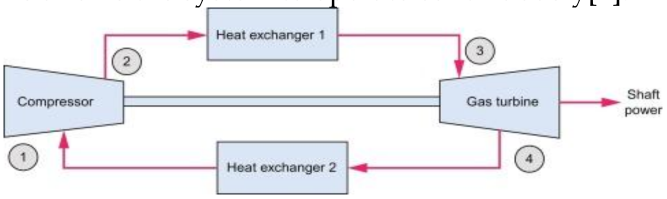

Fig 4. Close cycle gas turbine[8]

Figure 4 shows that the working fluid is recycled back to the compressor before the cycle is done, which is why the technology is called a closed gas turbine engine cycle.

III. FUNDAMENTALS OF GAS TURBINES EFFICIENCY

Turbine efficiency is often measured in relation to combustion efficiency and thermal efficiency. The amount of energy that is converted into a useable form, like electricity, from a gas's starting energy is called its thermal efficiency. The efficiency with which petrol burns in a combustion chamber is called combustion efficiency.

3.1 Factors affecting Efficiency

Some factors that influence the efficiency of turbines include:

- **Compression Ratio:** The pressure differential between the compressor input and exit is what this term describes. Since more heated and pressurised air is entering the combustion chamber at a greater compression ratio, efficiency improves as the ratio rises.
- **Pressure Drop and Airflow:** The airflow and pressure drop over the turbine and compressor components determine their performance. If there are any losses or restrictions in pressure or airflow, then there will be a reduction in efficiency.
- **Turbine Inlet Temperature:** As the turbine inlet temperature gets higher, it makes for more efficient energy extraction from the combustion gas.
- **Ambient Conditions:** In warmer atmospheric conditions, air density decreases, thus resulting in the compressor doing more work. Also, this leads to a drop in the airflow rate. Because air constitutes over 90% of the air-fuel combustion mixture under normal conditions, this drop in airflow results in a drop in efficiency.
- **Mechanical Losses:** Reduction in efficiency can also be due to friction between components such as bearings, seals, etc. Usually, these are accounted for and minimized during the design stage.
- **Fuel Properties:** The type and quality of fuel in use impacts on the gas turbine efficiency. Factors such as calorific value, composition, and combustion characteristics of the fuel are important, so should be in line with specifications.
- **Maintenance and Operating Conditions:** Deploying a good maintenance strategy and utilizing the turbine in line with specifications are key to optimizing its efficiency.

3.2 Combustion Efficiency

Combustion efficiency is an important aspect of gas turbine technology. The efficiency of a fuel-to-power system is closely correlated with its operating temperature; higher cycle temperatures result in better efficiency. Figure 5 shows the combustion chamber, which has the challenging duty of burning a lot of fuel with a lot of air. Both air and petrol are provided by the compressor and the fuel spray nozzles, respectively. The efficient transfer of heat from the combustion chamber to the air via acceleration and expansion is essential for producing a constant flow of uniformly heated gas that the turbine can use in any circumstance. In order to do this task, it is essential to minimise pressure loss and maximise heat escape within the constraints of the available area. The necessary temperature increase determines the quantity of fuel to be injected into the air. Turbine blades and nozzles are constructed from materials that can only withstand temperatures between 850 and 1700°C. Because of a work done during compression, an air temperature is already between 200 and 550°C, therefore temperature increases of 650 is required. to 1150 °C. by a combustion process. Because a power and thrust demands of an engine vary, a combustion chamber must be designed to maintain-stable and efficient combustion under a wide variety of engine operating conditions.

This is especially true for turbo-propeller engines. Aircraft emissions, often known as exhaust smoke, have been on the rise due to the fast expansion of commercial aviation, making efficient combustion a critical issue[9].

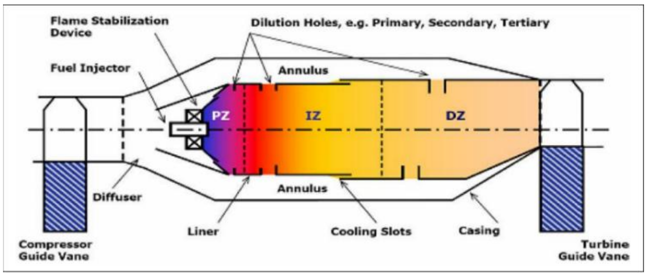

Fig 5. Combustion Chamber [9]

3.2.1 Ceramic coating combustion chamber

A combustion chamber is only one component of a more complex concept that includes ceramic coating. Following the same concept of combustion, the chamber is constructed. Our research into these combustion chambers led us to conclude that one with a ceramic covering would be ideal, therefore we built one using CATIA [9].

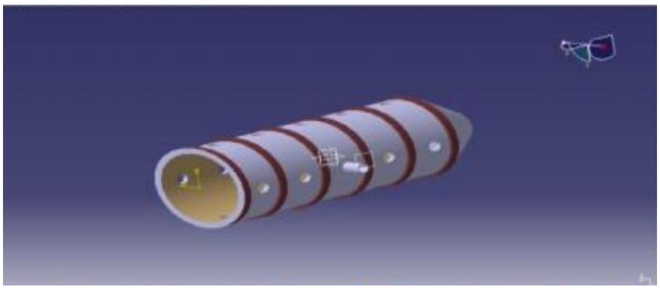

Fig 6. Ceramic coating Combustion Chamber[9].

