Computer Aided Intelligent Control of Inlet Air Cooling System in Combined Cycle Power Plant

Yuanji Sun [1, a, †], Hongxu Lai [2, *, †]

[1] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

[2] School of Engineering, The Ohio State University, Columbus 43210, United States

* Corresponding Author Email: lai.516@buckeyemail.osu.edu, [a]2196113910@stu.xjtu.edu.cn

[†]These authors contributed equally.

Abstract. In hot climate, the overall efficiency of combined cycle power plant (CCPP) decreases dramatically owing to the rise of environment temperature, which decreases the mass air flow to the compressor. Therefore, the gross power and thermal efficiency drop. Worldwide practice uncovers that gas turbines generate up to 20% less power in summer than in winter. A brief introduction of the CCPP and analysis of influence of ambient temperature are provided in this work. Furthermore, this essay gives a outline of the combined cycle based on several inlet air cooling technologies and why they are necessary. Since 1987, more and more inlet air cooling systems have been devised, each of which has its own advantages and limitations. They are mainly divided into 2 classes. Low cost and ease of operation are the main advantages of evaporation systems. However, they are strictly restricted by the wet-bulb temperature. In terms of the mechanical systems, which are not limited to it, command high initial and operating cost. The absorption chiller utilizes the waste heat of exhaust gases, which means they have great potential. In the end, economic criteria and problems to be solved are mentioned.

Keywords: component, combined cycle, thermal efficiency, inlet air cooling.

1. Introduction

In recent years, people lay more emphasis on the carbon emissions. However, fossil fuels are still the main energy source for most countries, which account for 85% of the world's primary energy consumption. In addition, fossil fuels, as non-renewable energy, will run out one day. One of the most critical solutions to reduce carbon emissions and improve thermal efficiency is using the CCPP, which increases the overall thermal efficiency to about 60% from the simple cycle about 34-42% [1]. It is widely used in commercial applications all over the world for its high thermal efficiency, mature technology and ease of operation [2]. With the improvement of natural gas-fired combined-cycle (NGCC) plants, in 2018, it replaced the coal-fired plants as the most adopted electricity generating method in America. In January next year, NGCC power plants generates 20 GW more electricity than coal-fired power plants. Recently the combined cycle gas turbine (CCGT) is the most efficient energy conversion system technology [3].

Environmental conditions have critical influence on plants by affecting cycle fluid. During hot climates like summer and tropical countries, the output of CCPP decreases dramatically owing to the drop of mass air flow into compressor. When the temperature rises about 1℃, the output of GT deceases by 1% [4]. At the same time, the rate of exergy destruction declines obviously [5]. In order to deal with this problem, various inlet air cooling systems occur.

Since a Michigan power plant firstly attempted to cool the GT inlet in the late twentieth century [3], many studies have focus on the inlet air cooling systems. Each of these have their own advantages and limits [6]. This essay will give an introduction about their work, and analyse present status and developing trend.

