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Research on the Optimization of Gas Turbine Combustion Chambers Based on Exergy Analysis: Locating Exergy Destruction and Improvement Solutions

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Abstract. Based on the second law of thermodynamics, this study systematically investigates the exergy loss in the operation of gas turbine combustors. Through a combination of literature review and theoretical analysis, existing research findings are comprehensively summarized, and the main causes of exergy loss under actual working conditions of gas turbine combustors are deeply analyzed. On the basis of accurately identifying exergy loss sources, a series of feasible optimization strategies are proposed. These strategies can effectively reduce exergy loss in gas turbine combustors, improve energy utilization efficiency, and provide reliable theoretical basis and practical guidance for the design optimization and performance improvement of gas turbine combustors.

Keywords: gas turbine, exergy analysis, combustor optimization, exergy loss factors

1. Introduction

A gas turbine is a rotary impeller-type heat engine that uses continuously flowing gas as the working medium. It converts energy by driving the impeller to rotate at high speed through fuel combustion, and is widely used in internal combustion power machinery. It plays an important role in power generation, aviation, marine navigation, industry and other fields. In previous studies, the thermal efficiency method commonly used to evaluate gas turbine performance is mainly based on the first law of thermodynamics, which only analyzes the total amount of energy. This method has obvious deficiencies because it ignores the qualitative differences between energy forms of different grades. Therefore, in the optimization research of gas turbine combustors, the exergy analysis method based on the second law of thermodynamics has distinct advantages. It extends the evaluation of energy efficiency from simple quantity conservation to the judgment of the available quality of energy [1].

Exergy (E_x) in this paper refers to the portion of energy that can be theoretically converted completely into other forms of energy when a system changes reversibly from an arbitrary state to a state in equilibrium with a given environment. As an important parameter for evaluating energy value, exergy not only concerns the quantity of energy but also reflects its qualitative utilization value, making it a core indicator for measuring the energy utilization level of a system.

Based on exergy analysis theory, this paper discusses the optimization methods of gas turbine combustors, aiming to break through the limitations of traditional thermal efficiency evaluation.

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Firstly, the exergy flow distribution in each part of the combustor is clarified, the relationship between input and output exergy flows is analyzed, and an exergy balance model for energy conversion in the combustor is established. Secondly, focusing on the sources of exergy loss, relevant literature in the past decade is systematically reviewed, classified and summarized, and the factors influencing exergy loss are divided into three categories: incomplete combustion loss, flow resistance loss and heat dissipation loss. Thirdly, targeted optimization suggestions are put forward corresponding to these exergy loss factors to improve the energy utilization efficiency of the combustor from the perspective of energy quality, providing theoretical support for the overall optimization of energy systems.

2. Investigation on exergy calculation methods

Exergy can be defined as the maximum work obtainable when a thermodynamic system undergoes a reversible process from an arbitrary state to the environmental state, interacting only with the environment without external disturbances. Since both components and the whole system operate under given environmental conditions, the selection of the environmental reference state is fundamental to exergy analysis. In this study, the environmental reference state is set as: ambient temperature T_0 = 298.15K (25℃) and ambient pressure P_0 = 101325Pa (1 standard atmosphere) [2]. This state conforms to the definition of the International Standard Atmosphere (ISA). Although ISA specifies a standard sea-level pressure of 101325 Pa and a temperature of 15 ℃ (288.15K), 298.15 K is closer to the common room temperature used in engineering and facilitates comparison and verification with data from other studies. In practical engineering scenarios, most gas turbines operate near normal pressure and temperature, such as ground power generation or marine power plants. Therefore, the combination of 298.15 K and 101325 Pa better reflects real working conditions and renders exergy calculation results more instructive for engineering applications.

