Proceedings of the 3rd International Conference on Signal Processing and Machine Learning
DOI: 10.54254/2755-2721/5/20230627

Gas & steam power systems: Current status and prospects

Chuanqi Cheng[1,2,3]

[1]Mechanical Engineering, Northern Arizona University, Flagstaff, AZ 86011, USA
[2]School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, 212000, China

[3]cc3436@nau.edu

Abstract. Gas power generation systems, steam power generation systems and combined cycle power plants play an important role and value in industrial production, and have attracted extensive attention from scholars at home and abroad this year. It is not only an important cornerstone of a country's industrial production, but also plays an important role in technological development in other fields. This article is an introduction to gas-power generation system, steam-power generation system and Combined cycle power plant (CCPP), covering their respective principles, working processes and modifications to improve thermal efficiency. Each system has its own advantages and drawbacks which should be considered in a case-to-case scenario. However, both standalone gas/steam power systems are less effective compared with CCPP, which is a more superior system to utilize fossil fuel for electricity generation. Based on the current situation of some countries, CCPP is the optimal way for power generation in the future.

Keywords: Gas power generation systems, Steam power generation systems, Combined cycle power plants, Working processes, Thermal efficiency.

1. Introduction

Electricity is the driving force of contemporary human society. Electricity not only provides power for factories, house hoods, but also drives modern information technology, the soul of third industrial evolution.

With the rapid increase in productivity and demand for higher living quality, electricity consumption has increased drastically in past decades. Such demand impels the advancement in power generation systems. Originally, the power generating system rely on piston-cylinder combustion engines like diesel engine, as the scientific breakthrough in metallurgy and deeper understanding of thermal dynamics, turbine-based power generating system came into existence and gradually became main means for thermal power plant.

Power generating systems include turbine driven generators, internal combustion (IC) engines, solar photovoltaic cells, fuel cells, Stirling engines and thermoelectric generators. The turbine driven systems can be further divided into steam turbines, nuclear power reactor, geothermal steam turbine system, combustion gas turbines, combined cycle power plants, hydroelectric turbines, wind turbines and ocean thermal conversion systems [1].

DOI: 10.54254/2755-2721/5/20230627

It is worth noting that the turbine driven systems are dominant in power generating industries, among which steam turbine system possesses the most share, producing 44% [1] of electricity for U.S. in 2020. IC, steam turbine and gas turbine power generating systems utilize heat engines to convert thermal energy to work [2], then the generator in this system can further convert output work into electricity. IC engines include spark-ignition engine, compression-ignition engine; gas turbine systems work on Brayton cycle and steam turbine systems work on Rankine cycle. For thermal power plants, there is an increasing trend to combine both gas turbine and steam turbine systems to form Combined Cycle Power Plant (CCPP). In U.S., 2020, CCPP contributed to 35% of electricity generation [1]. Thus, a thorough understanding of both cycles and their respective limitations is significant for power generating system design, optimization and analyzing CCPP. This article aims to provide a brief review of standalone Brayton cycle and Rankine cycle power generating system and CCPP, along with the prospects of CCPP.

2. Standalone Power Generating Systems

2.1. Simple gas-turbine cycle

Simple gas-turbine power generating system works on Brayton cycle, which is also used produce thrust in most of jet engines in aviation. Similar to other heat engines, there are 4 stages in gas turbine power system: air compression, fuel-air mixture combustion, gas expansion and exhaust.

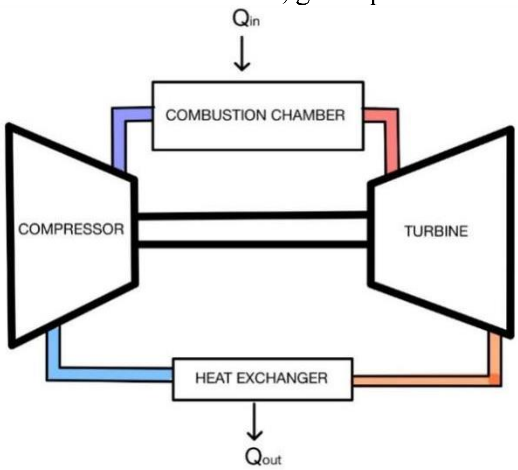

Figure 1. Simple Brayton cycle configuration.

