Application and Optimization of Stationary Gas Turbine

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Abstract. The gas turbine is a kind of efficient heat engine that has occupied a wide range of fields. Compared with other traditional heat engines, gas turbines are characterized by high thermal efficiency, operational flexibility, free fuel options and low pollutants and achieve an irreplaceable position in modern industrial production. The stationary gas turbine is mainly used for power generation and fits many additional units with ample space in plants. So far, many improvements on different parts of stationary gas turbines have been applied to practical production. Excellent high-temperature resistance materials are used for the blades themselves and the coatings. The cooling technique is also well developed so that blades can endure higher temperatures for higher thermal efficiency. Despite the flame instability, annular combustors are widely installed in stationary gas turbines for better combustion process. The monitoring method and cooling rings are applied to prevent the deformation of flame tubes and timely maintenance to ensure normal working conditions. Combined heat and power (CHP) is a better gas turbine-based system to supply both heat and electricity. But it has some efficiency problems when electricity demand changes. The possible solution may lie in units preheating and peak-shaving.

Keywords: Stationary gas turbine; power generation; application; improvement.

1. Introduction

The gas turbine is a kind of rotary heat engine based on the Brayton cycle. It uses air and gas or other fluid as a working medium and mainly consists of three parts: turbine, compressor and combustor. The concept of the gas turbine was first proposed in 1791 by Barber, but until 1939, the gas turbine was put into application after several improvements in the thermal efficiency and heating method. The first practical gas turbine for power generation was built in Neuchatel, Switzerland, and the test flight of a gas turbine-powered plane succeeded in Germany, both in 1939 [1].

With the development of high-temperature resistant materials and turbine cooling techniques and combination with other thermal cycles, the thermal efficiency and single-unit power of gas turbines have been constantly upgraded. Nowadays, the gas turbine and its based system have been widely used in various industrial production and power supply and have achieved irreplaceable status in many fields for high thermal efficiency, multiple fuel options, operational flexibility, low emission of pollutants and many other outstanding advantages [2].

Compared with intermittent combustion and reciprocating piston motion and the resulting unbalanced inertial force in spark ignition (SI) engines or compression ignition (CI) engines, the gas turbine employs a continuous combustion process and unidirectional rotation, so it has good mechanical inertia, improving mechanical transmission efficiency and life. As a result, the gas turbine can have a longer service life and lower mechanical wear and the scale and maximum power can be boosted thanks to the excellent mechanical transmission and combustion mode. The stationary gas turbine is used mostly for power generation because it is fixed on the ground and inconvenient to move, so it is mostly installed in power plants instead of airplanes or locomotives.

2. The Improvements on Parts of Stationary Gas Turbine

2.1. Shaft

The gas turbine is progressively assembled around a central shaft. So when the turbine turns, it turns the compressor with it. That is to say, some parts of the work are used to drive the compressor, and others are exported. There are also multi-shaft gas turbines, with one directly connected to the power generator and others driven by exhaust gas emitted from the upstream.

2.2. Compressor and Turbine

Compressors and turbines are made of many stages, and one stage consists of a row of rotating blades for energy conversion and a row of stationary blades for guiding and accelerating the airflow. While the blades of turbines and compressors work at high temperatures for a long time and are subjected to huge centrifugal forces brought by high-speed rotation, the material selection of the blades is very demanding. The temperature of the gas entering the turbine determines the efficiency. So, if the material can tolerate higher temperatures, the efficiency can be further upgraded. One way is to coat the surface of the blade with other high-temperature resistant materials, such as the ultra-high temperature ceramic layer and oxidation-resistant metal bonding layer, which can tolerate 1300 degrees Celsius [3]. But the highest temperature in the combustor can be reached to 2000 degrees Celsius, which is still far beyond the maximum temperature the blades can withstand. To bridge the gap between the tolerable temperature of materials and coatings of the blades and the maximum fuel temperature from the combustor, cooling techniques should be applied to the blades to prevent thermal damage and ensure normal working conditions. Cooling methods fall into two broad categories, and most gas turbines use both of them: internal and external cooling methods.

External cooling mainly uses gas film cooling. The cold air is sprayed into the mainstream in a certain direction near the wall. The cold air bends downstream under the pressure and friction of the mainstream and adheres to the wall. It forms a cold air film with low temperature, separates the wall from the high-temperature gas and takes away part of the radiation heat from the high-temperature gas or bright flame on the wall, thus playing a good protective role on the wall. This type of cooling is called film cooling. Stationary blades, especially located downstream of the combustor, tolerate the maximum fuel temperature and need efficient cooling. Drost's research suggested single or double-row holes on the suction surface and single-row holes on the pressure surface to ensure that the film holes are inclined in the mainstream direction [4]. This enlarges the film cooling area on the blades and improves the cooling efficiency. Compared with the stationary blades, the cooling technique on rotating blades is more complex because the blades are affected by centrifugal force and other forces and the state of air flowing into the gas film hole is greatly changed, leading to a distinct flow and heat transfer characteristic from stationary films.

