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Research on the Design of Advanced Combined Cycle Power Plants

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Abstract:
Combined cycle power plants are an important bridge technology between today's fossil fuel power plants and tomorrow's clean power plant facilities. The paper analyze from the perspective of thermodynamics, technology and engineering practice introduces the main structure, design points, fundamentals of advanced combined cycle power plants (CCPPs), key technology innovations, and application cases through the analysis of how the two cycles, namely, Brayton cycle and Rankine cycle, work together and how advancements have brought better CCPPs, which include Brayton cycle optimization, multi-pressure steam system, and regenerative heat exchange techniques. The description is based on the case study of Hassyan hybrid power plant, Huaneng Shantou 700°C A-USC Project and NET Power zero-carbon demonstration project, Compared with traditional power plants, the differences in fuel types, cycle methods, and fuel utilization are summarized. The working principles and special cycle methods of these typical cases are explained respectively, and the future trend of combined cycle power plants is further summarized. It is demonstrated that current modern CCPPs' operational efficiencies might surpass 60%, indicating potential and adaptability for the change in low carbon emission.

Keywords: Combined Cycle Power Plants; thermodynamics; carbon utilization rate.

1. Introduction

The world's energy is confronted with the following situation-the increase of electricity demands because of the progress in economics, together with the rising populations; reducing greenhouse emissions to stop climate change requires other measures. Conventionally, a single cycle power plant will discharge 67% heat [1]. Wasting a large part and making it rather inefficient for the means of both energy and the environment. However, for Fig.1, combined cycle power plants (CCPPs) achieve thermal efficiencies as high as 60% after putting together both Brayton cycle (gas turbines) and Rankine cycle (steam turbines). Recent advancements such as multi-pressure steam systems and A-USC technologies have significantly opti-

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mized the performance of CCPPs. Still other elements can reduce the amount of greenhouse gases without sacrificing the CCPPs' operational effectiveness, such as integrating renewable energy production. This report focuses on CCPP's design principles and innovations.

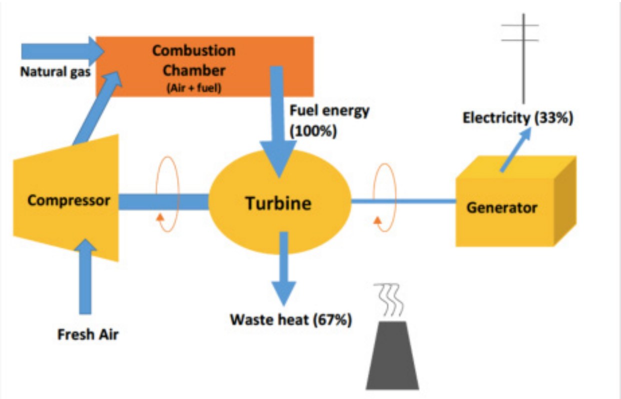

Fig. 1 A schematic diagram of a simple cycle gas plant

In China, the advancement of gas turbine technology has largely focused on increasing the initial combustion temperature, refining the aerodynamic design of turbine components, and enhancing air-cooling efficiency for high-temperature parts. While these efforts have contributed to performance improvements, they remain confined to conventional simple-cycle systems. To further boost efficiency, domestic researchers have explored more complex cycle designs, such as intercooling during compression, reheating of gases during expansion, and recovery of waste heat. These approaches have shown promising results, especially under moderate operating temperatures (700–800°C). Nonetheless, the adoption of water or steam cooling systems in industrial gas turbines has been limited, primarily due to technical complexity and questionable economic return. At present, efforts to improve efficiency continue to center on optimizing existing designs and materials, while combined-cycle power plants emphasize reliability and cost-efficiency over radical innovations.

Globally, the development of gas turbines and combined-cycle power plants has focused heavily on maximizing efficiency, with particular interest in advanced steam-cooling techniques. Several countries have built and deployed 300 MW-class gas turbines equipped with closed-loop steam cooling systems, integrated alongside intermediate steam heating stages in combined-cycle setups. However, while these systems introduce significant design complexity, the anticipated economic gains have remained modest, limiting the widespread use of steam cooling. At present, Alstom is among the few manufacturers implementing fuel recirculation under high-temperature conditions (1300–1450°C). Although their 240–300 MW turbines have reached commercial deployment, the economic payoff has not proven substantial. Currently, combined-cycle plants abroad can achieve gas turbine efficiencies of around 43%, with total system efficiencies nearing 63%. Looking ahead, if turbine inlet temperatures can be raised to 1600–1700°C, efficiencies may rise to 45% and 65%, respectively. Realizing these gains, however, will require major advances in high-temperature materials, cooling strategies, and overall cycle design [2].