2. Combined Cycle Power System

2.1. Working principles of CCPP

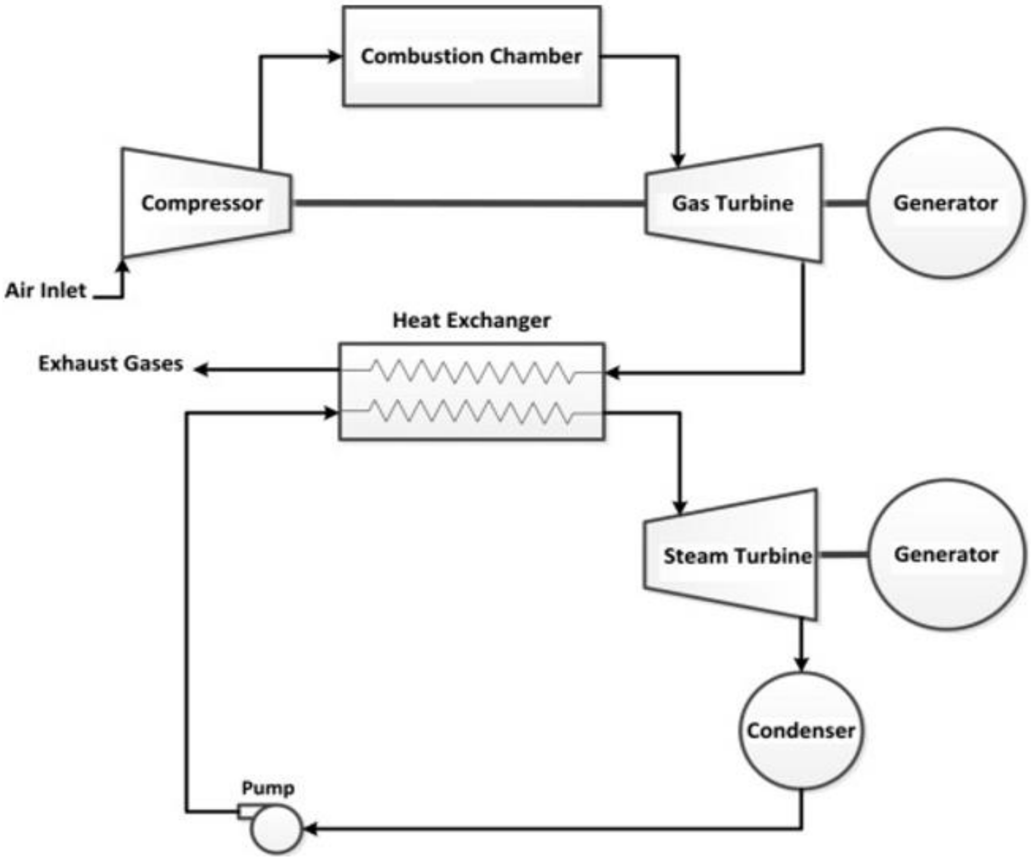

Figure 1. A Schematic diagram of CCPP

Fig.1 shows the basic principle of CCPP, a combination of the Brayton and Rankine cycle operating in different temperature [1]. First, the natural gas or other combustible gas is pressurized by the gas compressor and mixed with the air sent to the combustion chamber to generate high temperature and high-pressure gas. The gas turbine expands and does work to promote the gas turbine to drive the compressor and external load. In contrast to the conventional cycle, the heat exchanger is used to generate steam with high pressure and temperature, which together with the gas turbine drives the generator to produce power [4]. This increases the overall thermal efficiency to about 60% from the simple cycle about 34-42% [1].

In terms of the working fluids, almost all factories employ air and steam, while organism or other fluids are hardly adopted [4].

2.2. Influence of the environment temperature

Nowadays, the CCPP is widely used in commercial applications for its high thermal efficiency, low cost and ease of operation [2]. People pay more attention to what determine the performance. Ibrahim et al. found that the overall performance of a combined cycle is mainly affected by the environment temperature, compression ratio, and inlet temperature [7].

A simulation was founded by Eshoul et al. depending on the situation in Libya as Fig. 2 and Fig. 3 shows [8]. When the ambient temperature decreases by 10 °C, the power decreases by about 25MV, and the thermal efficiency decreases by about 0.05%. Meanwhile, Fig.4 shows that the CO_2 releases increase by about 0.36% for every 10 ℃ raise in ambient temperature.

Results by Zhang et al [9] show the output power of CCPP at full load increases by 14.2MV and the heat consumption rate rises by 2.3%, when the inlet air temperature deceases from 32°C to 12°C.