As shown in Figure 1, the system is made up of compressor for air pressurization, gas turbine for thermal energy conversion and combustion chamber for fuel ignition [3].

The heat exchanger in the diagram is to simplify the Brayton cycle process, which is to simulate gas exhaust process (heat rejection). But in reality, the exhaust gas is either directly emitted into the environment or goes through heat recovery mechanisms before leaving the power generating system.

The compressor has a series of rotating aero foil to elevate air pressure in stages and push pressurized air into combustion chamber where fuel injection and combustion happens [4].

The turbine is also made up of rotating aero foil but is used for work generation and drives the compressor to continuously pressurize air.

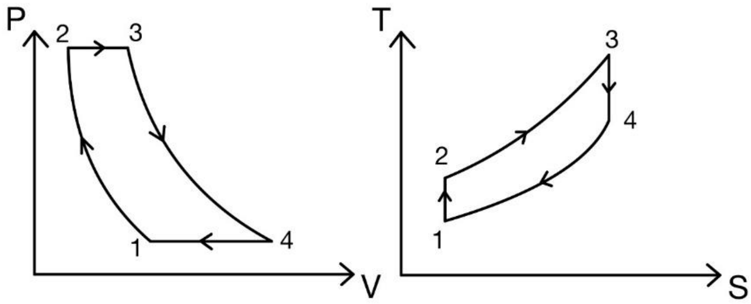

Figure 2. P-V and T-S diagram of simple Brayton cycle.

As shown in Figure 2, an ideal simple air-standard Brayton cycle consists of 4 processes: 1-2 is the compression process, which is isentropic in the ideal model, 2-3 is heat addition process, which takes place at the same pressure, 3-4 is isentropic expansion and 4-1 is heat rejection process at constant pressure. During the cycle, air is first taken into the compressor where its pressure increases and pushed into the combustion chamber, in which fuel is injected into air for fuel-air mixture and ignition happens. This process is simplified here as heat addition process. During the combustion, the flame temperature is over 2000 degrees Fahrenheit [3]. The drastic increase of the combusting air-fuel mixture temperature results in significant expansion. Due to such expansion, the mixture moves at high velocity towards turbine outlet which drives turbine to generate work from the cycle and do back work to the compressor for self-sustaining compression-combustion process. For power generating systems, the work is transmitted to power generator to produce electricity. Finally, heat is rejected into surrounding with exhaust gas.

2.2. Optimize standalone gas-Turbine power generation system

The standalone gas turbine has a thermal efficiency of approximately 40%. To improve its thermal efficiency, several methods are adopted, including reheating, regeneration, and intercooling.

2.2.1. Reheat. As shown in Figure 3, Reheat happens after the first turbine stage where there is unreacted oxygen, which can support further combustion in the second stage combustion chamber. Additional fuel is also injected into the second combustion chamber.

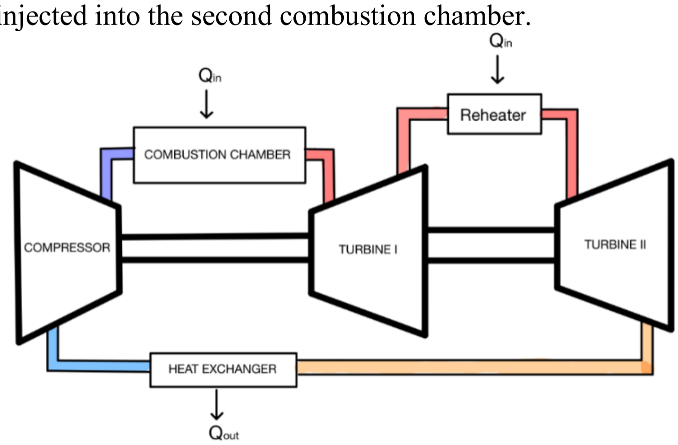

Figure 3. Brayton cycle with reheating.

