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Research on Factors Affecting the Operating Efficiency of Gas Turbines

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Abstract

Gas turbines are also considered major flexible power plants within the scope of China adopting the “dual carbon” policy since these power facilities enable the decarbonization of the energy system. Nevertheless, the local gas turbine sector encounters challenges, including dependence on foreign core technologies, limited performance of individual units, and inadequate ability to operate with zero-carbon fuels; additionally, earlier research cannot provide a complete theoretical basis that could describe the causes of efficiency differences between different types of gas turbines. Firstly, this paper has divided gas turbines into heavy-duty, aeroderivative, and micro gas turbines and then discussed five crucial factors that affect their efficiency and finally, it has outlined three main industrial bottlenecks that are made up of high-temperature materials, zero-carbon combustion, and localized application systems. The originality of this work is a comparative analysis of the patterns of degradation of the efficiency of all types of gas turbines and systematically summarize and compare the quantitative efficiency loss characteristics under hydrogen-ammonia co-firing and severe marine operating conditions. Based on this consideration, this paper offers four specific development directions. The next generations of hot-section components and clean combustion technologies will enhance the performance and self-production of locally produced gas turbines and contribute to the creation of the new energy system.

Keywords

gas turbine, combined cycle, zero-carbon fuel, domestic production

1. Introduction

The “dual carbon” goals, which include carbon peaking and carbon neutrality, are leading China to speed up its shift towards a clean, low-carbon, safe, efficient, and flexible working environment. By taking advantage of its fundamental strengths, which include fast start-stop, great peak shaving performance, small size, and low emission quality, the gas turbine has become an essential part of the key power equipment used to stabilize the operation of the new energy system and optimize the national energy structure. The level of technological advancement and industrial autonomy is closely linked to national energy security and the process of energy transition. Gas turbines are widely used as one of the key elements of integrated energy systems, distributed generation networks, offshore oil and gas platforms, and large-scale power plants, serving as power generators in heavy-duty plants, offshore power plants, and even micro-scale combined cooling, heating, and power plants, so they can be considered as a major strategic pillar in the energy sector [1]. Nevertheless, the Chinese gas turbine industry has been facing numerous challenges over the years, including reliance on imported core technologies, lack of self-developed high temperature components and control systems as well as inadequate production capabilities in order to realize efficient zero-carbon transformation, which is an urgent concern in terms of domestic independent innovation, low-carbon transformation and energy efficiency improvement. Although domestic-made 2 MW-class gas turbine units have already been deployed in practice on offshore platforms and progress has been achieved in terms of structural design, system integration, and installation technologies [2], there is still a gap between these achievements and international advanced standards, which indicates the need to conduct complete technical studies on the independent creation, optimization of their performances, and implementation of high-performance gas turbines in engineering practice.

The gas turbine developments and applications have created a well-developed industrial environment in terms of the global technological standpoint. International giants like General Electric (GE), Siemens, and Mitsubishi own proprietary core technologies of heavy-duty gas turbines, aeroderivative gas turbines, and micro gas turbines, respectively. Heavy-duty gas turbine combined cycle efficiency may be over 60 percent, and aeroderivative products have a dominant role in the distributed power generation and offshore power generation sectors due to both their high power density and rapid load response capability; micro gas turbines can be up to 40 percent efficient, and thus represent complete technological barriers at any power level and application. Conversely, the gas turbine technology in China has reached some level of improvement; however, serious gaps are still present: the efficiency of domestic micro gas turbines is just between 21.6% and 27%, which is much lower than the international advanced levels. Preliminary results of aeroderivative gas turbines have been obtained by modifying aero engines, but the core components and control algorithms continue to be imported. Imported technology has allowed localization of heavy-duty gas turbines, but there are gaps in the autonomy of performance monitoring, high-efficiency cycle design, and compatibility with zero-carbon fuels. Recent studies in academia and industry concentrate more on prospective topics such as data-driven performance monitoring, reheat combined cycle optimization, hydrogen-ammonia co-firing zero-carbon combustion technology, and fuel cell-gas turbine coupled systems. Nevertheless, no systematic analytical structure has been developed in the current research that would encompass all types of gas turbines and effectively combine such aspects as structural design, efficiency properties, technical bottlenecks, and future development prospects. In this context, the paper will offer a systematic review of the classification schemes, efficiency-influencing factors, and future development trends of gas turbines, seeking to address the outstanding issues restricting the growth of China's gas turbine industry and elucidate the technological evolution logic and upgrade pathway. The study systematically compares heavy-duty, aeroderivative, and micro gas turbines in terms of their structural characteristics and technical differences, quantitatively evaluates the impact of core component performance, cycle design, fuel flexibility, and external environment and operation and maintenance on efficiency, determines the critical technological bottlenecks in materials, combustion, and system integration, and finally suggests a development path of localized, high-efficiency, and zero-carbon in line with China's industrial reality and the dual carbon goals, thus offering theoretical and practical guidance to independent research, engineering application, and technological iteration in the domestic gas turbine sector.