3. Exergy analysis of gas turbine combustors

3.1. Function and working process of gas turbine combustors

The main parts of a gas turbine include the compressor, combustor, and turbine. The energy conversion process inside the combustor is complex and needs careful control. It mainly mixes fuel with high-pressure air. The mixture then burns and produces high-temperature and high-pressure gas. This gas drives the turbine to do work. In the whole gas turbine cycle, the combustor has the largest share of exergy loss. The loss from exhaust gas comes next. These two parts form the main exergy losses in the system [3]. So, the combustor is the key part that needs to be optimized to improve the overall economic performance of the system.

The flow and working process of the working medium in the combustor can be described as follows. The high-pressure gas from the compressor enters the combustor. It first passes through the diffuser section, where the flow velocity is reduced. This helps reduce flow resistance loss and keeps the flame stable in the decelerated flame tube. Then the airflow enters the flame tube with swirlers or rectangular channels. In this part, swirling and disturbance improve the mixing of fuel and air. Fuel is injected into the head of the flame tube through nozzles. It is then ignited by an igniter and forms a stable combustion zone. To prevent overheating damage to the flame tube wall and reduce heat dissipation loss, different cooling methods are used. These methods include arranging holes on the wall to introduce cooling air, adjusting the overall airflow distribution, and reducing the effect of heat dissipation loss.

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3.2. Exergy balance model and exergy efficiency of the combustor

The combustor is taken as an independent research object, consisting of an airflow inlet, a fuel inlet, a gas outlet and heat dissipation boundaries. Exergy analysis is performed on this system to clarify the composition of input and output exergy flows. The input exergy flow mainly includes the total exergy of the working medium and the chemical exergy of the fuel. In calculating the total exergy of the working medium, focus is placed on the thermodynamic process itself, while the effects of velocity and height variation are neglected. The exergy per unit mass is dominated by physical exergy, expressed as:

$$e = e_{x,ph} + \frac{1}{2}v^2 + gz \tag{1}$$

$$e_{x,ph} = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) \tag{2}$$

Where e: total exergy per unit mass, v : flow velocity, g : gravitational acceleration, taken as 9.8m/s², z : height, $e_{x,ph}$: physical exergy per unit mass, u : internal energy per unit mass of fluid, u_0 : internal energy per unit mass at the reference environmental state, p_0 : reference environmental pressure, 101325 Pa, v : specific volume of fluid, v_0 : specific volume at the reference environmental state, T_0 : reference environmental temperature, 298.15 K, s : specific entropy of fluid, s_0 : specific entropy at the reference environmental state.

Besides the total exergy of the working medium, the chemical exergy of fuel $e_{x,fuel}$ is another important part of the input exergy flow. It represents the chemical energy of fuel in the form of exergy, whose magnitude depends on fuel type and properties. The main component of the output exergy flow is the thermal exergy of flue gas $e_{x,gas}$, i.e., the exergy carried by high-temperature, high-pressure combustion products.

Overall, exergy analysis is conducted within the framework of reversible processes. Any irreversible process therefore causes exergy loss, which reduces the overall work-producing capacity of the system and degrades energy quality. The magnitude of exergy loss directly reflects the degree of irreversibility: a larger exergy loss indicates stronger irreversibility and lower effective utilization of exergy, corresponding to lower thermodynamic perfection of the system. However, exergy loss is an absolute quantity and cannot compare the effective utilization of exergy under different conditions. To characterize the exergy utilization efficiency of the system more intuitively, the exergy efficiency η_{e_x} is defined as:

$$\eta_{e_x} = \frac{E_{x,o}}{E_{x,i}} \tag{3}$$

Where $E_{x,o}$: total exergy output of the system, $E_{x,i}$: total exergy input of the system. The introduction of exergy efficiency overcomes the inadequacy of evaluating energy utilization only from the perspective of energy quantity, and provides a unified criterion for assessing the thermodynamic perfection of various practical processes.