2.2.2. Regeneration. The exhaust gas existing turbine stage is at high temperature; thus, its thermal energy can be partially recovered by implementing regenerator.

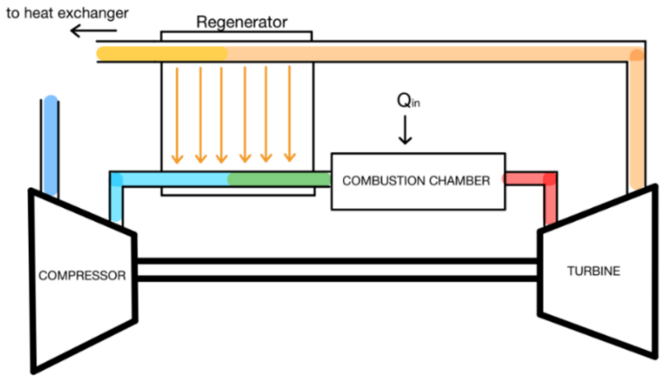

Figure 4. Brayton Cycle with Regeneration.

The regeneration system acts as a heat exchanger to transfer heat from high temperature exhaust gas to lower temperature compressed air from compressor. It is clear from Figure 4 that compressed air is pre-heated through regenerator before entering combustion chamber, thus reducing required heat addition to the combustion chamber [5].

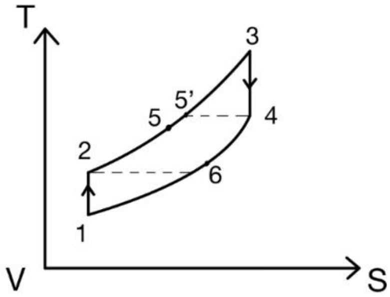

Figure 5. T-S characteristic for Brayton cycle with regeneration.

For a real regenerator, it is impossible for exhaust gas to fully transfer excessive heat to compressed air and achieve the equilibrium temperature due to regenerator size limitation and internal irreversibility of the regenerator, thus, the regeneration efficiency ε is applied to measure the effectiveness of the generator (Figure 5). For state 1-7: $\varepsilon = \frac{h_5 - h_2}{h_4 - h_2}$. Where h is the enthalpy of respective stage.

For air-standard assumption, the equation above is simplified to $\varepsilon = \frac{T_5 - T_2}{T_4 - T_2}$. Where T is the absolute temperature of respective stage.

2.2.3. Intercooling. Intercooling is a process which reduces the back work required by compressor to achieve the same pressure, thus increasing overall thermal efficiency.

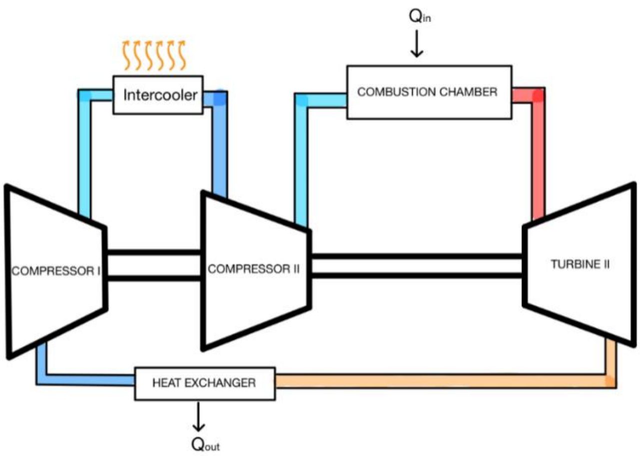

Figure 6. Brayton Cycle with Intercooling.

