Analysis on the development of micro gas turbine generation technology

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Abstract. Similar to the structure of small aero engines, the existing micro gas turbines generally apply radial impeller machinery and regenerative cycles to improve efficiency. This paper analyzes the development of micro gas turbine generation technology. After making breakthroughs in basic research fields such as combustion, structural materials and coatings, additive manufacturing, thermal management, and comprehensive simulation and verification experiments, the next-generation micro cogeneration system composed of micro gas turbine and renewable energy power generation equipment will effectively obtain stable power output, improve power energy quality, and overcome difficulty in technology, economy, and application scenarios.

1. Introduction

A micro gas turbine is a small heat engine with a single power range of 25 kW to 300 kW. It uses gas or liquid fuel and has a series of technical features such as fuel diversification, low consumption rate, low noise, low emissions, low vibration, and low maintenance rate [1]. The modular components with a capacity of more than 1000 kW can be provided to meet larger load requirements through flexible integration and parallel stacking of multiple units [2]; at the same time, when it is used in cogeneration, the thermal energy of the micro gas turbine exhaust can be recovered to generate hot water or low-pressure steam which can be used effectively with absorption refrigeration system [3]. At present, there are more than 360 sites in the United States using micro gas turbines for cogeneration with a total capacity of 92 MW, accounting for more than 8% of the total number of cogeneration sites in the United States. It is the best way for multi-purpose small distributed power generation and micro cogeneration. This paper starts with the existing micro gas turbine power generation unit at home and abroad, and systematically states the development status and future trends in 5 basic research areas such as combustion, structural materials and coatings, additive manufacturing, thermal management, and comprehensive simulation and verification experiments, and 5 system integration areas such as unconventional thermodynamic cycles, system integration, operation and maintenance based on equipment status, digital twins, as well as digital threads and pipelines application, and key technologies in terms of improving power generation efficiency, enhancing compatibility with renewable energy, improving fuel flexibility, and reducing exhaust gas emissions.
2. Key technologies of micro gas turbine generation

Except for the difference in scale, lower compression ratio and lower combustion temperature, both micro gas turbines and large combustion turbines can operate under the thermal cycle (Brayton cycle) and share many of the same basic components including combined compressors/turbine units, generators, regenerators, combustor and heat exchangers, etc. In the Brayton cycle, atmospheric air is compressed, and it is heated by burning fuel (such as natural gas), and then used to drive the expansion turbine which in turn drives the intake compressor and the drive shaft connected to the generator. The National Academy of Sciences, Engineering, and Medical Sciences put forward the priority research areas covered by 2030 micro gas turbines, including combustion, structural materials and coatings, additive manufacturing, thermal management, comprehensive simulation and verification experiments and other research areas.

2.1. Constant volume combustion cycle

Combustion greatly impacts the exhaust emissions of micro gas turbines and controlling the use range of alternative fuels can have an important impact on operating limits [4]. Early research and development for combustion focuses on fuel injection technology which aims to ensure complete combustion without explosion by generating a stable flame. In the last decade, the combustion design method limited by the international nitrogen oxide emission has undergone a fundamental change, which promoted the development of micro gas turbine systems in the direction of pre-mixture design, and correspondingly changed the important research for flame stability, emissions, turbulent combustion and combustion chemistry. In addition, the in-depth study of the quasi-constant volume combustion cycle has promoted the detonation limit, detonation wave dynamics, and the transition from deflagration (combustion propagates at subsonic speed) to detonation (combustion propagates at supersonic speed). It is possible to ensure that the system can work in a high-temperature and high-pressure environment required for high-efficiency cycles with unrestricted transient response or speed, and can be suitable for a certain proportion of multi-component mixed fuel by improving the theoretical foundation research required for low-emission combustion systems (including constant pressure and supercharged combustion systems), as well as breakthroughs in shut-off rate, transient response and operating conditions [5].

2.2. Composite material containing ultra-high temperature ceramic matrix

Structural materials and coatings are critical to the development of gas turbines. The path temperature of hot gas can be higher and the combustion can be more thorough by developing silicon carbide fiber materials with low cost and high quality and the technology required to prepare ultra-high temperature ceramic matrix composite materials, thereby reducing fuel consumption by 2% and reducing the weight of turbine components more than 50%, increasing the efficiency by 10% [6]. At the same time, advanced superalloy materials such as high-entropy alloys, high-temperature titanium alloys, cobalt-based superalloys and refractory alloys can improve the efficiency of single crystal rims and multi-crystal hole rotors of micro gas turbines and reduce life cycle costs [7].