2. Structural Classification and Technical Characteristics of Gas Turbines

A gas turbine is a rotary heat engine that uses a continuously flowing working fluid to convert chemical energy to thermal energy and mechanical energy. Gas turbines may be divided into various classes based on their output power, operating conditions, and thermodynamic cycle type with a wide range of applications in power plants, offshore facilities, and distributed cooling, heating, and power systems [1-3]. Depending on installed capacity and construction features, there are three types of gas turbines: heavy-duty, aeroderivative, and micro gas turbines. There are also four configuration schemes depending on the different thermodynamics cycles. The main parts are compressor, combustor, turbine and other related support systems [4-7].

2.1 Classification by Cycle Configuration

The mainstream gas turbine cycle systems consist primarily of four types: simple cycle, regenerative cycle, intercooled cycle, and combined cycle with reheat [2]. A simple cycle has only three elements, which are compressor, combustor, and turbine, and there are no waste heat recovery devices. Its construction is comparatively simple, and it has the ability to start up and shut down quickly. Nevertheless, the exhaust gas waste heat is directly released, therefore, its efficiency rate is only 38-42 percent, thus it can only be effectively used in temporary emergency power supply situations [2]. The regenerative cycle system has a recuperator to recoup waste heat from exhaust gas to heat inlet air. This is the usual design of micro gas turbines, and unit efficiency may improve by 5 to 15 percent [4]. Combined cycle with reheat is an efficient layout of large units; exhaust gas waste heat is employed to generate steam through a heat recovery steam generator to generate steam that drives a steam turbine. With a three-stage reheat configuration, the overall efficiency can be over 60 percent, and this technology has been used extensively in advanced models by GE and Siemens [2]. In the intercooled cycle, the consumption of the power of the compression is reduced by cooling the intermediate stages of the compressor. It has a significant use in custom ultra-high-power units; however, because of costs, it cannot be implemented in a wide range.

2.2 Classification by Power Output and Application Scenario

2.2.1 Heavy-Duty Gas Turbines

The units have a single-unit power output in the power range of 50 MW–500 MW, which is the main equipment of large combined cycle power plants. They come in sets of 17-22 stage axial compressors, annular combustors, and 3-5 stage heavy-duty turbines, and the weight of a single unit may be thousands of tons. The simple cycle efficiency is between 38 and 42 percent, and with a reheat combined cycle unit, it is more than 60 percent, and the unit design life is over 200,000 operating hours. Examples are PG9351FA and AE94.3A. These units can be used to provide both baseload power generation capacity and grid peak-shaving capacity. Despite the fact that foreign companies are at the forefront of technology, local F/H-class machines have been fully localized, but there are still issues with high-temperature blades and smart control systems. Quantitative performance monitoring based on data has been extensively used in the whole-life operation and maintenance of heavy-duty units, allowing analyzing the pattern of degradation of components quantitatively.