As shown in Figure 6, there are two stages of compressor. The first stage will pressurize the air to a higher pressure but less than the target pressure, then partially pressurized air will go through the intercooler where the air temperature drops. The reduction in temperature will result in an increase in air density, meaning a decrease in specific volume. For compressors with constant mass flow rate, less specific volume means less power required.

2.3. Simple Steam-turbine Cycle

The emergence of contemporary steam turbine was at 138 years ago, thanks to Charles Parsons who invented a steam turbine that could generate 7.5 kW electricity [4]. Since then, the steam turbine power generation system kept developing, with the largest turbine generator's output in 1910 being more than 25 times that from 10 years ago, reaching over 30,000 kW [5]. Nowadays, steam turbine technology has reached a point where some of the large steam turbines can output thousands of megawatts. One representative is the Arabelle nuclear steam turbine from General Electric, which has a maximum output of 1900 MW.

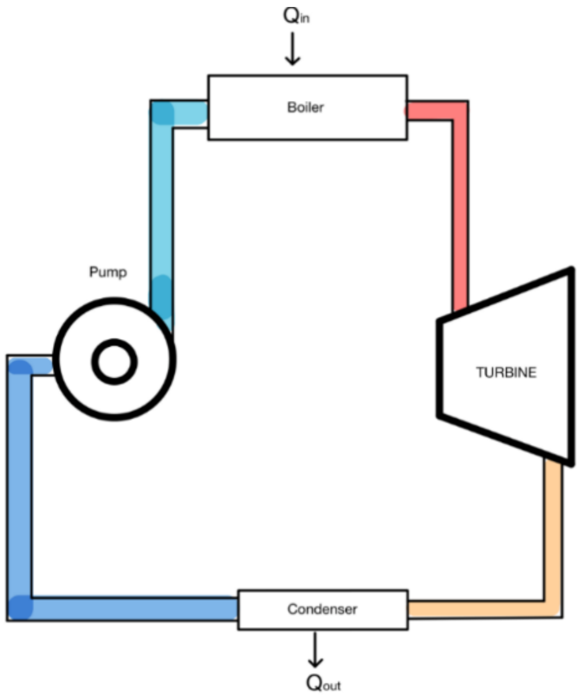

Figure 7. Basic configuration for steam-turbine power cycle.

Figure 7 shows the basic layout for a simple steam turbine power generation system. From state 1 to 2, water is pressurized by the pump, then water at with high pressure state goes through heat addition process in the boiler. During this process, liquid water becomes superheated steam. From state 3 to 4, superheated steam expands though series of turbine blades where thermal energy of the steam is converted to mechanical energy. Like gas turbine in the Brayton cycle, the foil shape is designed to receive the energy from steam expansion and convert it to rotational mechanical energy of the central shaft, then the generator will complete the final conversion from mechanical energy to electricity.

Then the exhaust steam goes through condenser to release excessive heat to return to subcooled liquid state again before returning into the pump again.

Steam-turbine generator works on Rankine cycle, which involves phase change of the working fluid between liquid and gas state. For an ideal steam power generator, water is the working fluid. The process can be described in a T-S diagram, as is indicated in Figure 8.

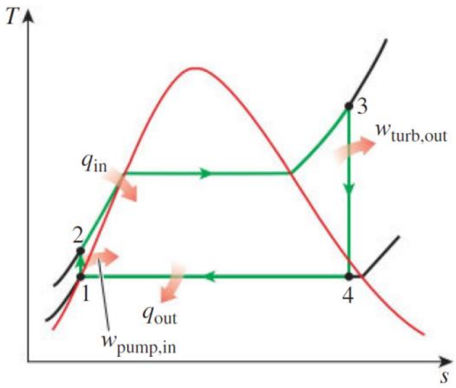

Figure 8. T-S diagram for ideal simple Rankine cycle [6].

