INCREASING ENERGY EFFICIENCY IN ENERGY PRODUCTION: THE ROLE OF HEAT AND POWER COGENERATION SYSTEMS

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Abstract

Growing global demand for energy and reducing environmental impacts create a need for energy-efficient technologies. Combined heat and power (CHP) is more efficient than traditional methods in terms of efficiency because it produces both electricity and thermal energy. In this paper, we review the current state of combined heat and power (CHP) technology, evaluate its performance in various applications, and discuss the importance and challenges of its wider use. Combined heat and power systems have both environmental and economic advantages. This is primarily due to their high efficiency. Today, it already reaches 60%, which is 82% of the theoretically possible level.

Keywords: energy efficiency, combined heat and power, cogeneration, sustainable energy, energy-saving technologies

I. Introduction

In the structure of world energy, the share of combined-cycle plants (CCP) producing electric and thermal energy is increasing. In this case, thermal energy is used for additional production of electric energy. A combined-cycle plant consists of two separate units: a steam power unit and a gas turbine unit. Both natural gas and petrochemical products, such as fuel oil or diesel fuel, can serve as fuel for a CCP.

Systems that simultaneously produce both heat and electricity are called combined heat and power systems or "cogeneration" systems. Combined heat and power systems are widely used in the paper, chemical, pulp and paper, and oil refining industries. These industries make maximum use of combined heat and power systems to meet the needs of the industry using both electrical and thermal energy. Most combined heat and power systems use steam turbines (Rankine cycle) and gas turbines (Brayton cycle) to produce electricity. In gas turbines, the working fluid is air, while in steam turbines, the working fluid is steam. Using waste heat in power production is economically advantageous.

Fig. 1 and 2 show idealized diagrams of thermal power plant systems with steam and gas turbines.gas turbines.

Power systems that only produce electricity dump large amounts of waste heat into low-temperature reservoirs such as rivers, oceans, and the atmosphere. Systems that only produce heat do not utilize the potential of high-temperature working fluids to create work. Thus, CHP systems attempt to utilize fossil fuels as much as possible.

Combined heat and power systems produce both electricity and heat using a single fuel source. This is also an indication of the high efficiency of combined heat and power systems, as they produce both heat and electricity without reusing fuel, thereby reducing greenhouse gas emissions and reducing waste to the environment.