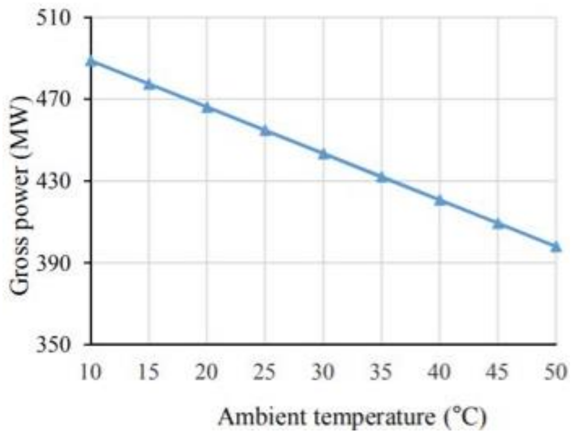

Figure 2. Effect of ambient temperature on CCPP gross power

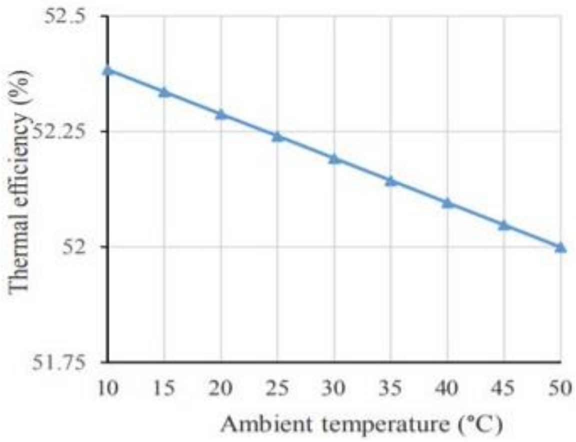

Figure 3. Effect of ambient temperature on plant thermal efficiency

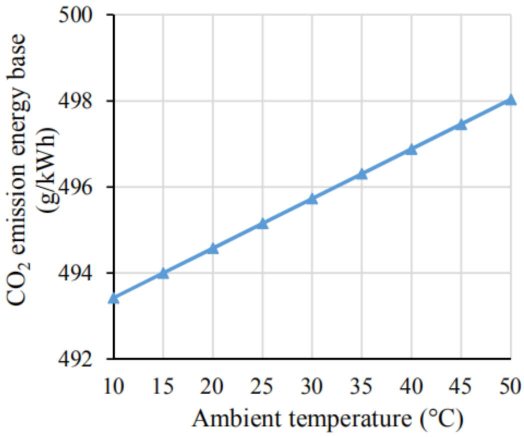

Figure 4. Effect of ambient temperature on CCPP CO2 emission (energy base)

3. Inlet air cooling methods

Cooling the inlet air is a means to boost the energy production of a gas cycle by reducing the temperature of inlet air to the cycle [10]. At present, there are a variety of inlet air cooling technologies, which are mainly divided into two categories: (1) Water evaporation system, which It uses the latent heat absorbed by water as it evaporates in the air to directly lower the temperature. (2) Direct Contact systems, including mechanical refrigeration and chillers. Different approaches have their own advantages and disadvantages. Whether to adopt it depends on local conditions [4], as shown in Figure 5.