Process 1-2 is the idealized compression process at isentropic condition, during which liquid water is pressurized from low pressure to high pressure. As water is an incompressible fluid, this process consumes much less energy per unit mass than compressing air in the Brayton cycle.

Process 2-3 is the heat addition process in the boiler. During this stage, the pressure remains constant.

Process 3-4 is the isentropic expansion in the steam turbine where work conversion happens. At state 4, as shown in Figure 7, steam is usually a mixture of liquid water and vapor under the vapor dome, whose quality is high.

Process 4-1 represents heat rejection from the exhaust steam. Heat rejection of steam is usually done by rejecting heat into low-temperature natural water body such as river and lake through the condenser. For regions of scarcer water supply, dry cooling method is adopted: instead of using water as cooling medium, air flow is utilized to cool down the steam.

2.4. Optimize standalone steam-turbine power generation system

The standalone simple Rankine power cycle could reach an efficiency around 40%. With the implementation of other mechanisms such as feed water heater and reheating.

2.4.1. Open Feed Water Heater. Open Feed Water Heater (FWH) is a mixing chamber where part of steam extracted from the turbine mixes with the pressurized water coming out of the pump. The mixing of the steam and water results in a rise in water temperature, thus reducing the heat input needed from the boiler to achieve the same steam temperature. Figure 9 shows the configuration of the steam turbine power system with open FWH, each circled number represents a state in the process.

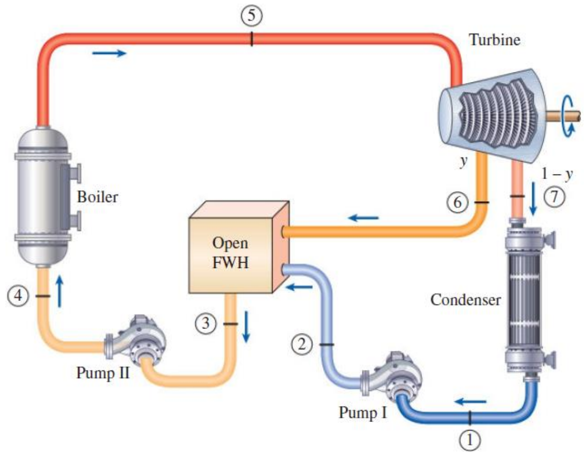

Figure 9. Configuration of Steam-turbine generator with open FWH [7].

In the turbine section, the flow of steam partially diverts from the lower pressure stage of the turbine to be the steam input of the open FWH (State 6). Note that the pressurization of water is divided into two stages, the first one is before water enters open FWH and the second one is after. This is because

DOI: 10.54254/2755-2721/5/20230627

the inlet pressure (aka from State 6 and State 2) in the open FWH must be the same to maintain the flow indicated by arrows in Figure 9. Since ideally pressure of State 4,5 are the same and the pressure of State 6 is lower than that of State 5 due to steam expansion in high pressure stage of the turbine, this means the pressure of the water from State 2 must be lower than that from State 4 thus requiring two compressors to pressurize water in two stages.

From the T-S diagram in Figure 10, state 6 represents extracted steam from turbine and State 3 is the outlet of the open FWH, the temperature is higher than without open FWH. Ideally, the water entering the open FWH would be heated to the same temperature as the extracted steam from State 6 and becomes saturated liquid when exiting. However, in reality, the temperature of State 3 is always a few degrees lower due to some heat loss to the environment.

2.4.2. Closed Feed Water Heater. Closed FWH is another form of FWH. Differs from open FWH, the extracted steam does not mix with the feedwater, thus larger pressure difference between extracted steam and feedwater can exist in closed FWH. The steam coming out of the closed FWH has two possible routes to complete the cycle depending on the practical design and configuration: either the steam returns to the feedwater line FWH just heated through another pump, or use a trap device to depressurize the steam and let it return to the condenser. Note that the steam has the same enthalpy before and after going through the trap.