2.2.2 Aeroderivative Gas Turbines

The units are created using aero engine technology and have a power output of 5 MW to 60 MW. They use an ultralight aerospace structure, and the footprint is just one-third to half the size of a heavy-duty unit of equivalent power rating. These units may be brought up to full-load operation in 5–8 minutes following a cold start, and their regulation rate of load is significantly superior to that of coal-fired units. The units have a combined axial and centrifugal compressor arrangement, and annular recirculating combustors are installed. They are particularly well adapted to a mobile installation like offshore oil and gas platforms, naval propulsion systems, and standby power stations. The LM2500 and QC280 models are the mature mainstream versions. Despite the fact that small-batch domestic manufacturing has been done on the basis of China's aviation industry background, there are still technical issues in low-NOx combustor design, high-temperature component durability management, and electronic control systems. The goal of the current work is to maintain high fuel efficiency operation.

2.2.3 Micro Gas Turbines

The systems are rated at 500 kW or less and have a one-stage centrifugal drive design. The compressor is combined with a centrifugal turbine and the rotor speed may be 60,000 -120,000 rpm. Regenerative cycle is also used to restore waste heat, and it has broad applicability to combined cooling, heating, and power plants in industrial parks and buildings [4]. The average efficiency of international state-of-the-art models is nearing 40 percent, whereas the efficiency of local models is merely 21.6-27 percent because of the constraints of recuperators and high-speed bearings. Currently, the industry emphasis is on maximizing the combustion process by methane-ammonia co-firing and optimization of combustor design by numerical simulation methods, thus balancing both NOx emissions and combustion efficiency as well as lowering CO emissions [4,5].

2.3 Structural Composition and Core Components

2.3.1 Compressor

The given form of the equipment has two designs, namely, axial-flow and radial-flow. Multistage axial-flow layouts are commonly used in heavy-duty and aeroderivative types, whereas compact versions have a tendency to implement radial-flow designs. The total efficiency may increase by 0.5%—0.8% when the unit pressure ratio rises by 1 percent [1]. Fouling and corrosion of blades will continually decrease the efficiency of compression. Through the use of big data monitoring, early warning of performance degradation can be provided, and regular water washing is the predominant on-site maintenance activity [1].

2.3.2 Combustor

The dry low emission (DLE) dry premixed low-NOx annular combustion configurations have been successfully used in numerous applications and can display very good combustion stability in standard natural gas conditions. Nevertheless, with hydrogen or ammonia addition, the flame propagation properties will change, which will raise the likelihood of flashback and thermoacoustic vibrations. On the other hand, with an increased blending ratio in ammonia co-firing conditions, CO emissions will approach zero, but NO formation will increase, and the combustion efficiency will decrease a little bit. That is why the optimization of the configuration of nozzles and combustors plays a central role in enhancing combustion stability.

2.3.3 Turbine

Blades work under high temperature conditions of 1200–1500 °C and present serious technical difficulties to the whole system. Flue gas produced due to hydrogen-ammonia combustion has a significantly larger amount of water vapor, which greatly raises the heat transfer load on the blade. The technologies needed to guarantee long blade life include single-crystal substrates, film cooling, and thermal barrier coatings [6]. Currently, there is some degree of technology gap between the domestic high-temperature materials and cooling systems and their foreign equivalents.

2.3.4 Auxiliary Systems

This system consists of five major subsystems, namely the lubrication system, inlet system, exhaust system, control system, and the fuel system [7]. The 2 MW gas turbine manufactured in the domestic market has an integrated lubrication module; its inlet air filter system that is resistant to salt spray is tailor-made to operate in the conditions of high humidity in the atmosphere at sea; and the pipeline that delivers the fuel can be used to deliver natural gas and hydrogen mixtures of fuels. So such a detailed modular structure was successfully implemented in many engineering activities, which serves as an example of localization of small and medium-sized gas turbines [7].

