Methods of Improving the Efficiency of Thermal Power Plants

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Abstract. As one of the most important power sources in modern society, electricity takes up a large proportion of modern energy consumption. Among all those methods of power generation, fossil-fuel thermal power generation is one of the earliest ways of large-scale electricity production. Its popularity in the modern society comes from its stability and controllability. Given the wide applications of electricity around the world, improving the efficiency of thermal power plants would be an effective way to reduce the total energy consumption and protect the environment. The paper discusses the efficiency of energy transition and its determinant during each stage of power generations along with proposals to improve the efficiency of thermal power generation.

1. Introduction

Coal-fuel thermal power generation is one of the earliest forms of large-scale power generation. The first rudimentary power generator was invented by Frenchman Hippolyte Pixii in 1832. 28 years later, in 1860, the power generator was upgraded to allow for continuous and direct current power [1]. Nowadays, fossil-fuel thermal power generation is still the dominant method of power generation in the world. In 2017, coal-fueled thermal power plant produced about as much electricity as nuclear power, hydropower and renewable energy combined, according to the statistics of the International Energy Agency (IEA) and BP Group[2].

The over consumption of electricity demands an urgent need to improve the efficiency of fossil-fueled thermal power generation to save fossil fuel resources while minimizing contaminants such as SO_2, fly ash, and other waste gases. Thus, improving the efficiency of thermal power generation has always been a core topic of the power generation industry. Energy loss during different stages of thermal power generation will be discussed in the paper while methods of improving the efficiency of thermal power generation in modern power plants will be introduced.

2. Energy lost in each stage of thermal power generation

In the operation of the thermal power plant, the fuel gets ignited in the boiler (steam), producing vapors that expand in the turbine and driving its operation; the turbine would then power the generator to produce electricity[3]. Transitions of energy in this process would lead to significant energy loss. Currently, sub-critical thermal power plants can attain an efficiency of around 38%, compared with 41% by supercritical thermal power plants, while ultra-supercritical thermal power plants can reach up to around 44%. The main components that affect the efficiency of thermal power plants include boiler, turbine, and generator.

The major energy loss in a thermal power plant includes boiler heat loss, pipe heat loss, cold source loss, mechanical loss, and generator loss, etc.

2.1 Boiler heat loss

Due to incomplete combustion and exhaust heat, the energy in the fuel cannot be completely transferred to the steam, thus causing energy loss. Modern boilers can attain an efficiency of around 90%-94%.

2.2 Cold source loss

As a heat engine operating between high and low temperature, the thermal power plant is bound to discharge a large amount of heat into the cold environment in order to fulfill its duty, resulting in huge energy loss. Energy loss from a cold source (560⁰C/560⁰C) caused by efficiency threshold stands at about 64%-67.57%. The actual thermal efficiency of a modern thermal power plant usually ranges between 35% and 49%.

2.3 Generator loss

Modern generators usually attain an efficiency of around 96%-99%.

As shown above, in the three main stages of thermal power generation, most of the energy loss comes from cold source loss. Thus, the key to improving the total efficiency of a thermal power plant lies at the steam cycle (where the cold source loss takes place).

3. Methods of improving the efficiency of thermal power plants

Rankine Cycle, a term describing the efficiency of a steam turbine, defines efficiency as

$$\eta = \frac{W_{generator} - W_{pump}}{Q_{input}} \tag{1}$$

In an idealized model, the work done by the generator can be described as the heat input minus the heat wasted, so

$$\eta = \frac{Q_{input} - Q_{output} - W_{pump}}{Q_{input}} \tag{2}$$

In a T-S diagram, the heat input is described as

$$Q_{input} = \int_{S_t}^{S_b} T_{steam} dS \tag{3}$$

Where T_{steam} represents the temperature of the steam output of the boiler; S_b is the entropy of the steam input of the turbine, and S_t is the entropy of the steam output of the turbine. The heat output of the system is calculated by

$$Q_{output} = \int_{S_t}^{S_b} T_{condenser} dS \tag{4}$$

where $T_{condenser}$ represents the temperature of the water in the condenser; S_b is the entropy of the steam input of the turbine, and S_t is the entropy of the steam output of the turbine. Since the compression process is isentropic, the work done by the pump can be represented as

$$W_{pump} = \int_{V_c}^{V_b} p \, dV \tag{5}$$

where P_b is the pressure after compression and V_b the volume before the compression; V_c is the volume after the compression while p represents the pressure of the water. Since the volume of the water is relatively small compared with the steam, the work done by pump could almost be ignored in calculation, so

$$\eta = \frac{\int_{S_t}^{S_b} T_{steam} dS - \int_{S_t}^{S_c} T_{condenser} dS}{\int_{S_t}^{S_b} T_{steam} dS} \tag{6}$$

Thus, by increasing T_{steam} or decreasing $T_{condenser}$, the total efficiency could be improved.

At present, the most popular approaches to improve the total efficiency of a steam turbine include increasing the initial steam parameters, decreasing final steam parameters, installing a feed-water heater, and applying combined-cycle technology.