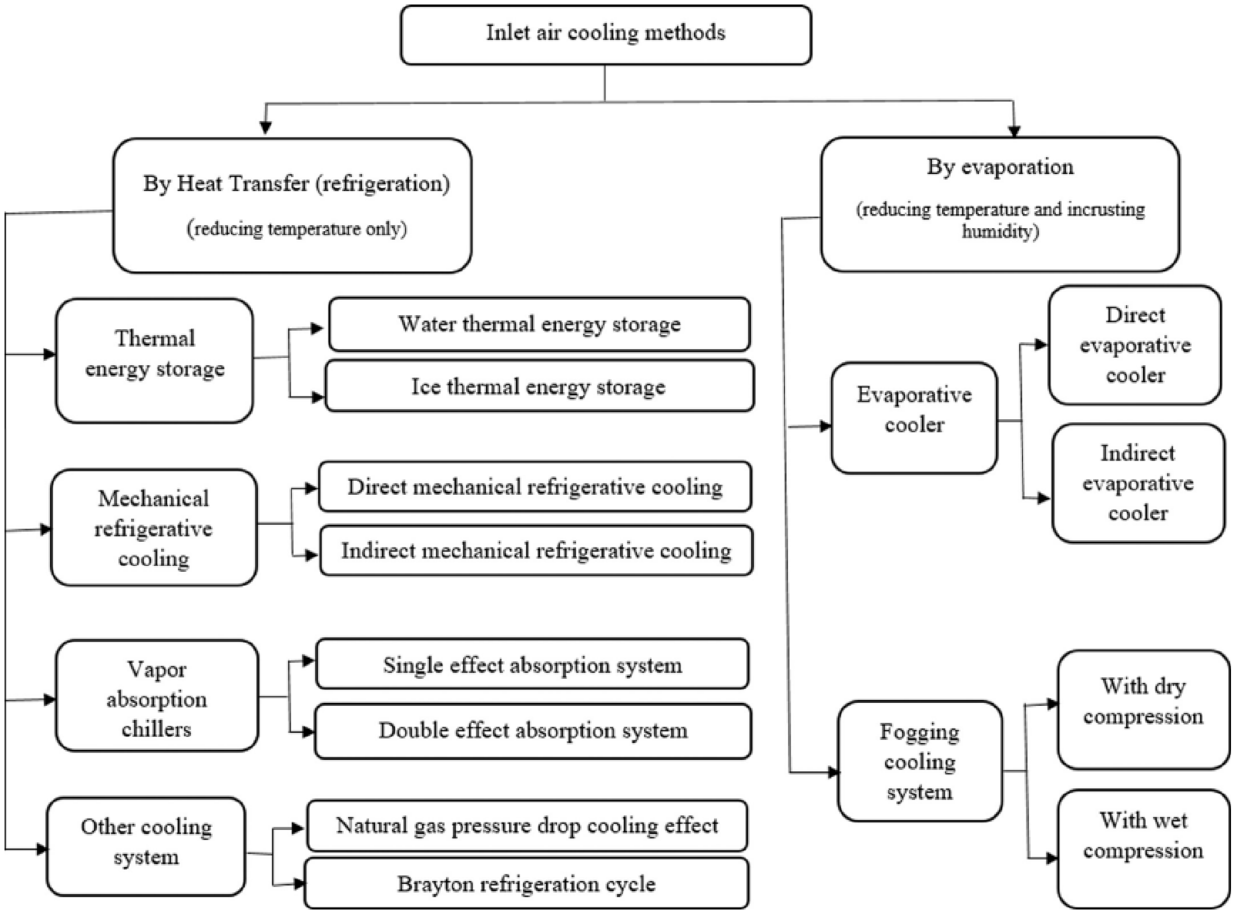

Figure 5. Classification of various inlet air-cooling technologies

3.1. Evaporation system

Evaporation system mainly consists of the evaporative cooler and fogging cooler system. When unsaturated air and water contact, heat and mess will be transferred between them. Therefore, the sensible heat of air is transferred into the latent heat absorbed by water as it evaporates, decreasing its temperature, which can be regarded as an adiabatic humidification process of air.

3.1.1. Evaporative cooler

It is to evaporate water to the inlet air of GT compressor, transfer the sensible heat in the airflow to the water supply to decrease the air temperature. Sometimes, the water mixture can be removed when the working fluids is hot enough.

The evaporated water passes through a rigid dielectric block into the surrounding airflow to increase the density of air, and vapor may enter the machine consuming more fuel.

3.1.2. Fogging

Direct fogging is a cooling method that converts the desalinized water into fog through a high-pressure nozzle operating at 70-200 bar. When the fog in evaporation of gas turbine inlet pipe, the fog refrigerate. Compared with traditional evaporative coolers, this technology allows efficiency to approach 100%. Fig. 6 shows a schematic diagram of direct fogging system basing on GT.

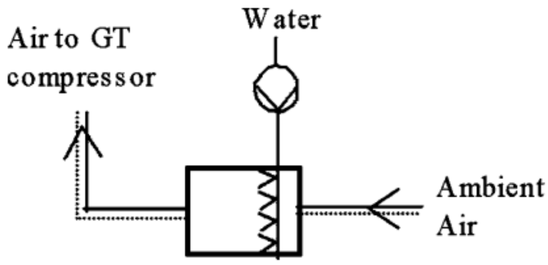

Figure 6. Diagram of direct inlet fogging of air

It consists of a set of atomizing nozzles and a range of high-pressure reciprocating pumps to provide desalinization [6]. When the fogging system is used, the net electrical efficiency decreases slightly. The energy consumption of water atomization in atomizer is the cause of efficiency reduction [11].

The main advantages of this cooling method are less initial investment. lower operation and maintenance costs. In addition, the formation of NOx is closely related to the combustion temperature. One disadvantage of this method is that when droplet drops on the compressor, it poses a threat to the blades of compressor. Moreover, its refrigeration capacity is also low, which can only be cooled to the wet-bulb temperature at most. Meanwhile, it is greatly affected by the environmental temperature. So, it is suitable for hot and dry areas. A fog nozzle can improve the power further. When air is heated during compression, droplets evaporate and flow into the compressor [7]. The US spray cooling system is applied to 5MW-250MW gas turbine inlet cooling by 11℃ and increased output by 10% - 18% per reduced intake temperature.

3.2. Indirect Contact system

Indirect contact systems are used when cooling below the wet bulb temperature is desired. It can maximize the power output depending on the chiller conditions. A critical disadvantage of indirect contact system is that increased heat exchanger inlet losses lead to a slight decline in GT plant output.