Another mode is the internal cooling. It makes use of various features to enhance the internal heat transfer in blades. An important device is the rib turbulator. It's applied on both the suction and pressure surfaces. The rib turbulators separate the flow from the heat transfer surface first and then reattach the flow to the surface. These separation processes reattach the boundary layer to the surface and, as a result, enhance heat transfer. Like external cooling, the internal cooling on rotating blades is more complex considering the continuous rotation and disorder of airflow, such as Coriolis vortices from rotational effects [5]. The used turbine's rotation speed is limited between a narrow interval because it has to be coupled with the generator. But now, with the gearbox, the turbine can freely choose the rotation speed (power lower than 100 MW for the limited mechanical load).

2.3. Combustor

For the combustor, it has to endure persistent high temperatures because of the continuous combustion process. What's more, the space limitation of energy and requirement for large power brings huge gas flow and a large amount of heat transfer. So, the material selection and design of combustors are very difficult. A kind of combustor is evenly distributed in a ring around the shaft for uniform temperature distribution and excellent ignition sensitivity. This is called an annular combustor, which is widely used in stationary gas turbines. With a bigger volume per unit surface, the annular combustor enjoys the least pressure drop and, as a result, is more efficient than other types [6]. The fuel and gas are premixed before they enter the combustion chamber. But this results in the risky higher flame instability, so it is seldom used in aeroengines or locomotives because these involve high-speed moving or bumping and increase the risk. The stationary gas turbine is fixed to the ground, so it is relatively safe.

For environmental performance considerations, the power generation plants mix lean air with fuel first before they enter the annular combustor, and this process, to some extent, causes some problems with high-amplitude pressure pulsations, which reduce the overall combustion stability. The high-amplitude pressure pulsations will lead to fatigue damage on combustors [7]. The cooling ring is applied along the liner to reduce the high temperature and ensure that the working stress is lower than the yield stress [8].

3. Application of Advanced Stationary Gas Turbine

A lot of excellent and unique characteristics, such as high thermal efficiency, multiple fuel options and operational flexibility, lead to different applications of stationary gas turbines from others. For all types of gas turbines, there are two iconic and important applications: jet engines for the aero industry and combined cycle power plants for electricity generation. The latter is the major application of stationary gas turbines nowadays.

The stationary gas turbines used for power generation vary in a wide range from a few kilowatts (microturbines) to several hundred megawatts (large, heavy turbines) in power. So far, the maximum power of a single gas turbine has come to more than five hundred megawatts. That is to say, a combined power generation cycle concluding heavy stationary gas turbines can easily reach hundreds of megawatts of working power. Due to considerable economic benefits coming from the high efficiency and large generation power, heavy stationary gas turbines have occupied the majority of the traditional power generation industry. A common combination model is one or several gas turbines paired with a steam cycle system. This joint mode takes full use of the heat energy of the gas and further improves the energy efficiency on the base of stationary gas turbines.

Although the stationary gas turbine is fixed on the foundation and can't move, this provides enough space to add thermal efficiency improvement units such as reheating, inter-cooling, regeneration multistage compression and other combined cycle systems like the steam cycle. It also doesn't have to put the ratio of weight and power as the priority, which is relatively significant on the aeroengines. Despite the flame instability of annular combustors, the power generation plants still choose the annular combustors for the better combustion performance they provide, the relatively steady and safe production by stationary gas turbines and more convenient and comprehensive maintenance and overhaul.

The flame tube affects pressure loss, mixing area, and turbulence intensity, which in turn affects combustion efficiency. An increase in widths and resultingly blockage ratio can enlarge the direct influence factor before. In real application and production, the flame tube will also bear fatigue damage under the influence of high-amplitude pressure pulsations [9]. Buckling may appear on a flame tube and can be a fifth of the entire pipe. This deformation seriously affects the combustion efficiency of the combustor and the entire efficiency of power generation. So, a monitoring method was established in many power plants to keep an eye on the combustor and flame tubes. The modeling approach is used to simulate the deformation of the flame tube so that the designers can judge and strengthen the weak part.

4. Practical Application of CHP

Nowadays, it is relatively difficult to improve the thermal efficiency of one single gas turbine for the technique limitation. So, people tend to combine it with other cycles and establish a combined system to raise the efficiency of energy use further. CHP is an important system based on gas turbines to use the energy better. Its core is to reuse the heat from the exhaust hot gas emitted.

