Current Status and Prospects of Gas Turbine Technology Application

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Abstract. The gas turbine is widely used in various fields, including powering aircraft, ships, trains, and electrical generators. This paper reviews multiple researches about two usages of gas turbines, including power generation and propulsion in aerospace. To be specific, two types of gas turbines have been considered in the power generation section. The first one is the micro-scale turbine, and its working principle has been introduced in section 2.1.1. In addition, six diverse kinds of gas turbines, sorted by a different manufacturer, are introduced in 2.1.2, and it has been found out that, compared to its counterpart, EnerTwin is obviously more sustainable. At the same time, both of them generally cost the same. The second type of gas turbine is used in a combined cycle power plant (CCPP), a popular power station. The working principle of CCPP is introduced in 2.2.1, while several optimization methods are illustrated in 2.2.2, including solar thermal power methods and other novel methods. The result indicates that the most popular method of optimizing the combined cycle gas turbine is integrating an additional unit. One of those outstanding technics is the integrated solar-combined cycle, contributing to 64% of fuel saving with 2.8% of output reduction.

1. Introduction

The gas turbine is widely used in various fields, including powering aircraft, ships, trains, and electrical generators [1, 2]. There are a lot of advantages it has. For example, the small size makes it more convenient than most reciprocating engines [3], low lubricating reduces maintenance costs, and the exhaust's waste heat can be used to improve efficiency [4]. Generally, the gas turbine is a continuous and internal combustion engine whose working cycle is assumed to be the Brayton cycle. Four thermodynamic processes are isentropic compression, isobaric combustion, isentropic expansion, and heat rejection [5]. And gas turbine has three main components, compressor, combustor, and a turbine on the same shaft as compressor [6].

From various types of gas turbines, the micro gas turbine is a new kind of energy-saving and environment-friendly power supply [7], which is suitable to apply in urban, rural, and remote areas. It has been one of the most promising technologies globally for power generation, and the requirements of installation gas grow every day [8]. As for the large-scale power plants, installing renewable power plants is ascending extremely fast, and relevant research is also publishing unprecedentedly fast. However, the instability of renewable power generation is still an unconquerable difficulty under the...
modern technological level [9]. It has been widely acknowledged that a steady electrical power supply is the foundation of modern industrial manufacture [10]. Although the power plant, which is based on unrenewable fuels, has many drawbacks in the environmental aspect, the climatic independence, which is a sign of stability and geographical flexibility, is a very outstanding advantage. Hence, the continuous research and optimization which focus on the unrenewable power plant are vital for industrial maintenance and development [11]. Compared to the conventional power station, which only uses the steam turbine, CCPP has many outstanding merits, including high efficiency.

This article reviews the current development of gas turbines from two parts: power generation and aircraft propulsion. The working principle and status quo of micro gas turbines and combined cycle power plants are analysed in detail, and the future development of gas is forecasted to lay the foundation for the further development of gas turbines.

2. Microturbine

2.1. Principles of Micro Gas Turbine

Looking at the components of a micro gas turbine, all kinds of gas turbines generally have the same components, like compressor, combustor, and turbine. Compared to conventional design [12], the micro gas turbine system has several special designs to improve its ability. For example, most gas turbines use axial compressors and turbines, but micro gas turbines use the centrifugal compressor and centripetal turbines [11]. Although the axial compressor is compact, safe, and efficient, it is more suitable for large flow. In contrast, the centrifugal compressor has such advantages as small volume and high single-stage pressurization. Moreover, the centripetal turbine is also more suitable for the micro turbine, as the small flow loss and residual velocity could improve the efficiency, especially for the flow in a small volume. According to the working principles, there are two kinds of gas turbine, simple gas turbine, and generative gas turbine. They can be operated on both open and closed cycles, while the open ones are more common [13].

For the open simple gas turbine, the air is continuously drawn into the compressor, where it is compressed to high pressure. Then, the compressed air flows into a combustion chamber, which will be burnt, resulting in combustion products at an elevated temperature. The combustion products expand through the turbine and are discharged to the surroundings. Part of the turbine work developed is used to drive the compressor, and another is used to generate power, drive the vehicle, or supply electricity. The workflow is shown in Figure 1.