2.4.3. Comparison between open FWH and closed FWH. The open FWH yields higher efficiency because extracted steam is directly mixed with feedwater, allowing higher heat transfer efficiency. In comparison, due to the indirect contact between extracted steam and feedwater in closed FWH, the efficiency of heat transfer is compromised. Also, the closed FWH is structurally more complex because of internally isolated heat exchange tubes.

However, closed FWH has its own advantage. For the configuration where exiting steam from closed FWH goes to condenser, there would be one less pump needed compared with open FWH, thus potentially reducing the overall cost.

Generally. steam power plants implement both open and closed FWH to achieve a more optimized result, as shown in figure 10.

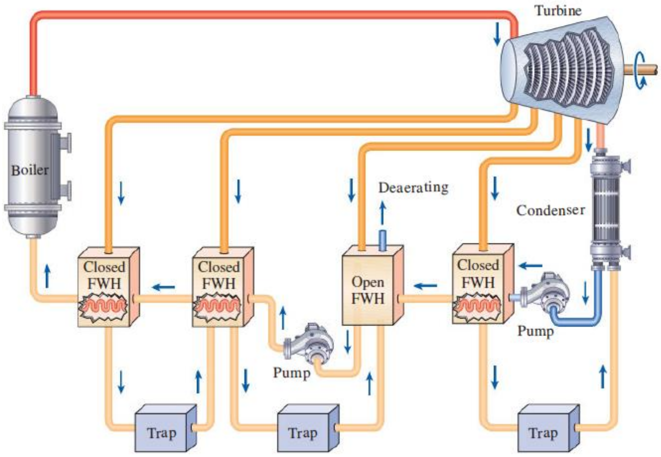

Figure 10. One configuration for multiple FWHs [8].

Multiple stages of closed FWHs are used in Figure 10 configuration, along with one open FWH.

3. Combined Cycle Power Plant

3.1. Fundamentals of CCPP

Combined Cycle Power Plant (CCPP) uses a combination of two different thermal cycles to generate electricity. The fuel input is from one cycle, the rejected heat is used to power the other cycle through the heat recovery mechanism. Many thermal power plants are a combination of gas power cycle and steam power cycle. This configuration works because the exhaust gas from Brayton cycle typically has high temperature, which is enough to cover the heat addition required by Rankine cycle. The exhaust gas of gas- turbine cycles can be above 500 degrees Celsius which is near the temperature where modern steam turbine usually operates.

As shown in Table 1, modern gas turbine development has gone from the 1st generation and beyond the 4th generation. Advancements in material science, combustion & cooling technology, and Computer Aided Engineering (CAE) are crucial for the existence of CCPP. All the efforts are for higher combustion temperature in the gas turbine so the Carnot efficiency can be improved. Also, high efficiency CCPP needs high temperature for steam power cycle in the CCPP, thus requiring higher flame temperature in the gas-power cycle. Advanced materials enable gas turbines to operate over 1400 ° C, which in return provides higher efficiency for both gas and steam power cycles. The turbine blade material; aerodynamic design improvement for aero foils enables optimized conversion efficiency from thermal energy to mechanical energy; new cooling techniques prolong the operation life of gas turbines.

Table 1. Development of gas turbine [9].

	First Generation	Second Generation	Third Generation	Fourth Generation
Inlet Temperature	Up to 1000 ℃	Up to 1100 ℃	Up to 1300 ℃	Up to 1400 ℃
Compression Ratio	Up to 10	Up to 12	Up to 15	Up to 20
Combustion Technology	Diffusive Combustion	Diffusive/Premixed Combustion	Augmented Premixed Combustion	Augmented Premixed Combustion
Cooling Method	Natural Cooling	Simple Convection	High-performance Turbulator + gas film	High-performance Turbulator + gas film
Coolant	-	Air	Air	Air/Steam
Blade Material	Polycrystalline High Temperature Alloy Steel	Polycrystalline High Temperature Alloy Steel	Unidirectional Solidification Alloy Steel	Unidirectional/Monocrystal Alloy Steel
Aerodynamic Design	Quasi-3D design	Quasi-3D design	Full 3D Design	Full 3D Design