2. Results and Discussion

2.1 Fundamental Principles and Core Configurations

2.1.1 Fundamental principles

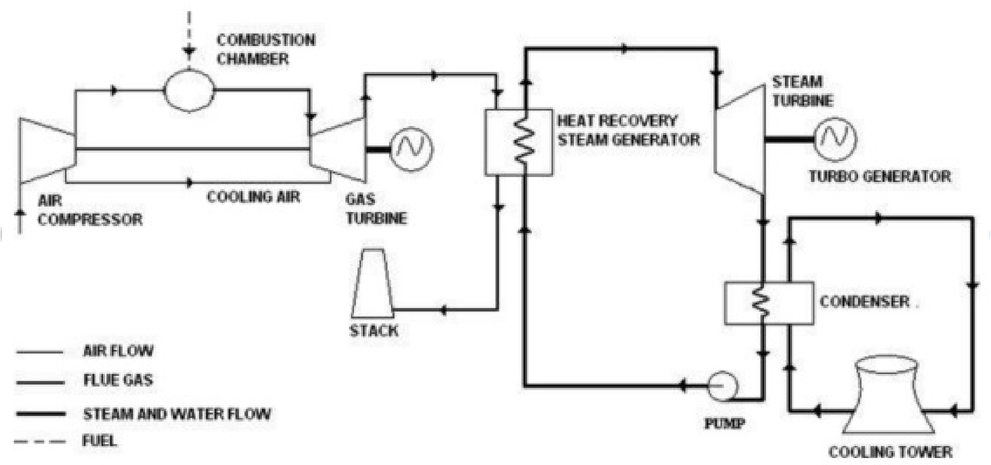

Fig. 2 Schematic diagram of combined cycle power plant

As illustrated in Fig.2, combined cycle power plants utilize the coupling of a gas turbine and a steam turbine by the tandem operation of the Brayton cycle (gas turbine) and the Rankine cycle (steam turbine) to realize effective energy conversion. The specific process can be explained as follows [3].

Gas Turbine (Brayton Cycle), first, air is compressed to high pressure by a compressor, then mixed with fuel and burned in a combustion chamber. The high temperature and pressure of the combusted gas drives a gas turbine, which converts mechanical energy into electrical energy. The exhaust temperature of the gas turbine is typically 550-600°C, and these high-temperature exhaust gases still carry a lot of heat energy [4].

The Heat Recovery Steam Generator (HRSG) is designed for accepting high-temperature exhaust gases from the gas turbine and then transferring such heat energy into the water thus producing steam.

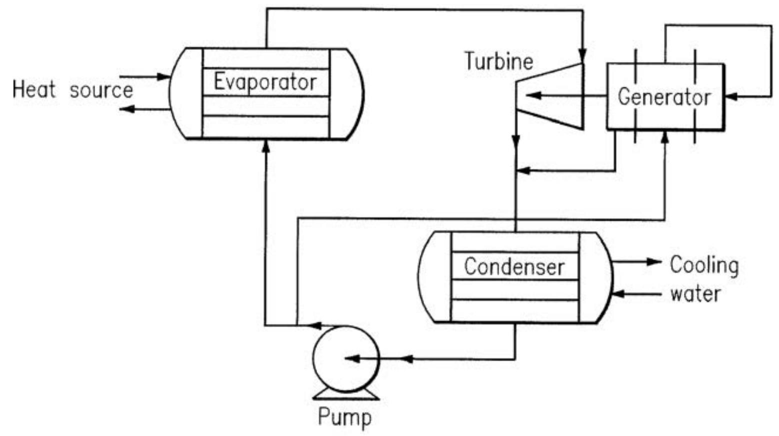

Fig. 3 Rankine Cycle

For Fig. 3 Steam Turbine (Rankine Cycle), the generated high pressure steam is passed through the steam turbine to do work and further generate electricity. The heat from the exhaust gases is recovered and converted into electricity, creating an “up-down” model of power generation [5, 6]

This type of co-generation, which combines two different thermodynamic cycles, not only increases the efficiency of energy utilization, but also significantly reduces fuel consumption.

2.1.2 The core configuration includes gas turbine, the heat recovery steam generator, steam turbine, auxiliary systems

Gas Turbine (GT) Module is used to burns natural gas into hot gas to drive turbines.

The Heat Recovery Steam Generator (HRSG) recycles waste heat gas to produce steam for the steam turbine.

Steam Turbine (ST) Module converts the energy of steam into mechanical energy to generate electricity.

Auxiliary systems include: fuel supply, lubrication, cooling, start-up and control system used for work support.

2.1.3 Energy conversion occurs in 2 levels

Level 1 is that mechanical energy from the gas turbine is converted into electricity.

Level 2 is that exhaust heat is used by the HRSG to produce steam, which drives the steam turbine, further converting energy to electricity. This synergy maximizes efficiency [7].