3. Analysis of Factors Affecting Gas Turbine Efficiency

Thermal efficiency is an important technical parameter in assessing the performance of fuel usage, economic returns of projects, and ability to reduce carbon emissions of gas turbines. In the context of the development of the new power system in China and the introduction of the dual carbon strategy, the gas turbine has gained even more prominence due to its fast start-up and flexible peak shaving capacity, and it has found widespread use in numerous applications including centralized power stations, offshore structures, distributed combined cooling, heating, and power systems, and emergency power supplies. The economic benefit of energy investment and the practicality of low-carbon transformation are directly linked to the on-site operating efficiency [1]. Gas turbine efficiency is usually limited by four major factors, which include the level of aging of the core components, thermodynamic cycle structure, fuel properties, and load operation conditions, and is also influenced by environmental conditions and life-time operation and maintenance policies based on experimental data on prototypes, long-term field measurements of domestic demonstrator units, and operation history. It can be seen that the sensitivity of efficiency to these factors varies widely due to the differences in structural design and operation limits between the heavy-duty, aeroderivative, and micro gas turbines [9,10].

3.1 Degradation of Core Component Performance

Three major elements of a gas turbine that convert energy are the compressor, the combustor, and the turbine. The components work continuously in very severe environments that include high temperatures, high pressures, and high-velocity gas flow erosion, and thus experience prolonged irreversible damage like blade fouling and wear, combustor deformation, and spallation of turbine coatings due to creep. It is the basic reason behind the slow degradation of the efficiency of long-term operation [3]. Experiments have shown that the wear patterns of these three parts and their extent of influence on efficiency depend on the specific turbine model used.

3.1.1 Compressor Performance Degradation

A compressor is the one that pressurizes air. Inlet air flow rate and compression ratio are directly related to the air-fuel ratio in the combustor. A small drop in compression performance may lead to fuel-air mismatch all over the engine, hence energy usage efficiency reduces [3]. Dust particles, sea salt crystals, and airborne suspended contaminants continuously adhere to the surfaces of both stationary and rotating blades when gas turbines are run for extended periods in complicated environments like inland industrial sites, offshore oil and gas facilities, or the desert. It changes the original aerodynamic shape of the blades, decreases the flow passages, increases interstage recirculation, and the energy expenditure during compression gradually increases. Experimental evidence indicates that severe blade surface fouling can directly decrease the overall efficiency of a gas turbine by 0.5–3.0 percent [10]. The dimensions of the blades of micro gas turbines are smaller than the large flow passages of heavy-duty gas turbines, and the cross-sections of the flow passages are fairly narrow, so the separation of the boundary layer is more probable in the process of airflow. With the same level of dust pollution, the efficiency deterioration of micro gas turbines is significantly higher compared to medium-sized to large gas turbines. As per quantitative analysis using data-driven monitoring technology, a 1% reduction in compressor compression efficiency results in a 0.6%–0.9% decrease in overall power generation efficiency of the gas turbine. Emergency power supply to islands and offshore platforms is extensively powered by aeroderivative gas turbines whose start-stop cycle frequency is significantly higher than that of stationary heavy-duty power units. The impeller and minor blade deformation often lead to slight wear due to alternating thermal loads caused by temperature variations, which in turn speeds up the deterioration of compressor performance. Currently, the domestic production of aero-engine derivatives and micro gas turbines has numerous restrictions since the precision blade machining technology is not developed yet. The blade surface is less smooth than the imported ones. With the same operating conditions, these parts are more susceptible to deposit formation, and the degradation cycle is significantly reduced. Nevertheless, through online condition monitoring of units and with the regular maintenance of water washing, most of the surface deposits can be eliminated, thus restoring the original compression performance of the compressor and reducing the tendency of efficiency decrease [3].