4. Main sources of exergy loss in the combustor

Many scholars have conducted extensive research on various factors affecting exergy loss in gas turbine combustors. To ensure the systematicity and representativeness of this review, multiple rounds of screening were performed on relevant literature, with the detailed procedure shown in

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Table 1. Focusing on exergy loss in gas turbine combustors, a rigorous literature screening process was carried out. First, using "exergy loss" as the core keyword, relevant literature was retrieved from databases including Web of Science and CNKI, yielding an initial collection of more than 80 publications. Next, preliminary screening based on titles and abstracts was conducted to exclude literature on pure technical applications and case reports, retaining 30 theoretically in-depth research papers. After full-text careful reading, priority was given to the top 20% most-cited articles published in the past five years, and 17 core papers were finally selected for analysis, fully reflecting the theoretical evolution and latest breakthroughs in the field.

Based on the established high-quality literature database, research emphasis was placed on in-depth exploration of key influencing factors. Factors directly or indirectly affecting exergy loss were extracted from each paper with corresponding sources cited. Through classification and summarization, 14 influencing factors were obtained. By analyzing the correlation between each factor and exergy loss, repetitive and less important factors were eliminated, and key results were retained. It is concluded that exergy loss in gas turbine combustors mainly stems from three parts: incomplete combustion, flow resistance loss, and heat dissipation loss, which provides a clear direction for subsequent optimization of exergy efficiency.

Table 1. Procedure for identifying key factors of exergy loss in the combustor

Step	Specific Procedure
Step 1	Using "exergy loss" as the core keyword, literature was retrieved from databases such as Web of Science and CNKI, yielding more than 80 preliminary studies.
Step 2	Titles and abstracts were screened, and purely technical application studies and case-report literature were excluded, leaving 30 research papers with substantial theoretical depth.
Step 3	Full-text analysis was conducted. Priority was given to the top 20% most-cited studies and publications from the past five years, resulting in the selection of 17 core references for detailed analysis.
Step 4	Factors influencing exergy loss were extracted from the core literature, with all source references carefully documented.
Step 5	A total of 14 influencing factors were identified through classification and synthesis.
Step 6	The relationships between each factor and exergy loss were further analyzed in depth. Repetitive or relatively less significant factors were eliminated, and only the key results were retained.
Step 7	Final conclusions were drawn, providing clear directions for subsequent optimization of exergy efficiency.

4.1. Incomplete combustion loss

Incomplete combustion loss refers to the loss caused by insufficient reaction between fuel and oxygen, which prevents the full release of chemical energy. The main causes of this loss are as follows.

Problems in fuel–air mixing, such as an improper mixing ratio or poor mixing uniformity, can lead to incomplete combustion. Guangzhu Wang et al. showed that the fuel–air flow ratio has a clear effect on the combustion process. It changes the combustion temperature and pressure distribution,

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so it can indirectly reduce the overall combustion efficiency [4]. Yinglin Yang et al. pointed out that changes in circulating flow rate and temperature can disturb the mixing quality of fuel and air. This further affects the completeness of combustion [5]. When the fuel–air ratio moves away from the stoichiometric air–fuel ratio, the air supply may become either insufficient or excessive. Both conditions can cause incomplete combustion and produce intermediate products such as carbon monoxide.

Limited combustion space also affects the diffusive mixing of air and fuel. This can lead to uneven temperature distribution and incomplete chemical reactions. Local fuel-rich zones and fuel-lean zones may exist at the same time. This further makes the reaction less complete [6]. Problems in combustor design also cause incomplete combustion. Dekang Qiao et al. noted several unreasonable design factors. These include the vane angles of swirlers in the main combustion air passage, mismatched diameters of prechamber inlet holes and constrictions, stepped wall structures, and combustor length. These factors can all lead to incomplete combustion [7]. Lizhi Zhao et al. stressed that the combustor structure has an important effect on performance. They also made detailed studies of nozzles, swirlers, and complex internal structures [8]. Poor design directly prevents enough mixing between fuel and air. Improper flow-path shape and length also shorten the residence time of fuel. As a result, fuel cannot burn completely in the limited space. This lowers combustion efficiency and thermal efficiency, and it directly increases exergy loss.