![Figure 1. Workflow of the simple gas turbine](image)

The open, generative gas turbine has an additional part when working, the generator. As the temperature of exhaust from the turbine is normally well above the ambient temperature, it always causes loss irrevocably when the gas is discarded directly to the surroundings. However, the generator avoids this potential loss, which makes the exhaust preheat the air in the compressor before entering the combustor, reducing the amount of fuel required. From the workflow of the generative gas turbine in Figure 2, it is clear that there are basically the same steps as the previous simple one. Still, the exhaust will not be expelled directly but flow into the regenerator to preheat air in the compressor. To a large extent, this design increases fuel use efficiency and becomes more sustainable [14].
If ignoring irreversibility when air passes each component, in other words, there is no pressure drop by friction, and the air is at constant pressure through the heat exchangers. And if the stray heat transfers to the surroundings are zero, the processes through the turbine and compressor could be isentropic. The whole working cycle is assumed as the ideal Brayton cycle, which is drawn in Figure 3. There are totally four stages in the Brayton cycle, 1-2 is the compression process at constant entropy in the compressor, whose pressure ratio is $p_2/p_1$, 2-3 is the endothermic process at constant pressure in the combustor, 3-4 is expanding at constant entropy in the turbine, whose temperature ratio is $T_3/T_2$, and 4-1 is exothermic process at constant pressure.

On the T-s diagram, area 2-3-a-b-2 represents the heat added per unit of mass, and area 1–4–a–b–1 is the heat rejected per unit of mass. On the p–v diagram, area 1–2–a–b–1 represents the compressor work input per unit of mass, and area 3–4–b–a–3 is the turbine work output per unit of mass. The enclosed area for the former is the network, and the latter is the heat added per unit of mass.

2.2. Current Status of Micro Gas Turbine

Distributed generation and combined heat and power generation (CHP) are two popular aspects of micro gas turbines, that they have gradually substituted some traditional machines. There are three microgrid benefits summarized, energy security, economic benefit, and clean energy integration. The most popular example of developing microgrids is the ‘New York Prize’, a $40M competition initiated by New York State to push the microgrid from feasibility studies to implementation [15]. For CHP, it is an environmentally friendly generation way that mainly uses renewable energy, such as solar, biofuel, and biomass. For example, biomass is a decomposable matter from plants or animals, avoiding NOx and Sox emissions in the combustor [16].

The micro gas turbine is applied in lots of CHP and microgrids. On the one hand, although the micro gas turbine is slightly inefficient at generating electricity, the energy utilization rate of the cogeneration system could exceed a lot of large units, which makes it is sustainable and suitable for applying in the city, countryside, and even remote area. On the other hand, it is lighter and has fewer rotating parts compared to internal combustion engines, so avoid expensive operation and maintenance costs. Hence, combined heat and power generation is a powerful competitor for an internal heat engine.
With the development of technology and the sustainable consciousness of the human, there are different kinds of micro gas turbine products invented and sold in several companies. Nowadays, the leader in the micro gas turbine market is Capstone, followed by Flexenergy, with a market share totally more than 95%. And from the forecast by Forecast International to 2029, the market share of both companies will increase more and more [17].

Table 1. Market Share in 2029.

| Company     | Total Sales volume | Production Value (Million dollars) | Market Share (%) |
|-------------|--------------------|-----------------------------------|-----------------|
| Capstone    | 3480               | 5.2057                            | 72.8            |
| Flexenergy  | 407                | 1.239                             | 17.3            |

Moreover, Forecast International projects a jump from the range of 600 to 750 per year to between 900 and 1,050 from 2021 to 2029. This leap is partly attributed to two European companies, Bladon and Micro Turbine Technologies (MTT), entering the market. Therefore, in this report, several representative companies and their products will be chosen for analysis, includes the famous companies, Capstone and Flexenergy, a newly developed company, MTT, and a Chinese company, ENN Power.

3. Combined Cycle Power System

3.1. working principle of CCPP

The combined cycle is shown on the T-s diagram in Figure 4. The upper cycle (1-4) is a Brayton cycle, and the lower cycle (a-f) is a Rankine Cycle. For the Brayton cycle part, in processes 1-2, the injected air is compressed and gains relatively high pressure. In processes 2-3, intensive combustion of syngas (a combination of injected air and fuel) occurs in the combustor. In processes 3-4, combustion, which has ultra-high temperature and pressure, expanded in the gas turbine and produced work. In progress 4-1, the exhaust gas pours out of the gas turbine and enters the HRSG. Thus, processes 4-1 are the “connection” of the Brayton and Rankine cycles in the CCPP.