One mode is that one or several large turbines in the CHP power plants replace the scattered boilers and thermal power plants in the surroundings. The large gas turbines supply both electricity and heat to the industrial district or city nearby. Considering the transportation cost and loss, the distance should not be too long. The loss mechanism of gas turbines has a minimum metric and does not vary with geometrical size, so the efficiency of large gas turbines is absolutely higher than that of the smaller ones. Besides, the CHP power plant works better on efficiency than traditional thermal power plants. So, this mode steps up a new ladder in energy utilization.

A good example is the underground steam system in New York City by Consolidated Edison Energy Company. It distributes about 66 billion kilograms of 180 degrees Celsius steam annually to 100,000 buildings in the borough of Manhattan, and about 50 percent of the steam comes from seven CHP power plants. It improves the fuel efficiency of electricity, thus reducing the emission of pollutants. While this mode also has some limitations. Only when there is sufficient demand for electricity and heat in the immediate area can this mode work well, or the loss will outweigh the gain compared to traditional power plants because of the cost and loss of long-distance transportation.

The other mode is called Distributed Energy Resources (DER). Some micro gas turbines are installed in residential houses, small businesses or hotels to displace the traditional boilers and convert fuels to both electricity and heat. The excess electricity can be sold back to the grid. This mode can also be combined with solar photovoltaic (PV). It has the potential to reduce energy waste in existing electricity and heating systems radically.

5. Problems in CHP Systems and Promising Solutions

However, there are still some problems in CHP that need to be solved. In China, the electricity power and heat power are coupled, and the heat power determines its overall power, so the system has a poor flexible peak-shaving ability, especially during the peak heat-supplying period [10]. When there are changes in demand for power supply and heating, the combined units need a long time to adjust the output power because of the huge inertia and low sensitivity. Besides, there is a considerable amount of cold source loss in most cogeneration units, especially those remolded from single power generation units. The extraction parameters are much higher than the demand side, and the following throttling step-down causes great exergy damage. All the factors above affect the economic benefits of the units and reduce the energy efficiency of power generation when facing demand changes.

The heat storage tanks partly solve this, but the total heat production goes down [11]. Besides, the way for electricity-heat conversion to make up for the lack of heat production is of very low thermal efficiency, seriously affecting the thermal efficiency of the system. So, it is not a fundamental solution. An important solving idea is to shave the peak. The electric boiler method and direct steam extraction method are both relatively effective compared with their low investment. On the other hand, the absorption heat pump waste heat recovery method and the electric heat pump waste heat recovery method require more investment and accordingly have a better heating process, with the latter method being the best for less limitation.

Another promising idea to face the peak of the electricity demand is to shorten the cold start requirement time. The plant sets an additional tube from the steam cycle to the gas turbine for preheating. The preheating steam acts on high-pressure cylinders and medium-pressure cylinders. After the preheating, the steam flow enters the low-pressure cylinders and gas turbines to do work. This is a highly effective method because it reduces the cold start requirement time by about 2 hours, enabling the combined power generation system to cold start rapidly and to give a quick response to peak regulation of the power network. Besides, the steam preheating system has good adaptability and does not conflict with the original control system when embedded in the original unit. Computer modeling and intelligent analysis is also good way to do a simulation for the whole plant and production line. Managerial personnel can set and input parameters as influence factors so that they can monitor and look for potential problems in the model. Different algorithms can also be applied to model and use the powerful computing power of the computer to optimize the entire unit.

6. Conclusion

The major application of stationary gas turbine is the power generation. And for its characteristic of no consideration of space and ratio of weight and power, additional units can be applied to it. Improvements in nearly all parts of gas turbines jointly promote the optimization of gas turbine units. High-temperature-resistant materials and coatings provide blades with a fitting working environment. Advanced cooling technique, including both internal and external cooling technique, bridges the temperature gap between hot gas and the maximum allowable temperature of blades. Applications of annular combustors improve the combustion performance, and monitoring devices on the deformation of flame tubes, to some extent, decrease the negative influence brought by flame instability.

A major application is the CHP. It connects gas turbines with steam cycles to make full use of the heat of exhaust gas emitted. The gas turbine-based system has two main modes, centralized and distributed energy resources and can raise the thermal efficiency to 80 percent to 90 percent. But when it comes to peak regulation of power networks, the system cannot efficiently produce and deploy heat and power resources due to a positive correlation between heat power and electricity power. Heat storage is a temporary solution at the expense of thermal efficiency and exergy and economic benefits. The promising solution first lies in the unhooking of electricity and heat so that the power range will not be limited by heat power. Secondly, waste heat recovery units can help to shave the peak to strengthen the capacity to respond to the changing demand for electricity. Thirdly, taking steam from the steam cycle as preheating resources for high-pressure cylinders and medium-pressure cylinders to shorten the cold start requirement time by about two hours. This enables the unit to give quick responses to demand changes.

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