Figure 6 shows the complete architecture of the electromagnetic plasma arc propulsion system.

3.2.2 Analyzing the process

Flow analysis methods are used to realistically accomplish ceramic coating combustion chamber flows. ANSYS software's flow analysis may be used to carry out these operations. Because of the precision of the flow as shown by the maximum %, ANSYS is an ideal analysis program for a ceramic coated combustion chamber [9].

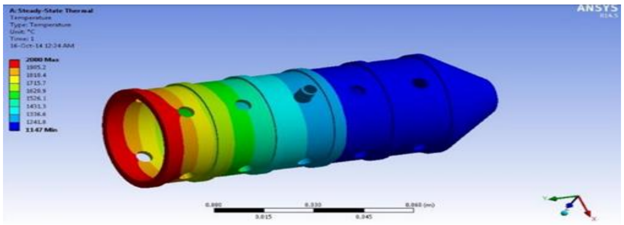

Fig 7. Temperature Contour of Ceramic Coating Combustion Chamber.

- The ceramic layer's effect on the combustion chamber's temperature profile is seen in Figure 7. This system analysis was carried out using the ANSYS program.
- A color red here denotes a high temperature value, whereas the color blue denotes a low temperature value.

- The graphic indicates that the input segment has a lower temperature than the exit chamber. The intake segment (or chamber inlet) has a lower temperature than the exit section (or chamber exit) due to the principle of combustion.

In this study, the interior surface of the chamber has been coated with ceramic material, which has lower thermal conductivity than typical materials. Consequently, combustion efficiency is inherently increased while the rate of heat transmission is decreased. As a result, the inside of the inflow portion is cooler than the outside, and vice versa[9].

3.2.3 Comparison of Combustion Chamber

We determined the combustion chamber characteristics for the ceramic coating. Table 1 also includes a comparison of chamber parameters to those of a standard chamber.

- **Thermal Efficiency:** The ceramic-coated chamber exhibits higher thermal efficiency at 48.5% compared to 42.7% for the conventional chamber, indicating better heat utilization in the coated chamber.
- **Heat Rate:** The ceramic-coated chamber has a lower heat rate of 0.023, signifying it requires less fuel to produce the same amount of energy compared to the conventional chamber, which has a heat rate of 0.028.
- **Combustion Efficiency:** The ceramic-coated chamber also shows improved combustion efficiency at 70%, compared to 65% for the conventional chamber, reflecting more complete fuel combustion in the coated chamber.

Overall, the ceramic-coated combustion chamber outperforms the conventional chamber in all evaluated aspects, indicating enhanced performance and efficiency.

Ceramic Coating Combustion Chamber		Conventional Chamber	
Performance	**Value**	**Performance**	**Value**
Thermal Efficiency (%)	48.5	Thermal Efficiency (%)	42.7
Heat Rate	0.023	Heat Rate	0.028
Combustion Efficiency (%)	70	Combustion Efficiency (%)	65

Table 1. Comparison of Combustion Chamber[9].

IV. TECHNOLOGICAL INNOVATIONS ENHANCING TURBINE EFFICIENCY

Improving the efficiency of gas turbines remains a high industry priority as OEMs continually invest in technological developments. There is a continual improvement in gas turbine technology as a result of technological advancement [10].

4.1 Advancements in Materials and Coatings

Leading turbine manufacturers have a strong hand in developing new superalloys. Turbine efficiency is increased by these super alloys' ability to withstand greater temperatures. They withstand the harsh conditions found within turbines, allowing for more efficient combustion.

They also lessen the abrasion that turbine components receive. Special coatings also increase the lifespan of turbine parts, reducing the time and expense of repairs.

4.2 Aerodynamic Blade Design

Enhancements in turbine blade geometry are also essential. Contemporary blades are engineered to reduce resistance and instability, resulting in a smoother gas flow. Turbine performance and power production may be greatly increased by making little adjustments to the blades' curvature and angle [10].

4.3 Inlet Air Cooling

One of the major deterrents to high turbine efficiency is a low compression ratio. The high air intake temperature is a major contributor to the low compression ratio. Moreover, the higher the air inlet temperature, the less dense the air and the more difficult to compress. However, this can be overcome by cooling the inlet air before each compression stage. Some common methods of cooling include:

- **Fogging:** This involves filtering the air entering the system and then injecting atomised water into it to lower the temperature. It is one of the easiest and most economical methods to deploy. However, it requires a steady water supply, can cause erosion within the compressor, and is not effective when humidity is high.
- **Evaporative Cooling:** Similar to fogging, this method cools the air stream after filtration by passing it through a porous media, which is constantly wetted by one or more water pumps. Erosion is not caused by this procedure because water droplets are not added to the air stream.
- **Inlet Chilling:** As cooling tubes are deployed inside the air filter system; this is the most efficient method of cooling the input air. To make sure the input air temperature doesn't rise over a certain level, cooled water is continuously pushed into these tubes. As a result, the operation follows a refrigerator-like concept.