Figure 4. T-s diagram of the combined cycle

For the Rankine cycle part, process a-d occurs in the HRSG. Specifically, a-b mostly occurs in the economizer and water-cooling wall where the supercooled water becomes saturated water and stored in the steam drum. Process b-c mostly occurs in the water-cooling wall where evaporation happens. The steam and liquid phases are separated in the steam drum, and the steam goes to the superheater where process c-d occurs. The saturated steam becomes superheated in the superheater, and it will drive the steam turbine to rotate in process d-e. The process e-f means the exhaust steam becomes liquid phase in the condenser (cooling tower), and it will be pumped back to the economizer.
Figure 5 is a comprehensive diagram of CCPP. From the knowledge of combustion, it has been proved that the theoretical temperature of combustion will increase if the injected air is preheated. Thus, an air preheater is built at point 1, which is the inlet of the compressor. After that, the injected air gains a higher pressure at point 2, which is the compressor. Then, the intensive combustion of syngas, which combines air and fuel, occurs in the combustor (Point 3). The combustion produces exhaust gas with ultra-high pressure and temperature to drive the turbine at point 4. The shaft on the turbine, which is connected to the generator, enables the generator to rotate with the turbine simultaneously to produce electricity. The pressure of exhaust gas decrease because it has already driven the turbine. However, the temperature is still high enough to heat the steam.

The blue tube (Point 5) in the HRSG is the economizer, and part of the supercooled water becomes saturated in these tubes. The saturated water is stored in the steam drum and evaporates in the water-cooling wall (Point 6). The steam phase and liquid phase get separated from each other in the steam drum. After that, the steam acquires a very high temperature and pressure in the superheater (Point 7). The superheated steam drives the steam turbine in point 7, producing electricity like the gas turbine. The exhaust steam gets cooled and becomes a liquid phase in the condenser. Finally, the liquid water is pumped back to the economizer.

![Figure 5. A comprehensive diagram of the CCPP [18]](image)

3.2. Current status and relevant research of CCGTs

The efficiency of the gas turbine is relatively high. Specifically, General Electric (GE) manufactured a 605 MW turbine (9HA) with an efficiency of 62.22% when its temperature is as high as 1540°C [19]. In 2018, GE founded an 826MW turbine (9HA.02), which has over 64% in the combined cycle. And this progress was due to the manufacturing and combustion breakthrough [20]. In addition, the 7HA turbine from GE achieved a gross efficiency of 63.08% in March 2018 [21].
3.2.1. Optimizing CCGTs through solar thermal energy. As the prices of fossil fuels and natural gas are increasing, there is an ascending interest in improving the efficiency via renewable energy, including concentrating solar power (CSP) [22]. The novel concept of integrating solar thermal energy in CCPP is called the ISCC (Integrated Solar-Combined Cycle). Compared to a single CSP plant or a CCPP plant, ISCCs have some additional advantages. Including a higher thermo-dynamical efficiency [22] and a lower cost of integrating a heliostat field in an existing CCPP than building the entire CSP plant [23]. It is worth noting that upgrading the CCPP via CSP is not contradictory to what is mentioned in section 1 because the CCPP is an independent system that can function steadily with or without the additional CSP system. Figure 6 is a typical ISCC with parabolic troughs with thermal oil as the heat transfer fluid (PT-HTF).

![Figure 6. ISCC scheme with solar field using PT-HTF technology [22]](image)

Ahmad M. Abubaker et al. [24] integrated a CSP system into a CCPP system. Specifically, parabolic trough collectors (PTCs) were installed to preheat the air at the inlet of the combustor chamber. The PTCs were then used to control the temperature of the compressor’s inlet by driving an absorption cooling cycle (a single effect LiBr/H2O system). Their result indicated that a 7.2% increase in thermal efficiency and a 27.7 MW ascent of power output were achieved. They also established a highly accurate equation, which is based on linear regression, to predict the system’s performance. They claimed that the optimum thermal efficiency was in the range of 53.1%-61.11% with a capital cost of 86.5-158.3 Mil$. Finally, they defined a favorable optimum point at an efficiency of 57.86% with a capital cost of 131.8 Mil$, and the payback period equals 2.8 years, which means it is a feasible novel cycle.

Evangelos Bellos et al. [25] established analysis and optimization on a solar-assisted gas turbine. PTCs are included in the model to achieve less consumption of fuels and a more environmentally friendly system. Their research aims to find the minimum size of the heliostats field while achieving a relatively appropriate fuel consumption. Their final result indicated that a gas turbine that integrated a CSP system which consists of 1050 heliostats, consumes 0.3389kg/s of natural gas and produces about 14.81 MW of electricity. When comparing the upper data to the initial gas turbine, which produces 15.27 MW of electricity while consuming 0.9404 kg/s of natural gas, the use of the CSP system contributes 64% of fuel saving with 2.8% of output reduction. Finally, they claimed that integrating an additional CSP on the CCGTs leads to considerable fuel conservation with slight power reduction.