3.1.2 Fluctuation of Combustion Efficiency in the Combustor

When burning pure natural gas, the combustion efficiency of current DLE dry low-NOx annular combustors is often kept at over 98 percent, and all the chemical energy in the fuel can be converted into the thermal energy of high-temperature flue gas. But due to the extensive application of zero-carbon fuels like hydrogen and ammonia, the physicochemical properties of these fuels lead to drastic changes in combustion properties. The conventional combustor designs have been abandoned, and thus there are frequent occurrences of the problems of flame shift, flashback, and thermoacoustic oscillations, which adversely affect combustion performance and the efficiency of the combustor [5-7]. Data obtained through the Datang Haikou AE94.3A heavy-duty gas turbine experiment indicate that the limiting hydrogen content of 7% or less leads to the same lack of anomaly change in the combustor noise level, casing vibration acceleration, and component temperatures, no flashback, and that the combustion efficiency is similar to that with pure natural gas operation [5]. Nonetheless, when the hydrogen concentration goes beyond the limit of 30%, the laminar flame velocity of hydrogen is significantly higher than that of methane, which causes the propagation of the flame across the upstream of the nozzle, and then, flashback and local flame extinction occurs with a large reduction in combustion efficiency [7]. Simulations done using CFD on a 10 kW micro gas turbine demonstrate that by increasing the mass fraction of ammonia in methane from 0 to 1.0, CO emission may be eliminated, but the combustion rate and reaction kinetics are significantly reduced, and the efficiency decreases from about 98.14 percent to 97.64 percent, and during the same time, NO_2 generation increases by about 1.16×10^{-4} to 3.68×10^{-4} [6]. Most of the combustors in use in China are developed on the basis of normal natural gas fuel specifications. Under high hydrogen or ammonia fuel ratios, without proper optimization of the nozzle and combustor construction, combustion will not be stable, which now becomes one of the main limitations of energy efficiency improvement in the zero-carbon retrofitting process, as mentioned in [6,7].

3.1.3 Decline in Turbine Thermal Efficiency

The turbine blades work in high-temperature (1200–1500 °C) and high-pressure gas environments throughout the year and are the most heavily loaded and crucial parts of the entire power generation system. Typical natural gas combustion yields carbon dioxide and nitrogen with little moisture in the flue gas, and existing film cooling systems have enough capability to provide the necessary heat dissipation. But full combustion of hydrogen and ammonia raises the amount of water in the flue gas, the specific heat capacity and heat transfer coefficient of the gas, and the heat load of the blade surface, reduces the adhesion of cooling gas to the surface of the wall, and reduces the effectiveness of film cooling. At high temperatures, the long-term exposure of single-crystal blades to thermal loads leads to the problem of creep deformation of the substrate material, patchy spallation of the surface thermal barrier coating, decreased integrity of the aerodynamic profile, and the continued reduction in turbine gas expansion efficiency. In gas-steam combined cycle units, a decrease in turbine performance would also change the inlet characteristics of the heat recovery steam generator, and result in a reduction in overall efficiency by 1.5% to 2.5%. Multistage design and a large temperature range of operation at high temperature are adopted by heavy-duty combined cycle turbines and under these conditions the detrimental effect of high-humidity flue gas becomes more apparent. Micro and small gas turbine blades have a thin wall and low thermal inertia rendering them vulnerable to thermal shock effects that cause higher efficiency losses. It is this element that plays a significant role in inhibiting the domestic production of micro and small gas turbines to achieve the international advanced performance levels.