2.3. High temperature resistant additive manufacturing

Additive manufacturing has become a technological trend in global industrial applications. The 3D printing technology can be used to manufacture special parts for turbines so as to speed up design, increase component yield, control micro-structure morphology, and reduce performance variability. There are few structural materials that can be used under high temperature conditions now, but materials such as alloy 718 and Ti-6Al-4V that can be processed into directional solidification or single crystal form have shown superior performance. In addition, with the continuous improvement of additive processing technology with columnar particles or single crystal components, such as powder fusion technology using electron beam or laser heating, and directional deposition technology using powder blowing or wire feeding technology, the control for the material composition and micro-structure of high-temperature components of micro gas turbines will gradually be realized.
2.4. Thermal management
Developing advanced cooling strategies and quickly and economically integrating them into the gas turbine development and production process can not only increase the turbine inlet temperature of the micro gas turbine, increase the cycle pressure ratio, reduce the cooling flow of the combustor and the turbine, but also meet the lifetime requirements of the gas turbine, and further improve the efficiency of the thermal cycle. It is the general method to increase the turbine inlet temperature while maintaining the same cooling flow, or keep the same inlet temperature while reducing the cooling flow [8]. That is, under the constant turbine inlet temperature, improving the overall cooling efficiency can reduce the temperature of the metal parts and increase the lifetime, or under the constant metal temperature of the turbine parts, increasing the turbine inlet temperature and the overall cooling efficiency at the same time can extend the lifetime of the parts. Especially the turbine inlet temperature and the cycle pressure ratio can be increased by developing advanced fully conjugate heat transfer technology, and optimizing the design of the combustion chamber and turbine cooling configuration. In addition, a recuperator installed in the micro gas turbine (power $\leq 300$ kW) can effectively reuse the waste heat of the gas generated from turbine. According to the effect of thermal exchange, the compressed cool air can be heated by waste heat which can increase efficiency of the micro gas turbine from 15% to 20%~30%. However, due to the low density and low thermal conductivity of the gas, the heat exchange process of the gas proceeds slowly. Hence, the plate-fin heat exchanger or primary surface recuperator are often used to improve the thermal conductivity of the gas.

2.5. Simulation based on physical model
Ten years ago, a multi-ideal comprehensive simulation has been performed by scholars for the combustor and diffuser of a gas turbine engine using the large eddy simulation method, and the Reynolds average stress computation is performed for rotating machinery [9]. With the rapid development of fluid dynamics and high-fidelity computing capabilities based on physical models, the interaction and off-design operating conditions of simulated gas turbine modules have been gradually realized. By capturing the interactions among the gas turbine modules, including characteristics like dynamic coupling, flow distortion, unexpected heating or loading, as well as thermoacoustic instability, scholars have deeply explored the factors causing the combustion instability of GE 7HA heavy gas turbines and provided more immediate detailed data, which lays a foundation for the test and calibrate of standard single-module and multi-module configurations applying high-fidelity numerical simulation tools, and for the improvement of degree for system coupling [10]. In the future, simulation modeling for turbulent combustion, wall heat transfer, interaction among wall, particle and turbulent flow, surface roughness and injection atomization of liquid fuel, as well as large data mining research based on equipment status can greatly reduce the number of experimental investigations, reduce costs, and shorten the design cycle [11].

3. Hybrid power system

3.1. Technical progress of hybrid power system
The heat loss of Brayton cycle in the gas turbine is closely related to the irreversibility of combustion. The combustion efficiency can be improved by using fuel cells, especially for solid oxide fuel cells, namely, fuel cells can directly generate electricity and hot gas, the remaining unreacted gas enters the turbine after being burned in the burner which can expand and generate power to improve burning efficiency. Although the research contents of the gas turbine hybrid power system are limited [12], for the hybrid power system in a solid oxide fuel cell and micro gas turbine hybrid power systems ranging from 250kW to 1MW based on the contribution of fuel cells, the efficiency may be various ranging from 55% to 60 %. As for 5MW~10MW gas turbine, the efficiency may vary from 55% to 60%, but the efficiency will be increased to around 68% when the gas turbine is coupled with a solid oxide fuel cell. The total efficiency of thermoelectric combination can reach 85%~90%. The emission of NOx is largely determined by whether the combustor is used in the hybrid system; however, its emission is significantly
lower than comparable conventional gas turbines in any case [13]. The coupling of fuel cell and micro gas turbine is not as simple as replacing the combustor with fuel cell. Additional design and development constraints will appear when the two components are integrated. Selecting the topping system as an example (showed in Figure 1), the air pressure at the cathode inlet of the fuel cell is generally increased by the compressor, part of the fuel and air will be consumed by the electrochemical reaction in the stack, and the unreacted gas will be mixed and burned in the burner and enter the turbine. In this process, after the electrochemical reaction participated by the air and the fuel under the high-pressure condition, the power output of the fuel cell will increase. The effective use of energy and the reduction of various electrochemical losses will improve the efficiency of the entire system [14].

Many companies have carried out prototype design and testing for solid oxide fuel cells and hybrid power systems of micro gas turbines, and a number of experiences have been obtained. As of the end of 2019, relevant work results can be roughly divided into two types. The first one is that complete hybrid system prototypes have been formed in companies such as Westinghouse Electric Corporation, Rolls-Royce Fuel Cell Systems, and Mitsubishi Heavy Industries. The other is that the development of some companies is the process, but only some components are involved.