The CCPP takes advantage of high temperature exhaust gas, which already contributed to system power generation in the Brayton cycle through linked generator, the exhaust gas with high temperature out of gas turbine releases excessive heat to feedwater in the Heat Recovery Steam Generator (HRSG) instead of going into atmosphere directly. The heat exchange process in the HRSG results in heat addition of feed water in the steam-power cycle to superheated state and expands through the steam turbine to output work. The corresponding generator will then convert mechanical energy to electricity.

Figure 11 shows the basic configuration of CCPP. HRSG allows remaining exergy to be extracted by Rankine power cycle.

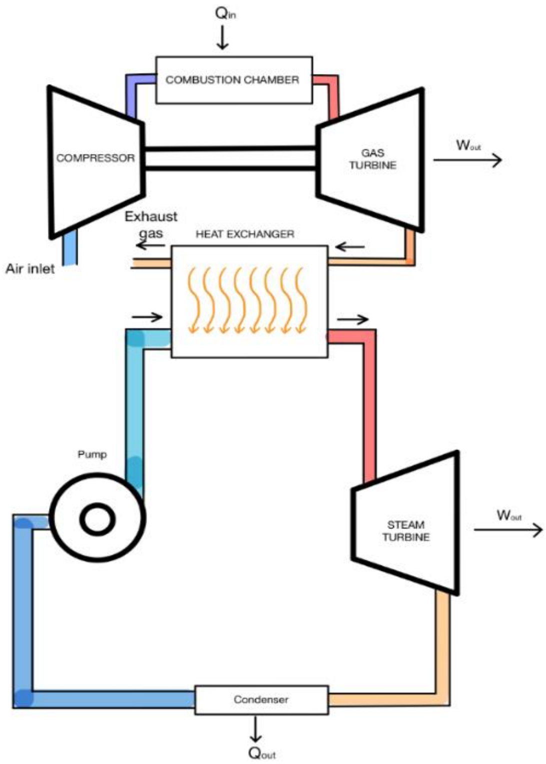

Figure 11. Configuration of CCPP.

3.2. Advantages of CCPP
First, CCPP can yield higher efficiency than stand-alone gas or steam turbine power plant because the exceeding heat is always being partially recovered. In other words, the exergy left over by gas-turbine cycle exhaust is partially picked up by the steam-turbine cycle. Exergy is a measurement of maximum useful work a system can do relative to the environment. The temperature of exhaust gas is well above the dead state of the surrounding, which makes exergy recovery possible.

Second, CCPP is more environmentally friendly. Thanks to higher efficiency than standalone power cycles, the source fuel consumed for the same amount of electricity output is less than standalone cycles, thus reducing emissions from burning the source fuel.

CCPP also enables various fuel sources compared with single steam power plants. The gas turbine, depending on the type, can use various fossil fuel like (liquified) natural gas, gasified coal, diesel, etc. This allows more flexibility if the type of fuel supply is biased. The fuel for CCPP can be categorized into two branches: liquid fuel and gas fuel. Liquid fuel includes diesel and other petroleum products. Gas fuel includes natural gas, liquified natural gas, gasified coal, etc. In general, liquid fuel results in more SO_2, NO_x and CO_2 emission than gas fuel, but much less than coal.

Moreover, the start-up time for CCPP is quicker than standalone steam power plant. During the start-up sequence, the gas turbine would be able to generate electricity first before the boiler in the steam-turbine cycle is fully heated to operational state.