3.2 Cycle and System Design Factors

The framework of the thermodynamic cycle has established the theoretical efficiency limit of gas turbines. The various cycle systems have different waste heat recovery configurations and air compression schemes. Nevertheless, the efficiency limits of a single-cycle system can be overcome by combining gas turbines with electrochemical energy storage systems, high-temperature fuel cells, and solar power generation devices, and the overall efficiency can be significantly enhanced through cascaded energy utilization [1,4,8,11]. In the context of basic design, the simple Brayton cycle consists of three parts, i.e., compressor, combustor, and turbine, and does not have a waste heat recovery mechanism, and so the exhaust temperature may be as high as 500 to 600°C and hence high-temperature thermal energy is very much wasted. Its conventional efficiency is within 38 percent to 42 percent, and it thus finds its primary application in mobile aeroderivative emergency power stations or temporary micro power generating units [1,4]. A regenerative cycle uses a recuperator to recover the heat of the high-temperature exhaust gas that is used to warm the low-pressure air exiting the compressor, reducing the consumption of natural gas in the combustor. It is an exceptional optimization tool regarding micro gas turbines. With no recuperator, efficiency is around 20%; but a plate-type or tubular recuperator, when properly installed, will add 5 to 15 percent to the overall efficiency, bringing the efficiency range to 25 to 40 percent [10]. Three-stage reheat gas-steam combined cycle is the best technical choice for heavy-duty gas turbines. This methodology involves the introduction of the high-temperature exhaust gas flow into a heat recovery steam generator to generate high-, medium-, and low-pressure steam to operate a steam turbine generator. The most popular models, like the GE 9HA and Ansaldo AE94.3A, also embrace this configuration, and the combined cycle efficiency of advanced versions can be more than 60% [4]. The intercooled cycle provides an intercooler between the high-pressure and the low-pressure compressor in order to save energy by cooling the temperature in the compression process. Combined with combined cycle technology, this method can even enhance overall efficiency by 1–3 percent, but it requires considerably more system piping and the complexity of heat exchanger equipment, making it cost-prohibitive to install. Thus, this technology is implemented in only a few large custom-built heavy-duty units [4]. Gas turbines coupled to electrochemical energy storage systems have become a mainstream optimization strategy in the multi-energy complementarily coupled application of modern power generation systems. Power regulation of electrochemical energy storage systems is measured in milliseconds and can quickly alleviate transient peak load changes on the grid, avoiding the problems associated with the frequent start-stop operation of gas turbines and long-term operation in low-efficiency and low-load regimes. Consequently, the total efficiency of integrated gas-energy storage power plants is raised by 8 to 12 percent [11]. The result comes out of multi-scenario system computation simulation. Deep coupling systems composed of a combination of high-temperature solid oxide fuel cells (SOFCs) and gas turbines are characterized by direct electricity production by the electrochemical reaction of fuel in the fuel cell, and the high-temperature exhaust gas is fed into the gas turbine combustor to further power it. This bypasses the efficiency boundary of the conventional Brayton cycle to achieve a full system efficiency of 65 to 70 percent in theoretical simulation [8] . Besides, there are also distributed micro gas turbines that come with solar thermal collector systems, whereby waste heat produced by the collectors can be used to preheat inlet air, decreasing fuel usage, improving the level of the renewable energy integration, and stabilizing operational efficiency [10].

3.3 Fuel and Operating Condition Factors

Gas turbine efficiency fluctuations in the short term are mostly due to variations in the physicochemical composition of the fuel, variation of the load ranges during the actual unit operation, and variation of the frequency of start-stop operations. Various fuel blends and operational environments result in various burning properties, which directly alter the conversion of chemical energy to mechanical energy. Natural gas, having a consistent composition and equilibrium calorific value, has historically served as a viable conventional fuel, allowing the unit to operate near design efficiency over an extended period. The experimental findings indicate that at a hydrogen level less than 7%, the combustion rate is quite stable, without the presence of flashback or thermoacoustic oscillations, which does not affect the unit efficiency considerably and may also be used to lower carbon output. But with hydrogen content higher than 30%, the rate of flame propagation is increased and the chances of flashback are considerably increased; thus, the load is decreased to ensure stable combustion, whereas the cost-benefit and efficiency of the unit are also diminished. With methane and ammonia co-firing, an increase in ammonia concentration can bring CO emissions to zero, but it reduces combustion activity and rate of reaction, raises the rate of incomplete combustion, and progressively lowers combustion efficiency as thermal and fuel-derived NOx emissions rise [6]. Load compatibility analysis indicates that various types of gas turbines have different optimal operating ranges [1]. Heavy-duty combined cycle units can achieve stable efficiency within the range of 70-100 percent rated load only when the air-fuel ratio, compressor operating conditions, and the turbine parameters are all designed to meet the requirements. Nevertheless, the efficiency would drop quickly with the load dropping to below 50% due to the fact that the compressor operation diverges from the design parameters, there is a poor distribution of the airstreams in the combustor, and the amount of burnt air is reduced. Aeroderivative gas turbines are designed to run at a rated full-load. However, when working at medium and low loads, i.e. 30%—50% load, the gas-phase operating state and combustion performance degrade, and the efficiency decreases by 10-20 percent [1]. Moreover, many short-term load changes and high-frequency start-stop regimes cause cyclic thermal stresses to combustors and turbine components, leading to cumulative thermal fatigue damage, slow deterioration of the performance of the components, and constant reduction of the baseline operating efficiency of the unit.