4.4 Thermal Energy Storage

This entails using a system that stores the thermal energy generated by the turbine for later use. As a result, the turbine can generate energy during off-peak periods, which is then stored, and used during on-peak periods. Despite a shift towards greener energy resources, natural gas still holds a significant market share as an energy source. As a result, manufacturers are continually developing new technologies that improve the efficiency of gas turbines.

V. LITERATURE REVIEW

The following section provides the literature review of Advanced Methods for Analysing Combustion Efficiency in Gas Turbines. A literature study was done to determine the components addressed by current frameworks, as well as the shortcomings they share.

In[11], The use of dynamic data for factors like injected steam-ratio and rotor cooling air temperature has led to findings from the current model being more accurate than those from prior models. The WIGT power plant operates more smoothly with the use of the current model. A useful thermodynamic model was created and verified by contrasting it with actual data from the Macau power plant to determine an efficiency of a single cycle WIGT with RAC.

In[12], out the steps to take in order to build a vibrational model of a gas turbine's combustion chamber; this will hopefully serve as a springboard for further studies on acoustic phenomena. Based on the findings of impact testing along an axial axis of the combustion chamber, which confirmed the presence of flexible modal modes and their associated natural frequencies, the degrees of freedom of the sub-damped modal model that captured the chamber were determined from these tests.

In[13], gives an account of the outcomes of a theoretical and experimental studies conducted on an injector-like plasma-assisted combustion mechanism used in a newly-designed synthesis gas afterburner. The afterburner's fundamental overall dimensions with the injection mechanism are established. Improving performance, expanding turndown ratios, using synthesis gas more efficiently, and meeting crucial ecological standards are all possible outcomes of this design strategy.

In[14], details the results of theoretical and practical studies into the inner workings of a low-emission combustor for gas turbines that use the idea of lean burning to burn a partly premixed mixture. Designs and engineers working on power generating units, gas turbine combustor operating mode models, geometry optimisation, and future propulsion may all benefit from the findings and suggestions that were generated.

In [15], thermodynamic and energy studies for the cycle are constructed, demonstrating that regeneration is a method for increasing the gas turbine cycle's thermal efficiency. This method involves preheating compressed air with the turbine's exhaust gas before it enters the combustion chamber. Next, a computation code is created using EES software to examine how operational and geometrical factors impact the cycle's performance.

In[16], conducts computational analysis of the temperature and component field distributions in the combustion chamber of a 30 KW micro gas turbine design under four distinct oxygen/carbon dioxide combustion circumstances. The tiny gas turbine runs on biomass gas with oxygen concentrations of (O 2 = 21%, 30%, 35%, 40%) in ascending order. The outcomes of the simulation allow us to deduce the following: The combustion chamber's temperature increases steadily as the initial oxygen concentration rises.

In[17], an annular combustor from a gas turbine was analysed in three dimensions using simulation. The responding flow's numerical results were derived using the SIMPLE method. An annular combustion prediction was made using the non-adiabatic probability density distribution combustion model, the discrete ordinates method radiation model, and the realistic k -ε turbulence model. All three simulated operating circumstances matched the design operating parameters with respect to combustion and flow.

Recent studies on gas turbine combustion efficiency reveal diverse approaches. One method enhances accuracy by integrating dynamic parameters, improving operational efficiency. Another study develops a vibrational model of the combustion chamber to support acoustic analyses. Innovations in plasma-assisted afterburners and low-emission combustors focus on performance, turndown ratios, and ecological compliance. Regeneration techniques improve thermal efficiency by preheating air with exhaust gases. Numerical simulations of micro gas turbines and annular combustors provide insights into temperature distributions and combustion flows under varying conditions.

VI. CONCLUSION AND FUTURE WORK

Improving gas turbine engines relies on determining the optimal distribution of combustion chamber temperatures. This paper provides an in-depth analysis of gas turbines, focusing on their historical development, basic components, and efficiency factors. It highlights the evolution from early inventions like Hero’s Aeolipile to modern gas turbines, underscoring the significance of advancements in materials, aerodynamic blade design, and innovative cooling methods. The comparison between ceramic-coated and conventional combustion chambers demonstrates the benefits of new technologies in enhancing thermal and combustion efficiency. These findings illustrate the importance of ongoing technological advancements in optimizing gas turbine performance, making them more efficient and sustainable for various applications, from power generation to industrial processes.

Future research should focus on further enhancing gas turbine efficiency by exploring new materials and coatings that can withstand even higher temperatures and pressures. Additionally, there is potential for integrating advanced computational methods, such as machine learning and AI, to optimize the design and operation of gas turbines in real-time. The exploration of alternative fuels and hybrid systems combining gas turbines with renewable energy sources also holds promise for improving efficiency and reducing environmental impact. Finally, conducting long-term studies on the performance and durability of ceramic-coated combustion chambers in various operational conditions will offers valuable insights for their widespread adoption in an industry.

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