Poor matching between operating conditions and equipment is also an important factor. Yonghong Zhou et al. found that under low-load or off-design conditions, the temperature distribution inside the combustor becomes uneven. Local low-temperature regions then cause incomplete combustion. By contrast, combustion is more stable under full-load conditions, and incomplete combustion is clearly reduced [9]. These factors work together and lead to incomplete fuel–oxygen combustion. As a result, the chemical energy of fuel cannot be fully released or efficiently converted. Extra heat dissipation loss also occurs, causing large exergy loss in the combustor.

4.2. Flow resistance loss

Flow resistance loss refers to exergy loss caused by energy dissipation during working fluid flow. The main factors related to this loss are as follows.

4.2.1. Basic friction loss

When the working fluid flows inside the combustor, friction arises from wall contact, and vortices form during fuel–air mixing. Both consume fluid energy, cause pressure loss, and consequently increase exergy loss [10].

4.2.2. Limitations in combustor flow capacity

Restrictions in combustor flow capacity also increase exergy loss. Qiufeng Zhang et al. used experiments and numerical simulations to show that unreasonable geometric design, such as swirler flow area and diffuser dimensions, limits flow capacity and increases flow resistance [11]. Yiqian Xiao et al. indicated that insufficient flow capacity of the burner causes non-uniform air–fuel mixing and local hot spots, raising the OTDF value [12]. Such temperature non-uniformity intensifies thermal stress and fatigue while increasing irreversible loss, i.e., exergy loss. Essentially, improper

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flow-path size or structural design raises flow resistance and worsens incomplete combustion, leading to energy waste and efficiency degradation.

4.2.3. Dynamic matching of system components

Mingchao Liu et al. demonstrated that a combustor with a reasonable compression ratio accelerates the heat release rate and improves thermal efficiency. Unreasonable pressure ratio design causes inlet or outlet parameters to deviate from design values, increasing flow loss [13]. Zuozhi Qin et al. showed that low ambient temperature reduces the effective recovery of exhaust heat, increasing exhaust back pressure and further raising flow resistance at the combustor outlet [14]. Therefore, the control of system flow resistance requires coordination between internal parameter matching and external environmental constraints, such as pressure ratio coordination among components and backpressure variations caused by temperature changes. These two aspects jointly determine the energy loss level during working fluid flow.

4.3. Heat dissipation loss

Heat dissipation loss refers to exergy loss caused by heat transfer from the combustor wall to the environment or heat removal by the cooling system. The key influencing factors are as follows.

4.3.1. Temperature differences among working fluid, wall and environment

Temperature differences exist between the working fluid, the wall and the ambient environment. When obvious temperature differences appear between high-temperature gas and the combustor wall, cooling components or the surroundings, high-temperature parts dissipate heat to the outside through radiation and convection, resulting in increased exergy loss. For example, heat dissipation loss of diesel engine combustor components can account for up to 20% of total heat loss [15].

4.3.2. Combustor wall structure and materials

The complex flow passage structure inside the combustor, including sudden expansion and contraction, increases the contact area between the wall and the working fluid. Shallow-bowl combustors suffer more serious heat dissipation because the flame contacts the wall prematurely [16]. Although the cooling structures and schemes adopted by the combustor protect the wall, the cooling air absorbs heat and is discharged, which degrades the exergy quality of the combustion gas [17, 18]. In addition, higher thermal conductivity of the material leads to greater heat dissipation loss.

4.4. Summary of exergy flow loss analysis

Based on the above analysis, factors affecting exergy loss in gas turbine combustors can be classified into three categories: 1. Incomplete combustion loss $e_{x,\text{loss burn}}$, caused by insufficient fuel–air mixing and poor combustion conditions leading to incomplete reaction; 2. Flow resistance loss: $e_{x,\text{loss flow}}$, caused by pressure drop and velocity variation due to friction, vortices, limited flow capacity and mismatched components during gas flow; 3. Heat dissipation loss: $e_{x,\text{loss heat}}$, caused by heat loss to the environment through the wall and heat consumption by cooling measures, mostly occurring at the combustor wall via thermal conduction and convection between high-temperature

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gas and the wall. According to the exergy analysis results of the combustor, the corresponding exergy flow diagram is plotted.