3.2.2. Optimizing CCGTs through other methods. In the academic field, scholars have many novel concepts of optimizing the CCGTs. Roberto Carapellucci et al. [26] investigated a new concept for optimizing the existing CCGTs by integrating an additional unit on the current gas turbine. This
additional unit enables the superheated steam to be used in three different ways. As shown in Figure. 7, in option A, the superheated steam is directly injected into the combustor of the current turbine. In option B, the superheated steam is used to promote methane reforming. And then, the syngas of reformed methane and steam is used as the fuel of the existing combustor. In option C, the syngas are also used as the fuel of the combustor, which is in the supplemental gas turbine. In option B&C, the heat recovery is greater than the conventional method since the produced syngas absorbs the heat from superheated steam thermally and chemically. Their result shows that option A has the best economic performance, with the highest operational simplicity when the power augmentation is lower than 50%. Differently, when the power augmentation is larger than 80%, option C is more competitive than option A.

Hany A. Al-Ansary et al. [27] pointed out that a proven method of upgrading the efficiency of CCGTs is declining the inlet temperature of the compressor, especially during the hottest time in the summer. Hence, they investigated the prospect of using a TIAC (hybrid Turbine Inlet Air Cooling). The TIAC is made up of a mechanical chilling system which is followed by an evaporative cooling system. Figure. 8 and 9 are comprehensive diagrams of the mechanical chilling system, including dry and wet cooling condensers. In this research, Al-Ansary defines 4 different scenarios, which are shown in Table 2. Their result showed that the TIAC systems have the ability to boost the output of CCGTs by 10% or more (in ISO condition). In addition, the comparison of four different scenarios showed that scenario 4 is the most attractive option.

| Case I          | Mechanical chilling only with dry cooling of the condenser |
|-----------------|----------------------------------------------------------|
| Case II         | Mechanical chilling only with wet cooling of the condenser |
| Case III        | Hybrid TIAC system with dry cooling of the condenser     |
| Case IV         | Hybrid TIAC system with wet cooling of the condenser      |
Andrea Giugno et al. [28] integrated an additional high-efficient heat pump in a CCPP as a flexibility enhancement to improve the global efficiency and operational flexibility in part-load operation. Specifically, the heat pump allows crews to modify the intake temperature of the compressor, which is a positive way of increasing power production. They also pointed out that the combined cycle’s efficiency is more influenced by the auxiliary consumption than the ambient temperature. Thus, selecting the appropriate size of the heat pump is important. They analyzed the climatic data and its correlations with energy market conditions and then established a model to calculate the thermoeconomic potential. Their result shows that the ratio of electrical consumption of an air-cooled heat pump to the maximum electrical production increase is 1:100. Based on their result and the characteristic of the heat pump, Giugno points out that the electrical market conditions could harm the profits of installation even under favorable climatic potential. Hence, they came up with a concept that “using the off-design curves and optimization algorithm in performing coupling analysis appears to be more effective.”

4. Conclusion
(1) Micro gas turbine has been widely applied in various areas, like providing electricity and heat to residential buildings, making business buildings more sustainable, and producing more stable and efficient energy for remote countryside and island. However, it has not been applied to hybrid cars, as several difficulties make efficiency low, frequent engines stop, and lack of space for big heat exchangers. Hence, in the future, to realize the application, it is essential to ensure the efficiency of the micro turbine
with a small volume to reduce the energy cost, cut the production cost to be affordable, and reduce the noise level to ensure the passenger comfort.

Moreover, methods for prospective health monitoring are usually used for large scale gas turbines, rarely for micro gas turbine. However, it can largely increase the availability and reduce the cost for operating and maintenance. The future research could focus on estimating and predicting performance degradation of gas turbine to achieve condition-based maintenance. The reason why is sudden failure mechanisms, such as bearing failure or object damage, are hard to be predicted. These may lead to fuel consumption increasing, uneconomical operation and greenhouse gases developing.

(2) One of the most popular optimization methods of CCGT is to integrate another additional unit instead of directly modifying the specific characteristics of the gas turbine. Among these integrated technologies, ISCC may be one of the most developed applications. Many countries have installed concentrated solar power plants, which means that the application of solar thermal energy is a relatively mature technology. Therefore, integrating mature technology into the existing CCGT may be a viable option. Also, the reference (2) indicates that one of the investigated ISCCs model can contribute to 64% of fuel saving with 2.8% of output reduction, which means that this technic has considerable expectation.

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