2.2 Key Technological Innovations

Combined Cycle Power Plants (CCPPs)have achieved above-60%-efficiency rates via three principal technologies.

2.2.1 Introducing the exergy-based efficiency optimization

Exergy, also known as available energy, refers to the maximum work a system can do as it reversibly transitions to equilibrium with the environment. It measures the portion of energy that can perform useful work. Traditional energy balances don’t show how effectively energy is used, so the exergy efficiency metric is introduced. It is the ratio of gained exergy to supplied exergy.

Exergy analysis allows one to know the energy quality loss.

Burning releases 28% of the exergy loss since the inefficiency in the conversion from chemical to heat energy is irreversible.

Heat Recovery Steam Generators (HRSGs) cause 17% of exergy loss due to the temperature difference between exhaust gases and steam, which is usually more than 200°C [8].

2.2.2 Optimization strategies include following

Premixed swirl burners improve the mixing of air and fuel, reducing nitrogen oxide emissions to 9 ppm and reducing effective energy loss by 12%.

Optimization of HRS tube bundles increase in the heat

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transfer coefficient from 55 to 68W/m2K, increases heat transfer and consequently increases the recovery efficiency.

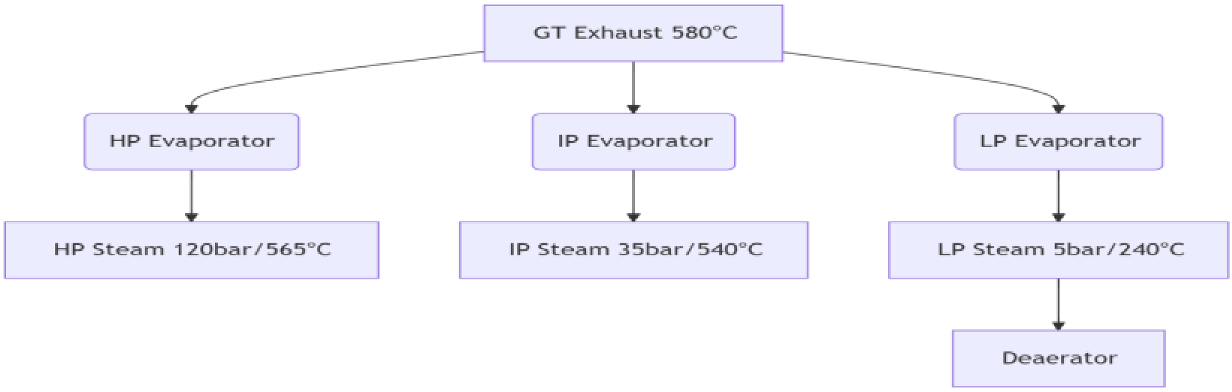

Fig. 4 Multi-Pressure Steam Cycle

2.2.3 Multi-Pressure steam cycle

In Fig. 4 the multi-pressure steam cycle makes the best use of waste heat via a triple-pressure system. (HP) Pressure stage generates 120 bar and 565 °C steam driving the main steam turbine to produce 45% of the plant's power. (IP) intermediate Pressure (IP) stage produce 35 bar and 540 C steam to prevent wet-steam losses. (LP) Load Pressure (LP) Stage: Produces saturated steam of 5 bar and preheats feed water to 150°C so that less heat is required for any further heating needed.

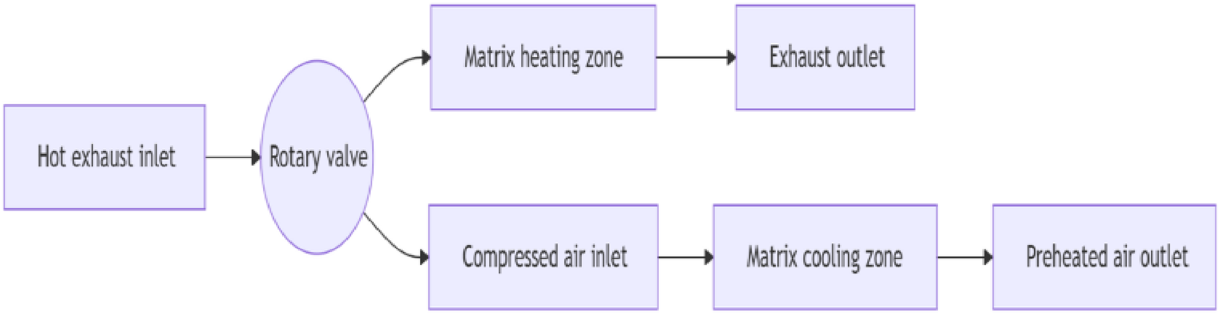

Fig. 5 Regenerative Heat Exchange

2.2.4 Regenerative heat exchange

For Fig. 5, regenerative heat exchange systems have rotary regenerators that can achieve an exergy increase of 2.3% by creating a closed-loop energy cycle which reduces the difference in temperatures between exhaust gas and compressed air.