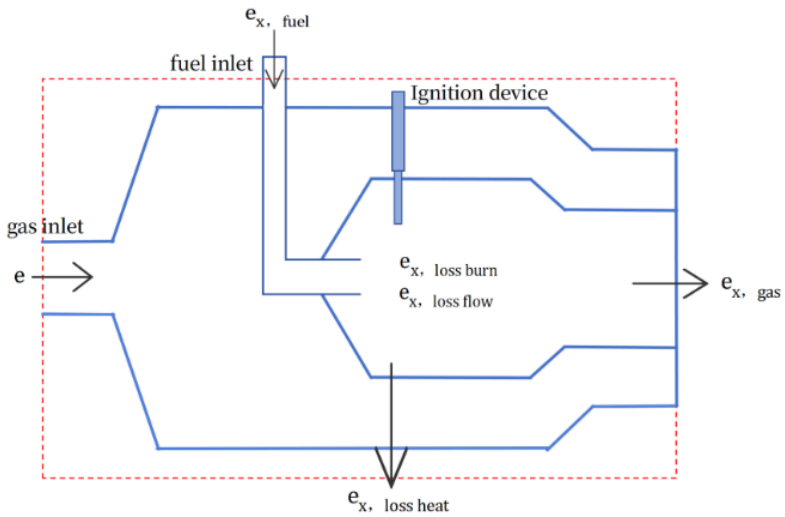

Figure 1. Exergy flow diagram of the combustor

5. Optimization suggestions based on exergy analysis

Based on the sources and internal mechanisms of exergy loss, this paper puts forward specific optimization suggestions from three aspects: combustor design, environmental parameter adaptation, and operating condition-component matching.

5.1. Optimization of combustor structure

The design and structure of the combustor are closely related to combustion completeness, flow resistance, and heat dissipation loss. Targeted optimization ideas are proposed from the perspectives of mixing-combustion enhancement and wall treatment with cooling technology, aiming to improve combustion stability, reduce flow resistance loss, and lower exergy loss caused by heat dissipation.

5.1.1. Strengthening fuel–air mixing

On the one hand, mixing uniformity should be improved through premixed combustion technology for fuel pretreatment and better passage structure design. The main measures include properly extending the mixing distance, arranging mixing holes in a more reasonable way, adjusting the parameters of fuel injection holes, and using a graded mixing design that combines rectangular passages and swirl passages. These methods can strengthen fuel–air mixing, improve mixing performance, and raise the overall combustion efficiency. On the other hand, the air–fuel ratio should be adjusted in a dynamic way. Oxygen sensors can monitor the oxygen content in flue gas in real time. Based on this information, the air–fuel ratio can be adjusted continuously and kept close to the stoichiometric value. This can reduce incomplete combustion, lower exergy loss, and improve the overall efficiency of energy use.

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5.1.2. Optimization of wall treatment and cooling technology

On the one hand, wall treatment can use low thermal conductivity materials together with compact structures. This helps keep heat near the heat source and reduce heat dissipation loss as much as possible. Thermal barrier coatings can also be sprayed on metal substrates. This can extend service life and effectively reduce heat transfer to the environment.

On the other hand, cooling methods can be upgraded and improved. Gradient fins can be used to improve convective cooling. By optimizing fin geometry, they can reduce temperature gradients and exergy loss caused by flow resistance. Adaptive film cooling driven by shape memory alloys can adjust the cooling air flow in a dynamic way according to gas temperature. Optimizing the geometric parameters of transpiration cooling holes can also greatly reduce temperature gradients. It can improve mixing, reduce flow resistance exergy loss, and further raise cooling efficiency. The combined use of several cooling methods can make their advantages work together. This leads to a more reasonable cooling design and higher overall efficiency and operating reliability of gas turbines.