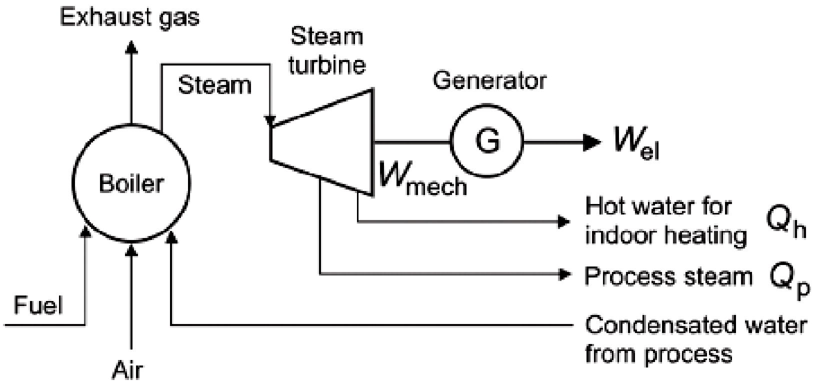

Figure 1: *Steam Turbine Combined Heat and Power System*

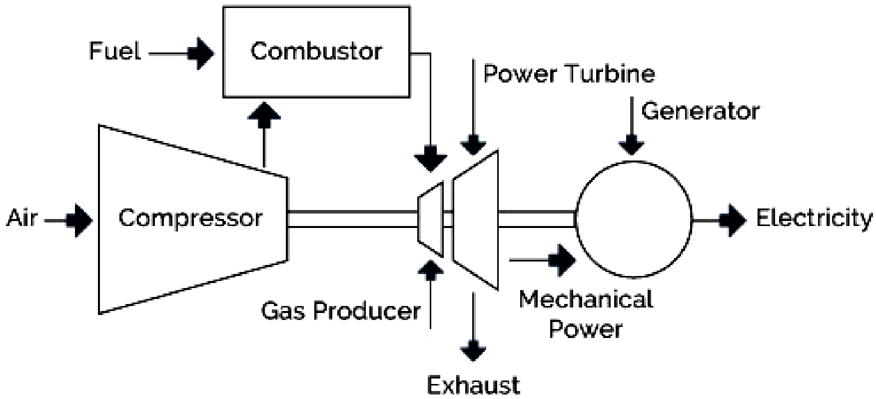

Figure 2: *Gas Turbine Combined Heat and Power System*

The concept of cogeneration was first used in the 19th century to produce industrial waste heat. Previously, this waste heat was used in industrial processes. Technological advances in the 20th century, as well as the development of turbine and engine technologies, have had a positive impact on the development of combined heat and power systems.

CHP technology has developed significantly in recent years. Advances in combustion engineering, materials science, and control systems have helped improve the efficiency and reliability of CHP.

CHP systems with different configurations such as gas turbines, steam turbines, and combustion engines have expanded the applications of CHP. The main results are that CHP reduces greenhouse gas emissions, increases efficiency, and saves energy or fuel, which reduces emissions to the environment.

In addition, research is focused on optimizing the integration of the CHP system with renewable energy sources. Combined cycle systems and fuel cells are also under development and are an ongoing topic of research.

II. Main configurations of the CHP system project

There are three main types of CHP plant configurations: a steam turbine design (Fig. 1), a gas turbine design (Fig. 2), and a combined cycle design that includes both a gas and steam turbine (Fig. 3).

A steam turbine is powered by high-pressure steam. This high-pressure steam is produced by a boiler or a heat recovery steam generator (HRSG). It differs from gas turbines in that it does not consume fuel directly. The fuel that powers the process is a fired boiler or plant equipment that produces heat for the HRSG.

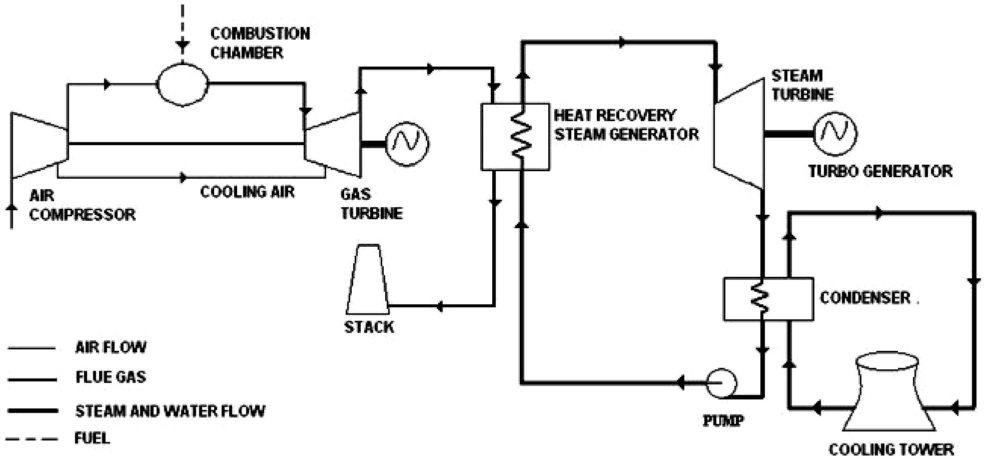

Figure 3: *Gas and Steam turbine design*

Steam turbines follow the Rankine cycle (see Fig. 1). This thermodynamic cycle involves pumping water at high pressure and heating it to produce high-pressure steam. Steam turbines convert the high-pressure steam into mechanical energy, which powers an electric generator. CHP systems use low-pressure steam from the steam turbine to meet on-site heating needs. The condensed liquid is returned to the pump and the process is repeated.