The works process is that high temperature exhaust gas enters the system that contains VOCs or industrial process gas, which pass through a ceramic matrix to transfer heat. Cooled exhaust goes out of the outlet, while a rotary valve directs hot exhaust toward cooled matrix areas and sends cold treated exhaust gas to the outlet and cold compressed air to the heated matrix. The matrix releases stored heat to compressed air, making the preheated air exit out. The valve will continue rotating constantly and alternate between the heating zone and the cooling zone to keep continuous heat recovery by utilizing dynamic switching functions.

Breakthrough design 135° counterflow configuration increases heat exchange performance 20% over the standard 90° right angle flow design and the angle of air flow relative to the rotating axis is 135°. When all of these processes are applied together, there is an increase in plant efficiency by more than 10% and the emission reduction exceeds over 10,000 metric tons annually per each one percent efficiency improvement.

2.3 Application Cases

2.3.1 Introducing the hassyan hybrid power plant (Dubai)

Hassyan Hybrid Power Plant makes use of dual-fuel systems-coal as well as natural gas-to change fuel according to availability and the environment needs. Burning natural gas power a gas turbine that later warms up water into steam, which then turns a steam turbine to generate additional electricity. This scheme allows the plant to have a higher efficiency since it can utilize the same fuel source in multiple processes. The plant produces a huge amount of energy, giving 20% of Dubai's power and proving that modern plants can also be efficient and environmentally friendly [9].

2.3.2 Introducing the huaneng shantou 700°C A-USC project (China)

The Huaneng Shantou project uses advanced 700°Ctechnology to improve plant efficiency by converting more heat into electricity and reducing fuel use. It uses superheated steam to drive turbines, boosting efficiency and lowering pollution. This cutting-edge technology improves coal plant performance, making energy production cleaner [10, 11].

2.3.3 Introducing the NET power allam-fetvedt cycle demonstration (USA)

(AFC)ET Power project uses AFC cycle through which pure oxygen burns natural gas to produce CO2 that spins a turbine. The CO, then is gathered and sequestered underground so as to prevent CO, discharge to the air.The cycle is a close one, circulating the extracted CO2 again in the system to catch the discharged heat of the exhaust; hence, achieving zero emission, making it a ground-breaking innovation of clean energy technology [12].

2.4 Future Trends

Looking ahead, the development of advanced combined cycle power plants is moving toward greater efficiency, lower emissions, and improved adaptability. A prominent trend shown in Table 1 is the integration of renewables—such as solar energy (both photovoltaic and thermal) and wind power—into combined cycle systems to enhance flexibility and reduce reliance on fossil fuels. At the same time, advanced ultra-supercritical steam cycles, which operate at temperatures above 700°C, are being explored to boost thermal efficiency to around 50% while reducing fuel usage. Another area of focus is the incorporation of carbon capture directly into the power cycle, aiming for near-zero emissions with efficiencies approaching 59%. Efforts are also underway to retrofit turbines to run on low-carbon fuels like hydrogen and ammonia, supporting long-term decarbonization strategies. Finally, there is growing interest in smaller, modular combined cycle units (typically 10–50 MW) designed for local power generation, which offer benefits such as reduced transmission losses and greater reliability. Together, these advancements signal a shift toward cleaner, smarter, and more resilient energy systems.

Table 1. Future trends in advanced combined cycle design

Model	Trends	Benefit
Renewable Integration	CCGTs combined with solar (PV/thermal) or wind.	Greater flexibility and lower carbon emissions.
Advanced Steam Cycles (A-USC)	Steam temperatures >700°C.	Higher efficiency (up to 50%) and lower fuel use.
Built-in Carbon Capture	Next-gen cycles with CO_2 capture embedded.	Zero-emission gas power, 59% efficiency.
Green Fuels (Hydrogen/Ammonia)	Retrofitting turbines for low-carbon fuels.	Supports long-term decarbonization.
Modular & Distributed Systems	Small-scale (10–50 MW) CCGTs for local use.	Lower transmission losses, higher reliability.

3. Conclusion

CCPP acts as an important bridge technology between present-day fossil-fuel power plants and future clean power plant installations. In this paper, high efficiency and low emissions of CCPP have been analyzed on the basis of thermodynamics, technologies, and engineering practices, and such evaluations revealed the superiority of CCPP. Successful examples including the Has Yan Power Plant and the NET Power Project show the technical potential of CCPP, while generating significant environmental benefits. Future upgrades of CCPP can be achieved by integrating green fuels, carbon capture, and renewable energy into the system, contributing.

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