3.2. Problems with hybrid power technology

Over the years, the technical field has focused their analysis on component manufacturing, maintenance costs, reducing technical costs, and expanding market penetration and other aspects in terms of the thermal economic of the solid oxide fuel cell and micro gas turbine hybrid power system. There are even many contradictions and even incompatible conclusions among scholars due to changes in technology and costs. There are different views on the cost of micro gas turbines [15]. Through analysis of 6 machines in the range of 301 MW, it is found that the equipment costs are various ranging from 1251$/kW (1MW machine) to 1896$/kW (30kW machine). If heat recovery and gas compression systems are included, then the total equipment cost will be 1,710$/kW~2289$/kW [16]. Moreover, the facility costs will be inevitably further increased considering labor, materials, installation project/management, engineering activities, project emergency, financing and other costs. If the scope of the factory, local emission requirements and other requirements related to the installation site are included, it is estimated that the cost may be 787$/kW for 1MW machine, and 1,611$/kW for 30kW machine. When fuel cells are in stationary applications, solid oxide fuel cells and molten carbonate fuel cells are the most suitable fuel cell types for distributed power supply (output power> 10 kW) [17]. For a 100kW planar solid oxide fuel cell with a current density of 0.4A/cm², the total cost of producing the solid oxide fuel cell system at a rate of 100 sets/year is 2275$/kW where the stack accounts for 31.8%, fuel and air supply components account for 6.7%, fuel processing components account for 5.4%, heat recovery components account for 13.9%, power electronics, control and instrument components account for
34.9%, component assembly activities and additional engineering account for 7.3%. However, the current density of the SOFC is relatively lower (close to 0.25 A/cm²) in some actual situations, hence, the cost for the solid oxide fuel cell stack in the hybrid power system may be close to 3000$/kW due to the additional stacks cost required for increasing voltage. Based on the above problem, in order to solve the problem of the cost, improving the scale of the production to increase scale economies could be an effective solution to significantly reduce system costs. For example, the cost for producing 50,000 sets/ year will drop by about 37%.

There are still challenges in terms of the reliability and availability of hybrid systems. Reliability refers to the probability that a device can fully achieve its purpose within a fixed time under the operating conditions encountered. Reliability evaluation is a very broad subject and an important part in design and development of any new engineering system. When conducting reliability research, the types of systems are divided into two categories: task-oriented systems and continuous operating systems. The cost of the solid oxide fuel cell in the hybrid and micro gas turbine hybrid power system is a continuously operating system, and a large number of system failures may occur [18]. Therefore, it is required that the fault shall not occur frequently or shall not last too long.

At present, there is no micro gas turbine which can optimize coupling with solid oxide fuel cells. Therefore, the retrofit of a commercial gas turbine may bring important restrictions on the size of the stack, or there will be a significant reduction in efficiency due to the need for exhaust or bypass methods [19]. In order to avoid component damage or significant life degradation, several additional performance constraints must be considered [20]: factory layout, component layout and constraints, attribute range and control equipment. Another important limitation is related to chemical composition and kinetics, because it is necessary to keep the flow composition within a very narrow range for effective stack operation. For example, even if methane can be directly used as fuel for the solid oxide fuel cell, electric considerations regarding specific consumption issues indicate a slower reaction rate, implying that it is important to maintain a large amount of hydrogen in the anode (produced by steam reforming and shift reactions). In addition, any change of fuel cell thermal exhaust (i.e., the thermal energy of the exhaust gas flow) due to the transient state of the fuel composition may affect the stability of the turbine cycle.

Another challenge in developing hybrid system is the control system [21]. Due to the complexity and related issues of system integration, it is necessary to specifically carry out in-depth research activities in terms of system dynamics as well as appropriate design appropriate control for hardware and algorithms. The main challenges to determine the transient thermal control of the engine include non-design performance, multi-shaft gas turbine configuration, gas turbine pressure ratio, mass flow matching, etc. [22].

There are strict lifetime requirements for solid oxide fuel cells that have been successfully commercialized. Performance degradation at high temperatures is caused by various problems and proceeds through complex pathways, including the degradation of a single material, the interaction of multiple components, and the response to pollutants from external environment. In the past few decades, scientists have tried to clarify the mechanism of performance degradation and identify various reasons of performance degradation [23]. It must be pointed out that the degradation of the solid oxide fuel cell has an important impact on the hybrid power system, because a longer service life of the solid oxide fuel cell and micro gas turbine hybrid power system (accompanied by high performance) can make up for the high cost of components compared with traditional power plants.

4. Conclusions

According to the above analysis, it indicates that the valve and timing mechanism of the micro turbine is not complicated, and the power generation efficiency of the micro turbine is able to increase from 31% to more than 80% if the waste gas can be reused by the co-generation technology. Meanwhile, due to the wide fuel adaptability and the high operating temperature, the solid oxide fuel cell is often combined the micro gas turbine to effectively utilize the heat and exhaust gas generated during the operation of the system, so that the dual goals of improving work efficiency and reducing pollution emissions can be
achieved. On the other hand, the problem of the thermal management control and the hybrid power technology of the micro gas turbine still need to be solved.

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