Gas turbines are open-cycle, constant-pressure heat engines. An application of the Brayton thermodynamic cycle. The gas turbine (see Fig. 4) compresses air and then mixes it with fuel. Combustion chamber. The combustor receives high-pressure fuel (200-400 psig) depending on the number of compressor stages and the compression ratio. If the fuel supply pressure at the field is insufficient, a gas compressor can be used to increase it. The combustor sends the hot gas to a turbine, which drives a mechanical shaft. The rotating shaft drives an electric generator and an air compressor.

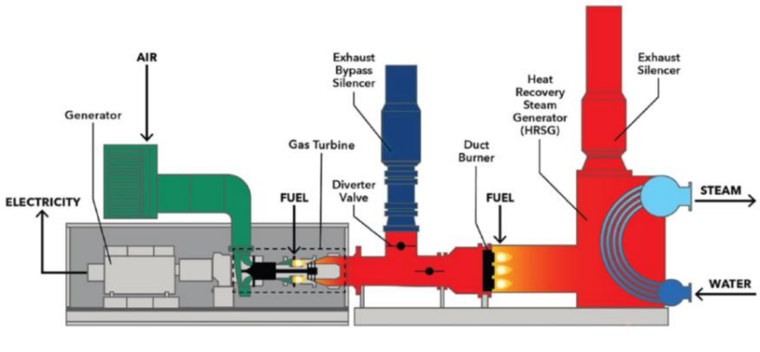

Figure 4: *Gas turbine design*

A combined cycle gas turbine (see Fig. 5) uses both a gas turbine and a steam turbine to generate electricity from the same fuel source, resulting in higher efficiencies than standard simple cycle plants. In a combined cycle plant, natural gas or other gaseous fuels are first burned in a combustion turbine to generate electricity.

After passing through the turbine, the hot exhaust gases retain useful energy that would otherwise be wasted. This residual heat is recovered by a heat recovery steam generator, which uses the thermal energy in the exhaust gases to boil water and generate steam.

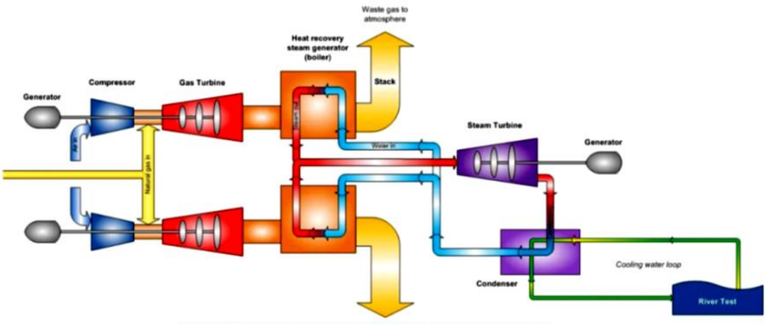

Figure 5: *Combine Cycle Gas Turbine Design*
https://www.marchwoodpower.com/ccgt/

III. Methods of calculation of system efficiency of heat and electricity production

CHP applications involve recovering heat that would otherwise be wasted in each application. Here's how CHP improves fuel efficiency.

The two metrics most commonly used to describe the efficiency of a CHP system are total system efficiency and net electrical efficiency.

The metric that compares the efficiency of a CHP system to its traditional counterparts (electricity supplied from the grid and useful heat generated in a local boiler) is called total system efficiency. Total system efficiency may be an appropriate performance metric for comparing the energy efficiency of a CHP system to traditional power sources on-site, if that's your goal.

Effective electrical efficiency is a metric used to compare electricity generated by power plants with electricity generated by cogeneration plants. If cogeneration power is to be compared with conventional electricity generation, the effective electrical efficiency metric is the correct choice. It is normal that one methodology does not fit all cases. Therefore, the methodology used must be chosen carefully and the results verified.

Overall System Efficiency

The overall system efficiency (ηo) of a CHP system is the net useful heating output (∑Q) and the sum of the net useful electrical output (W) divided by the total fuel energy input (Q), as shown below:

$$\eta_0 = \frac{W_0 + \sum Q_{TH}}{Q_{FUEL}}$$

Overall system efficiency is based on the fuel consumed and evaluates the combined outputs of the CHP plant (useful heat output and electricity).

CHP systems typically achieve overall system efficiencies of 65-70%.