3.3. Prospects of CCPP
Although there are various advantages for CCPP, there are yet some limitations for combined cycle power plant. One is that the efficiency of CCPP is more sensitive to environmental factors. When considering standalone power plants, only their respective environmental factors influence efficiency. With CCPP, the joint factors from both power systems are now all relevant to the efficiency. For example, the air temperature mainly affects the efficiency of Brayton cycle due to varied air density under different temperatures, influencing the power needed for compressor to keep constant mass flow rate; wet-bulb temperature affects the efficiency of the cooling tower in the Rankine cycle. When

designing the CCPP, these environmental factors will need to be taken into consideration for optimized efficiency.

CCPP installation and upgrade will be the trend for developing countries like China. In 2021, the total installed capacity was 237692 MW with 16.45% hydro power [10], 54.56% coal-fired power, 2.24% nuclear power, 13.82% wind power and 12.90% solar power. It is obvious that the coal-fired power plant is the main means of power generation, which is convenient due to abundant coal existence in China. However, this will cause a significant environmental footprint. One potential upgrade for coal-fired power plants would be introducing Integrated Gasification Combined Cycle (IGCC), which turns coal into pressurized flammable gas while removing hazardous elements in the coal such as sulfur and mercury, thus significantly reducing emission.

Currently, the total normal form natural gas reserve in China is about 38.4*10^13 cubic meters, which is abundant. Also, China is ramping up pace to import natural gas from neighboring country. Since natural gas is one of the usable fuels in CCPP, there is immense potential to adopt CCPP on a larger scale.

4. Conclusion

Gas-turbine power cycle and steam-turbine power cycle are fundamental workhorses for electricity generation thus is significant for modern society. Both power systems have their own advantages, disadvantages, and optimization methods, which are crucial to realize when designing and implementing them. In the light of the high-performance gas turbine, Combined Cycle Power Plant became possible and can further boost the efficiency, outweighing both standalone systems with respect to thermal efficiency. Apart from potential restrictions and limitations, the future of CCPP is very promising given its economic and environmental merits. Especially for countries with abundant traditional fossil fuel resources or use fossil fuel as main means of power generation, CCPP is the trend for the foreseeable future.

References

[1] Dzida M, Olszewski W. 2011 Comparing combined gas tubrine/steam turbine and marine low speed piston engine/steam turbine systems in naval applications. Polish Maritime Research, 18(4): 43-48.

[2] Dincer I, Zamfirescu C. 2014 Advanced Power Generation Systems ed Dincer I and Zamfirescu C (Canada: University of Ontario Institute of Technology), 199-310.

[3] Nishida K, Takagi T, Kinoshita S. 2003 Performance Analysis of Regenerative Steam Injection Gas Turbine Systems. Energy and resources, 20: 24.

[4] Breeze P. 2018 Gas Turbine Combined Heat and Power Systems - ScienceDirect. Combined Heat and Power, 20: 51-59.

[5] Chen Q, Qi Q, Zhou Y. 2013 Interior Ballistic Research on Gas and Steam Launch Power System. Advances in Intelligent Systems & Computing, 181: 81-85.

[6] Shayan M, Pirouzfar V, Sakhaeinia H. 2019 Technological and economical analysis of flare recovery methods, and comparison of different steam and power generation systems. Journal of Thermal Analysis and Calorimetry, 139(3): 78-84.

[7] Mei J I. 2001 Discussion on Control System Interface of Integrated Gas-steam Combined Cycle Power Plant. Journal of Shanghai Institute & Electric Power, 20: 31-38.

[8] Yinka B, Afon D, David V. 2012 An Assessment of Air Emissions from Liquefied Natural Gas Ships Using Different Power Systems and Different Fuels. Journal of the Air & Waste Management Association, 58(3): 404-411.

[9] Klochenko V S, Karamanyan A K. 2002 Use of steam-gas ejector for improvement of capacity and explosion safety of pulverization systems in thermal power plants. 43(4): 274-280.

[10] Habib M A. 1994 First- and Second-Law Analysis of Steam-Turbine Cogeneration Systems. Journal of Engineering for Gas Turbines & Power, 116(1): 15-19.