3.1 Increasing initial steam parameters

The temperature difference between the heat and cold sources determines the limit of the efficiency of a heat engine. As discussed above, the efficiency of thermal power plants could be improved by increasing the initial steam parameters.

High-volume-high-parameters supercritical (SC) and ultra-supercritical (USC) thermal power plants have proven stable and effective for large-scale commercial power generation. Supercritical power plants (25MPa, 566ºC/566ºC) can attain an efficiency 2%-3% higher than sub-critical power plants while ultra-supercritical (30MPa, 600ºC/600ºC) thermal power plants boast an efficiency even 2%-3% higher.

Since the end of the 20th century, organizations around the world started to develop Advanced Ultra-Super Critical (A-USC) thermal power plants and Circulating Fluidized Bed (CFB) combustion in an effort to improve the efficiency of thermal power plant [4]. In an A-USC thermal power plant, the steam parameters can reach 700ºC-760ºC, 30MPa-35MPa. The thermal efficiency of such a power plant can reach 55% (based on Lower Heating Value), where the major challenge lies in limitations of materials [5].

3.2 Lowering final steam parameters

Given a fixed set of initial steam parameters, lowering the final steam parameters would allow for a greater temperature difference between T_{steam} and $T_{condenser}$, thus lifting the theoretical efficiency threshold for thermal power plant.

In a thermal power plant, condenser is the place where the waste steam is condensed, after which the water will be pumped back in to the boiler. Most modern thermal plants use either water-cooled condenser or air-cooled condenser as the cold source in the cycle. Water-cooled condensers could be classified into cooling systems with open or close cycle [6]. Air-cooled condensers could be classified into direct or indirect cooling systems [7, 8, 9].

Among the three determinants of thermal efficiency of a power plant (namely initial temperature, initial pressure, and exhaust pressure), exhaust pressure plays a key role in determining total efficiency. The lower the final steam parameters, the higher the total thermal efficiency of the power plant. In the condenser, the pressure will be close to vacuum to guarantee an effective enthalpy drop of the steam in the turbine. Calculations have proven that when the initial steam parameters are set at 9.0MPa under 490ºC, every 10ºC drop in temperature would boost an increase of 3.5% in efficiency. If the exhaust pressure drops from 0.006MPa to 0.004MPa, the efficiency would increase by around 2.20%.

3.3 Water pre-heater

In the water pre-heater, the expanded steam is extracted from the turbine under certain parameters, which is then used to heat the water before pumping it into the turbine (as shown in RH$_1$—RH$_{10}$ in the diagram) [10, 11]. In such a system, energy from extracted steam is transferred back into the system, where the cold source loss would be much smaller than a simple Rankine cycle. Furthermore, the extraction consists of several stages [12]. The longer the extraction from the turbine takes, the lower the temperature of water for heating. In this way, steam could do more work on the turbine before getting extracted, thus increasing the thermal efficiency of the turbine. Each turbine has a distinct set of optimum steam extraction parameters. Theoretically, the more stages involved in steam extraction inside the power plant, the higher the total efficiency of the power plant would be. However, in a real-world scenario, more stages would also lead to an increase in the construction cost of thermal power plants. Modern high-parameter-high-power thermal power plants usually have 7-9 stages of steam extraction.
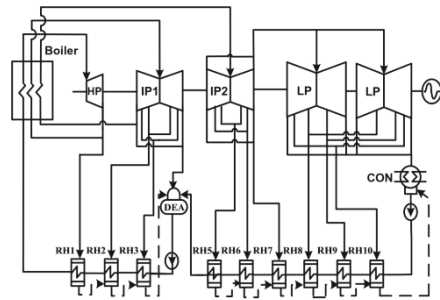
Figure 1 Stages of steam extraction a power plant[10]

3.4 Combined cycle (CC) power generation

Among all existing thermal power generation devices, gas turbines and steam turbines are the only two types of devices suitable for large-scale power generation. However, they both suffer from a lower thermal efficiency.

High initial (around 1350ºC to 1430ºC) and final temperature (around 450ºC to 630ºC) in the gas turbine has a high initial temperature. However, its final temperature is also highwould lower the turbine's efficiency. steam turbines are confronted with similar restrictions, with an initial temperature of around 600ºC and a final temperature of around 30ºC to 33ºC. However, since the final temperature of a gas turbine is usually higher than that of a steam turbine, the exhaust gas of the gas turbine could be used as a direct heat source for the steam turbine, which means more work is extracted by adding a steam turbine as an auxiliary system for the gas turbine. Integration of the gas turbine and the steam turbine would boost the Carnot efficiency of the whole system due to the greater difference between the initial temperature of the gas turbine and the final temperature of the steam turbine [13].

4. Conclusion

Above all, most of the energy loss in a fossil-fuel thermal power plant comes from the steam turbine. The efficiency of a thermal power plant can be improved by either energy conservation within the system or expansion of differences between initial steam parameters and final steam parameters. The paper, however, did not take the impact of pressure into consideration when discussing the efficiency under Rankine Cycle. Also, the paper offers merely a simple introduction to different methods of improving efficiency of thermal power plants. Further studies will apply mathematical formula in describing and determining the parameters for the optimum efficiency under different situations.

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