3.2.1. Direct Mechanical refrigeration

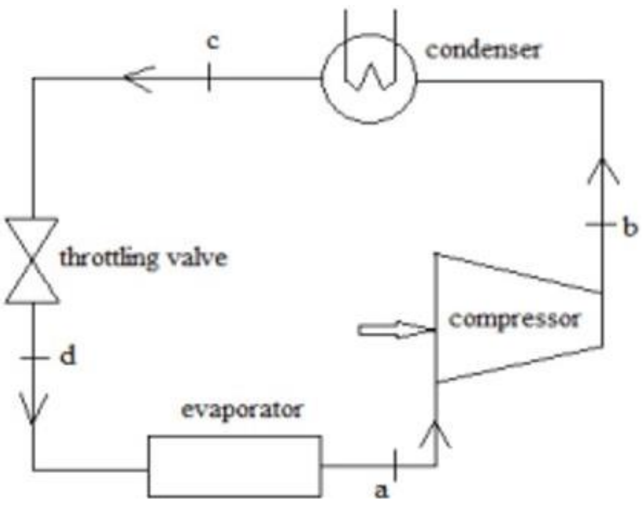

Figure 7. Schematic diagram of Vapour Compression

Direct mechanical refrigeration can reduce air temperatures by circulating refrigerant fluid directly through heat exchangers mounted on air intakes. The heat exchanger thus becomes the evaporator for the refrigeration cycle [8], as shown in Figure 7.

It uses compression refrigeration cycle, where the cold source is obtained at the cost of mechanical work consumption. Compressor inlet air is absorbed by cooling water or coolant in the heat exchanger. The advantages are simple system, low initial investment, and low cooling temperature. However, it consumes electricity, which means about 25% to 30% of the inlet cooling power generation has to be used to drive the system, thus reducing the benefits of intake cooling. In addition, the class CFC work quality used by compression refrigeration machines will damage the ozone layer and affect human health and survival. According to the relevant provisions of the Montreal Protocol [10], the work quality is about to cease from use [12].

3.2.2. Water Storage

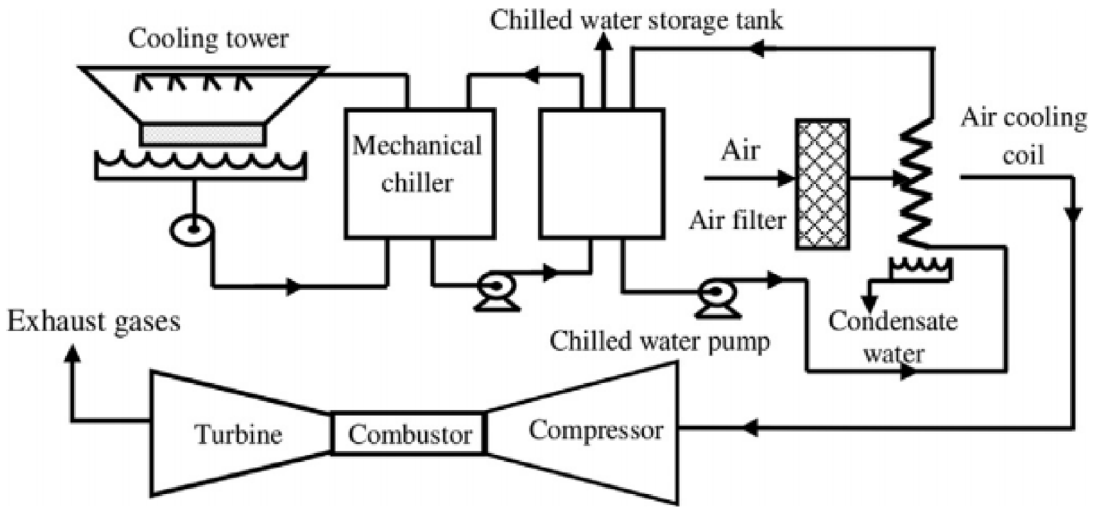

Figure 8. Flow chart of mechanical refrigerator with chilled water storage unit

Mechanical refrigeration system is a common refrigeration method, in which hot air enters a cooling coil to be cooled by the flow of the mechanical chiller, as illustrated in Fig.8.

The cost of this approach is lower than absorption chiller in facilities, operation and maintenance. Nevertheless, about 30% of benefits will pay for electricity consumption [13].

The air temperature can be reduced from 35℃ to 7℃. Therefore, considering that the financial cost of the cooling system is directly related to the total cooling time, it improves the performance of the plant by 10% [14].