5.2. Adaptive design for environmental parameters

In actual operation, fluctuations in environmental parameters significantly affect equipment performance. Optimization suggestions are proposed for inlet temperature control and environmental temperature difference control to enhance adaptability to changing environmental conditions and improve operational performance and efficiency.

5.2.1. Inlet temperature control

Inlet temperature control should balance improved combustion efficiency with system safety, reliability, economy, and emission performance. A combined preheating-precooling technology is adopted to meet full operating conditions. When ambient temperature is below the design baseline, preheating via waste heat recovery or electric heating prevents inlet icing and improves combustion stability. When ambient temperature exceeds the design value, spray evaporation is used for cooling to maintain inlet temperature near the designed level.

5.2.2. Environmental temperature difference control

Environmental temperature difference can be controlled by introducing aerogel insulation interlayers to block thermal radiation from high-temperature walls to the environment. Further optimization of insulation layer structure and airflow organization strengthens the thermal insulation effect, cuts off direct heat transfer from high-temperature zones to the surroundings, and stabilizes surface temperature and pressure of the insulation layer, ensuring high and steady power output.

5.3. Optimization of operating conditions and component matching

In addition to the structure and operational characteristics of the combustor itself, external conditions such as operating regimes and the matching between system components also significantly affect the exergy efficiency of the combustor. Therefore, corresponding optimization strategies are discussed focusing on operating conditions and component coordination. By precisely regulating the working load and enhancing inter-component cooperation, the energy utilization efficiency of the combustor is improved.

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5.3.1. Appropriate working load

The optimization of unit working load needs to balance efficiency and stability. The working load should be adjusted in a dynamic way according to real operating conditions. These conditions include power demand at different periods, the stability of fuel supply, and the performance status of equipment components. The system can match the load with the operating parameters of each component more accurately. It can also improve the combustion process and energy conversion efficiency, and make the operating benefits of the unit as high as possible. This can avoid incomplete combustion in local low-temperature regions caused by uneven temperature distribution inside the combustor under low-load conditions. It can also avoid faster wear and lower efficiency of unit components caused by excessive loading at full load.

5.3.2. Strengthening system component matching

A thermodynamic model under full operating conditions is built by using thermodynamic system modeling methods. It covers key components such as gas turbines, waste heat boilers, and steam turbines. The performance change laws of the unit under different loads are analyzed to provide a reliable basis for optimized operation. For example, in the pressure ratio and flow rate matching between the gas turbine compressor and the combustor, variable geometry guide vanes are used. They can adjust the compressor outlet pressure in a dynamic way to match the inlet pressure requirement of the combustor. This can avoid a sharp rise in the turbulence intensity of the working fluid caused by an excessively high pressure ratio. Such a rise would increase flow friction exergy loss. It can also prevent insufficient inlet kinetic energy caused by an excessively low pressure ratio. This condition would lead to exergy loss from poor fuel mixing. As a result, flow exergy loss is reduced. Better component matching also improves the flow state of the working fluid.

6. Conclusion

Based on the second law of thermodynamics and exergy analysis theory, this paper conducts an in-depth investigation into gas turbine combustors. By analyzing the exergy flow distribution in each part of the combustor in detail, the key factors affecting exergy loss are systematically summarized, and targeted optimization suggestions are proposed. The main conclusions are as follows: through exergy flow analysis and detailed decomposition of loss exergy, the factors influencing exergy loss in the combustor can be classified into three categories: incomplete combustion, flow resistance loss, and heat dissipation loss. Corresponding optimization strategies are proposed from three aspects: structural optimization of the combustor, adaptive design for environmental parameters, and matching optimization of operating conditions and components, so as to improve the quality and utilization efficiency of energy in the combustor.

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