Note that this methodology does not differentiate between electricity production and heat production. Thus, this methodology treats electricity and heat production as having equal value. In fact, electricity considered the more valuable type of energy due to its unique characteristics.

Effective Electrical Efficiency

Effective electrical efficiency compares the efficiency of combined heat and power systems to that of conventional power plants. The effective electrical efficiency calculation isolates the electrical output of a CHP system and takes into account the net heat output and fuel consumption.

The formula for calculating effective electrical efficiency is:

$$\mathcal{E}_{EE} = \frac{W_e}{Q_{FUEL} - \sum(Q_{TH}/\alpha)}$$

This metric is critical to comparing the efficiency of electricity generated by a CHP plant with electricity supplied from the grid, the primary source of electricity generation.

Effective electrical efficiency provides a clearer picture of the efficiency of electricity generated by CHP systems by calculating the thermal efficiency and the efficiency of conventional thermal generation.

Typical boiler efficiencies are 80% for natural gas boilers, 75% for biomass boilers, and 83% for coal boilers. Combustion turbine based CHP systems have an efficiency of 60-70%. Reciprocating engine based CHP systems have an efficiency of 70-85%.

IV. Advantages and disadvantages of combined cycle gas turbine plants

In the production of electricity, a combined cycle power plant is an assembly of heat engines that operate in tandem from the same heat source, converting it into mechanical energy to drive electric generators. The process begins with a gas turbine. In a gas turbine plant, the turbine is rotated by burning fuel (fuel oil, diesel fuel, natural gas). Natural gas enters the combustion chamber of the gas turbine, where it is burned, creating a stream of hot gas at high speed. The expansion of the hot gas flow through a series of turbine blades causes the turbine to rotate. The principle of operation is that in combined cycle plants, on the same shaft as the gas turbine is the first generator, which produces electric current due to the rotation of the rotor.

Then comes the stage of waste heat recovery. Passing through the gas turbine, the combustion products give it only part of their energy and at the exit from the turbine still have a high temperature (1300-1400°C). Then the combustion products enter the waste heat boiler (WHB), which is a series of heat exchangers that can transfer heat from the exhaust gases to water. There they heat the feed water and water vapor is formed. This reduces fuel consumption and increases the efficiency of the entire plant. The temperature of the combustion products is sufficient to bring the steam to the state necessary for the rotation of the steam turbine ($t=500^0C$ and $P=80$ atm.). The second generator mechanically connected to the steam turbine.

Advantages of a combined cycle gas turbine plants

➢ *High efficiency.* Combined heat and power plants are known for their high thermal efficiency. By combining the steam and gas turbine circuits, this system is more efficient than traditional gas or steam turbine power plants because it uses a larger share of the energy contained in the fuel. Today, it already reaches 60%, which is 82% of the theoretically possible level. Previously, all the heat contained in the fuel that could not be converted into electricity was released into the environment, causing thermal pollution. The reduction in thermal emissions from a CCP compared to a steam power plant is exactly to the extent that the fuel consumption for electricity generation is lower. The use of a combined cycle reduces specific fuel consumption by approximately 6-12%.

➢ *Flexibility:* Combined cycle gas turbines operate efficiently at part load and provide stability during the growing but intermittent growth of renewable energy generation.

➢ *Low emissions.* Compared to other power plants, burning natural gas in a gas turbine results in lower emissions of pollutants and greenhouse gases, such as nitrogen oxides (NOx), sulfur dioxide (SO_2) and carbon dioxide (CO_2). The consumption of cooled water in a combined cycle plant is approximately three times less than in a steam power plant per unit of generated electricity. This is due to the fact that the capacity of the steam part of a combined cycle plant is 1/3 of the total capacity, and a gas turbine plant requires virtually no cooling water;

➢ *Fast start-up and load response.* The combined cycle gas turbine plant has high maneuverability, which is an important factor in ensuring the reliability of the power system, significantly easing the problem of covering the variable part of the electric load schedule. In addition, combined cycle gas turbine plants can function as power sources with both base and peak load. This means that they can operate continuously, providing a stable power base, and their ability to quickly increase capacity makes them valuable for meeting sudden surges in demand;