3.4 External Environment and Operation/Maintenance Factors

The external environmental parameters, including atmospheric temperature, humidity, salinity, and altitude, have a direct influence on the inlet air density and heat exchange conditions in the power unit. The degree of degradation of unit parts depends on the integrity of the unified operation and maintenance plan. Both these factors together influence the average annual operating efficiency, as stated in references [2,3]. With an increase in ambient temperature by 10 °C, air density also varies. At the same rotational speed, the mass of air entering the compressor reduces so that the output power falls by 3% -5% and the cycle efficiency decreases by 0.8% -1.2% as also reported by [2]. Due to their exposure to high-humidity and salt-spray environments during prolonged periods, offshore oil and gas platforms are susceptible to the invasion of salt into the system through the air and subsequent corrosion of the compressor blades. Based on the field data of domestically manufactured 2 MW offshore gas turbine demonstration unit, the rate of blade fouling and corrosion in the marine environment is 2 to 3 times higher than that in inland power plants. Absence of any specific anti-corrosion measures would lead to the increased annual efficiency decline. Low atmospheric pressure in high-altitude regions worsens the issue of insufficient inlet air, which is especially problematic to compact gas turbines with limited flow paths; the efficiency loss is greater in comparison to onshore facilities. In the context of operation, implementation of a data driven intelligent monitoring system allows managing equipment in its entire life cycle. Predictive maintenance can be achieved with real-time data to forecast equipment failures and provide timely preventative maintenance, including compressor water washing. More than 90 percent of the recovery of compression performance can be achieved after blade descaling to ensure effective operating efficiency. On the contrary, When the maintenance mode is incomplete or there is no standardization of inspection plans, a number of faults may be caused, including oil leakage due to lubrication, failure of the inlet filter, and drift of control system parameters. The combined effect of all these factors may lower the total unit efficiency by 5-15 percent. When it comes to various operating environments (offshore, inland, and plateau), the development of specific maintenance procedures has huge importance in the reduction of component aging and the achievement of long-term high efficiency in the work of the unit [2,3].

4. Major Bottlenecks and Future Development Trends of Gas Turbines

The three main bottlenecks have been identified in the Chinese gas turbine sector due to the dual-carbon objectives and the needs of domestic industrialization as high efficiency, low emissions, and indigenous development. Considering this, this paper suggests four specific directions of development that can be used to solve these issues.

4.1 Core Industrial Bottlenecks

4.1.1 High-Temperature Materials and Cooling Limitations

Domestic single-crystal superalloys with a high degree of resistance to high temperatures, creep, and corrosion are much lower quality than their imported counterparts, which means that they cannot be used under the conditions of hydrogen/ammonia combustion at 1500 degrees Celsius. Micro gas turbine rotor materials have inadequate strength and fatigue life, and this limits increasing rotating speed and efficiency [7]. Conventional film cooling and convective cooling technologies are poorly suited to the complicated conditions of high temperature, high humidity, and changing combustion conditions when burning zero-carbon fuels, and so are associated with poor cooling efficiency and large aerodynamic losses. Core thermal barrier coating technology and advanced porous cooling technology depend on imports, thus reducing the useful life of hot-section components.