3.2.3. Ice Storage

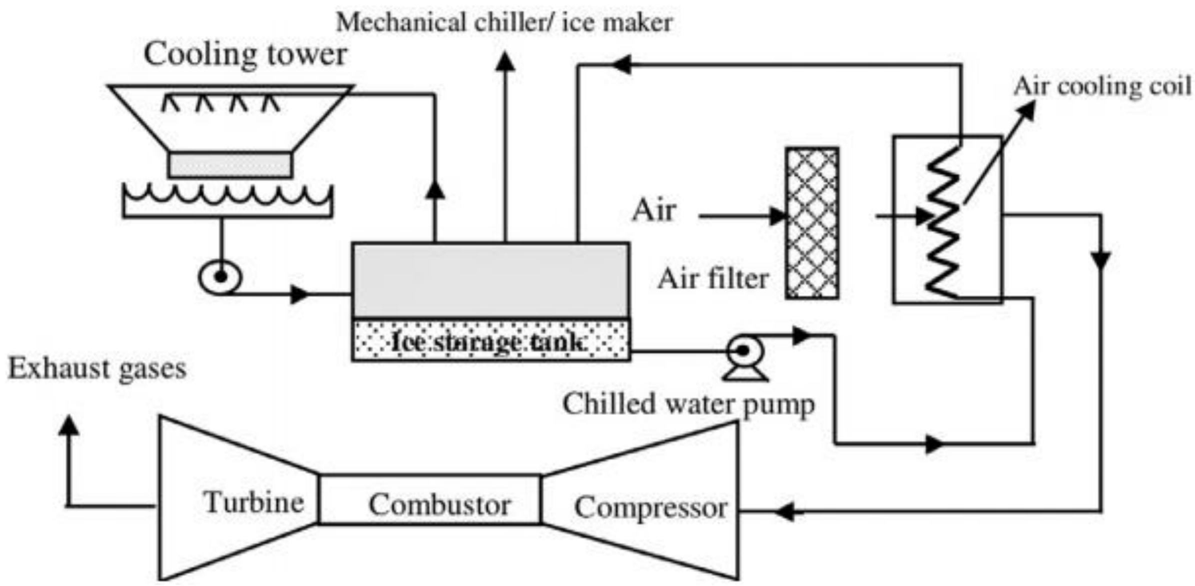

Figure 9. Diagram of ice storage refrigeration

It is also one of the compression refrigeration, which use electricity price difference in different periods. In the off-peak period, the low price of electricity is used to drive the compression refrigerator to refrigerate, and the cold energy obtained is stored in the cold storage device. During peak demand, the refrigeration unit shuts down and releases cold energy stored in the storage unit as shown in Fig.9.

This can increase the power consumption in the off-peak period and expand the power generation in the peak period to adjust the load of the grid. Low - price electricity is used for cold storage, and high - price electricity is used for power generation in peak period. The system is suitable for the area with large difference between peak and valley of electricity consumption. In addition, high load operation during cold storage reduces investment to some extent.

Shirazi et al investigated an ice storage refrigeration model from thermal, economic and environmental perspectives [15]. The results show that the output power and efficiency of this system are increased by 11.63% and 3.59%. In addition, additional expense associated with it will be earned within about 5 years.

3.2.4. Absorption chiller

Another promising method of inlet air cooling is steam absorption cooling, which uses waste heat from power plants to drive chillers, providing cold source. And it reduces the intake temperature through the surface type heat exchanger. Because it uses a low grade of thermal energy to drive the system and take full advantage of waste heat from power stations. The most common absorption cooling systems are and systems. Due to the strong on-site installation process of ammonia absorption refrigeration machine, huge equipment, high cost, high explosion-proof level requirements, and even the toxic low concentration of ammonia, lithium bromide absorption refrigeration technology is generally adopted [16].

Absorption chiller can be designed to be either single or double effect. Kakaras et al. argue that a single-effect system will have a coefficient of performance (COP) of 0.7–0.8 and a double-effect unit a COP of 1.2–1.3, also depending on the quality of the heat source [17], as shown in Figure 10.