- Combined-cycle power plants have a lower (approximately 40%) *specific cost of installed capacity*. This is due to the smaller volume of the construction part, the absence of a complex power boiler, an expensive chimney, a regenerative feed water heating system, the use of a simpler steam turbine and a technical water supply system, etc. CCP have a significantly shorter construction cycle. The main equipment of a CCP is delivered to the construction site in large modules, which allows for a significant reduction in installation time and provides the ability to introduce equipment in stages. It is much more profitable to build power plants with CCP than nuclear power plants;.
- *Significantly smaller construction cycle (9-12 months);*

Disadvantages of combined cycle gas turbine plants.

- *High temperatures mean high maintenance requirements*. Due to the high temperatures generated in a combined cycle power plant, care must be taken both at the design stage and during maintenance. The combustion chamber temperature can reach 1700°C, which is dangerous for the materials in the system and can reduce their service life.
- *Seasonal capacity limitations*. Seasonal capacity limitations are one of the disadvantages of combined cycle gas turbine plants, as combined cycle gas turbine plants are more efficient in the winter months due to heat recovery and the useful capacity is at its highest.

V. Practical use of a combined cycle gas plant

Currently, 3 combined cycle gas plants have been installed in Azerbaijan at the power plants of Azerenerji OJSC.

One of them is installed at the Sumgayit power plant with a capacity of 517 MW. According to experts' forecasts, the annual productivity of the Sumgayit Thermal Power Plant will be 3.8 billion kW/hours at a cost of 230 grams of fuel per 1 kW/hour of electricity. The demand for gas fuel will be 100 thousand m3 per hour or 630 million m3 per year. The general contractor for the construction of the power plant was Siemens.

At the Shimal State District Power Plant there is a combined cycle gas plant with a capacity of 400 MW, built by the Mitsui/Mitsubishi alliance. At the Shimal State District Power Plant (Shimal-2) there is another combined cycle gas plant with a capacity of 409 MW. Construction is carried out by the Japanese company Toyo Engineering Corporation.

According to Azerenergy estimates, due to the joint operation of the Shimal and Shimal-2 Combined cycle gas turbin units, the total volume of electricity generated by the power plant will be 5.7 billion kWh per year.

Currently, modernization work is ongoing at Azerbaijan's largest power plant, resulting in the construction of a combined gas turbine facility with a capacity of 1800 MW and its integration into the energy system.

The difference between the combined gas turbine station and the previous station is that while 335 grams of fuel used for 1 kW of energy in the previous station, this number will decrease by 110 grams to 225 grams in the new station.

As a result, the amount of waste released to the environment will decrease and 1.2 billion m3 of natural gas will be saved annually, and if the price of natural gas in Azerbaijan is taken into account, 200 million AZN financial funds will be saved annually. The efficiency of the station will increase between 22 percent and 60 percent.

Compared to steam power of the same capacity, the difference between combined heat and power plants is that the combined cycle gas turbin unit uses about three times less cooling water.

Today, the use of combined cycle gas turbines is a factor in energy security and welfare of the state.

VI. Conclusion

1. Combined Heat and Power systems increase efficiency by simultaneously producing both electricity and heat using a single fuel source. This not only reduces fuel consumption, but also reduces greenhouse gas emissions and waste to the environment.

2. Combined Heat and Power systems are more efficient than other conventional plants in different configurations. Brayton cycle gas turbine systems and Rankine cycle steam turbine Combined Heat and Power systems are economically and environmentally more efficient than other conventional plants.

3. The combined cycle gas turbine design, which combines both gas and steam turbines, is the most efficient in terms of efficiency, with efficiencies as high as 70%. Despite the disadvantages of temperature and seasonal power limitations, the benefits of combined cycle gas turbin are high.

4. The practical application of combined cycle gas turbin systems in Azerbaijan's power plants emphasizes their role in increasing the energy efficiency and sustainability of the country. The modernization and integration of new combined cycle gas turbin units is expected to significantly reduce fuel consumption and environmental impact, saving significant financial resources each year.

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