4.1.2 Poor Compatibility with Zero-Carbon Fuels

Hydrogen has pure flashback and thermoacoustic oscillations, and ammonia has low flame propagation speed and ignition problems. Current combustors fail to provide steady zero-carbon combustion. Combustion of ammonia leads to a significant rise in NOx emissions that do not fulfill emission limits [6]. The possibility of hydrogen leaks and the corrosive nature of ammonia are possible safety threats to fuel delivery pipelines, pressure regulation equipment, and seals. The lack of full storage and transportation systems also limits the use of green hydrogen and ammonia on a large scale in offshore and distributed projects.

4.1.3 Deficiencies in System Integration and Localization

Critical parts, including turbine blades, recuperators, air bearings, and entire control systems, continue to depend on imports [9]. The domestic producers have only demonstrated application of 2 MW offshore gas turbines, do not have a developed accumulation of experience in large combined cycle and multi-energy complementary systems and the appropriate standards of testing and maintenance are not at international standards. The high initial investment expenditures and poor market profitability models make domestically manufactured gas turbines less competitive against wind power and photovoltaic power plants.

4.2 Future Development Roadmap

The gas turbine industry will develop in four integrated directions due to the three major bottlenecks outlined above, i.e., low-carbon transformation, energy efficiency improvement, intelligent operation, and full-scale localization. During the course of zero-carbon transformation, the advancement of micro-mixing and RQL (Rich-burn, Quick-quench, Lean-burn) low-NOx combustors is able to provide stable pure hydrogen/ammonia combustion, and combined systems that integrate gas turbines with CCUS, wind power, solar energy, and green hydrogen are going to be commonly used. To enhance the efficiency of energy usage, three-pressure reheat cycles will be advocated and implemented in heavy-duty units; ceramic waste heat recovery equipment may improve the efficiency of micro gas turbines beyond 40 percent; and new cycle technologies like supercritical CO2 and SOFC-gas turbine coupling will overcome the upper limit on energy efficiency. As far as intelligent operation is concerned, full-life-cycle monitoring, early warning of faults, and coordinated operation with electrochemical energy storage systems can be achieved by digital twin and artificial intelligence algorithms, which can help to satisfy multi-timescale grid flexibility requirements. Regarding the attainment of independent industrialization, the high-temperature alloys, rapid speed bearings, and automated control systems breakthrough will complete the entire localization of heavy-duty, aeroderivative, and micro gas turbine manufacturing, with the applications being offshore platforms, distributed combined cooling, heating, and power (CCHP), mountain railway traction, and emergency power supply [2, 9, 12].

5. Conclusion

With the "dual carbon" objectives, there are a lot of problems in the gas turbine industry, including low efficiency, a high level of reliance on foreign core technologies, and a lack of flexibility to use zero-carbon fuels. To address these concerns, this paper has reviewed and analyzed the structural classification, factors that influence the efficiency, and evolution of gas turbines in an organized manner.

The present research is based on dividing the gas turbines into three significant groups—heavy-duty gas turbines, aeroderivative gas turbines, and micro gas turbines—and comparing their structural features and the thermodynamic cycles that should be used in them. Using four dimensions, i.e., core component aging, cycle system design, fuel and operating conditions, and external environment and maintenance strategies, the study examines the trends that affect the change in efficiency. As the outcomes indicate, compressor fouling and creep of turbines at high temperatures are the predominant reasons behind the degradation in efficiency over time, whereas hydrogen-ammonia co-firing and low-load operation result in the oscillation of efficiency over time. The study has found three key industrial bottlenecks, including high-temperature materials, zero-carbon combustion, and system integration, and suggests four major directions of technological development: low-carbon and zero-carbon transformation, efficiency improvement, intelligent upgrade, and domestic substitution.

Due to the constant development of high-temperature materials and zero-carbon combustion technologies, it is anticipated that the domestic gas turbine will be able to make two progress in terms of energy efficiency and self-supply capabilities and offer important power assistance during the construction of the new power system and eventually become on par with and eventually better than the international advanced level.

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Conflicts of Interest

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