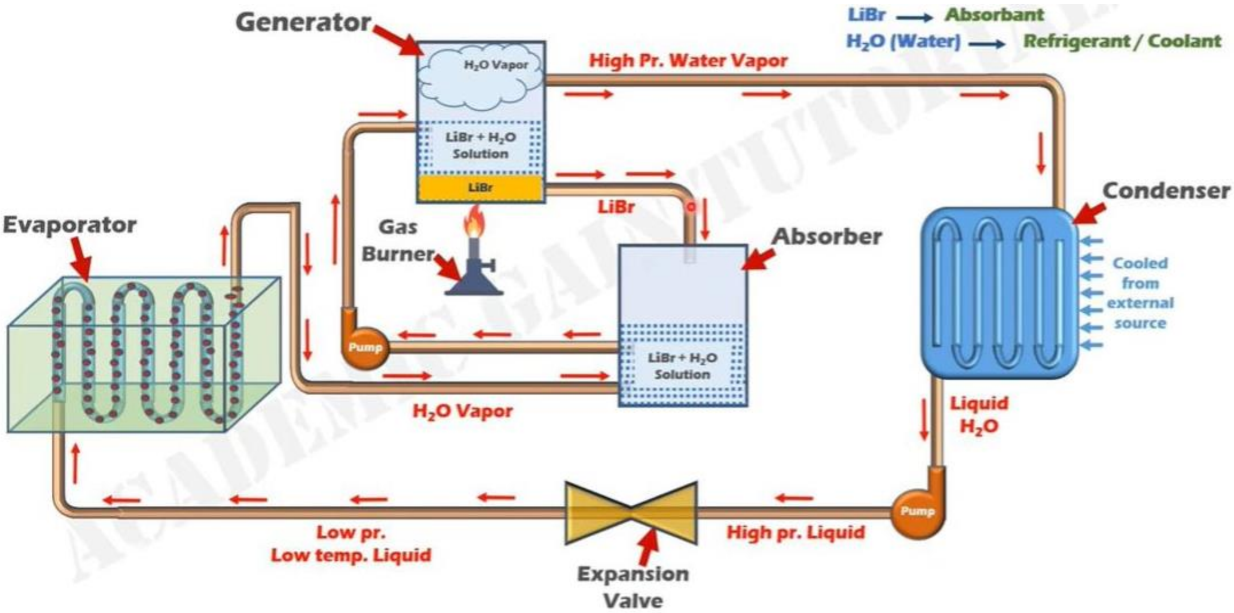

Figure 10. Schematic of absorption chiller [12]

3.2.5. Liquid Gas Refrigeration

The liquid natural gas with methane as the main component is desulfurized and dehydrated, then liquefied into liquefied natural gas (LNG) through low temperature. LNG has the advantages of available long-distance transportation, low transportation cost, clean and environmentally friendly. There is a large quantity of cold energy released during gasification, which can be utilized. Then the cold energy is transferred to the gas turbine inlet air by using $C_2H_6O_2$ solution as intermediate medium. Recycling LNG cold energy investment is comparable to direct contact, with a unit kW investment of new generation capacity of \$100 ~ \$150 [18].

4. Economic criteria

Economics fundamentally determines whether it is feasible. There are several main factors that need to be fully considered [19]:

(1) Local ambient temperature and humidity
(2) Cost of installing and maintenance
(3) Cost of electricity, water and fuel
(4) Energy revenue [20]
(5) Electricity price at peak and valley [21]
(6) Financial condition [22]

5. Conclusion

This paper gives an introduction about the CCPP and the significant impact of the ambient temperature. Further, it renders a review about the inlet air cooling methods and its application.

The inlet air cooling methods are mainly divided into water evaporation system and heat transfer system. The expenditure of initial investment, operation and maintenance are less. The evaporative systems are limited by the wet-bulb temperature and ambient humidity. One problem to be solved is the water carryover issue. In fogging systems, the wet-bulb temperature can be reached, thus achieving an efficiency of 100%. However, the compressor can cause serious damage due to dripping water. Compared with heat system, the cooling capacity of mechanical system is much higher as they can produce air temperature whatever people want. The corresponding is the cost of 25%-30% benefit of air cooling depending on the chiller conditions. Absorption chiller is a great alternative for utilizing the waste heat. The feasibility of increasing the output power of a simple GT unit during high temperature periods without the use of CHP and single-stage libr absorption chiller needs to be investigated. And a combination of refrigeration systems may have a great potential.

Acknowledgments

Yuanji Sun and Hongxu Lai completed the collection and search of information and wrote different parts of the article.

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