Research on structural integration of thermodynamic system for double reheat coal-fired unit with CO2 capture

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Abstract. Taking the MEA chemical absorption carbon capture system with 85% of the carbon capture rate of a 660MW ultra-super critical unit as an example, this paper puts forward a new type of turbine which dedicated to supply steam to carbon capture system. The comparison of the thermal systems of the power plant under different steam supply schemes by using the EBSILON indicated optimal extraction scheme for Steam Extraction System in Carbon Capture System. The results show that the cycle heat efficiency of the unit introduced carbon capture turbine system is higher than that of the usual scheme without it. With the introduction of the carbon capture turbine, the scheme which extracted steam from high pressure cylinder’s steam input point shows the highest cycle thermal efficiency. Its indexes are superior to other scheme, and more suitable for existing coal-fired power plant integrated post combustion carbon dioxide capture system.

1. Introduction
In recent years, with the fossil fuels are widely used in industrial areas, global warming caused by greenhouse gases has been a general concern of governments, environmental organizations and research institutions. In September 2016, China formally signed the Paris Agreement, which promised to reach the peak of carbon emissions by 2030 and cut its carbon dioxide emissions per unit of GDP by 18% in 2020 compared to 2015. China’s energy structure determines the coal-fired power plant is the main source of carbon dioxide emissions, so control of coal-fired power plant carbon emissions is a viable way to reduce carbon emissions. At present, coal-fired power plants generally use chemical alcohol amine method to capture carbon, this method has high yield, high absorption efficiency, but the energy consumption is huge, the carbon capture system extract a lot of steam leads to power plant power generation efficiency decreased by about 11%-15%. So how to reduce coal-fired power plant carbon energy consumption, improve the whole plant thermal efficiency, has become the focus of the current study.

With a view to achieve the demand of carbon capture under the premise of improving the efficiency of the whole plant, domestic and foreign scholars ameliorate the study in terms of CO2 absorption side and the thermal system side. In the aspect of absorber, Liu Bingcheng et al. simulate the effect of several absorbents on carbon capture at different concentration, circulation and working temperature by using PRO II software and screened the absorbents. Miran Yoo et al. investigated the Sodium hydroxide’s characteristics of high concentration CO2 capture in the gas mixture, including the ability to absorb CO2, the rate of absorption, the capture efficiency and the detailed absorption mechanism [1]. Pellegrini compares the ability to capture carbon dioxide of two primary amines (MEA and DGA with ammonia. Ammonia captures CO2 by forming a stable salt, which is separated...
from the solvent by filtration or sedimentation [2]. These salts can be used commercially as fertilizers. Due to solvent regeneration does not require heat, and no require to compress the separation of CO₂, greatly reduced energy consumption could be achieved. In the absorption process, some scholars have studied the performance parameters of circulating fluid, such as Jassim and Oyenekan, simulated the relationship between the lean liquid load and the energy consumption of the system, and obtained the optimal value of the liquid-rich regeneration [3]; Abu-Zahra et al. used Aspen Plus to simulate the energy consumption of keeping parameters such as removal rate of specific carbon dioxide, solvent concentration, analytical column pressure, lean liquid temperature [4]; Li Qing et al. simulated the process of absorbing CO₂ used the alkanol solution in carbon capture power plant. The influence of parameter change on the carbon capture process was analyzed and the optimal operating conditions were obtained; Duan has optimized the carbon dioxide capture rate and the number of plates in the carbon capture system, and analyzed the influence of the number of plates on the flow of lean liquid [5]; On the side of the thermal system, Xu et al. proposed a 600 MW unit integrated carbon capture system scheme, acquire additional power from the rear turbine [6]; Zhang Kefang proposed and calculated the fourth paragraph, the fifth, and the sixth paragraph’s exergy wastage rate of steam to evaluate the energy efficiency of different steam pumping points; Duan et al. simulated the improvement process of the alcohol capture system and the soft water circulation system of the power plant, and the effective utilization of the extraction steam energy by rear steam turbine to improve the thermal efficiency of the whole plan; Yang et al. analyzed the influence of different extraction parameters of 600MW unit on the net power generation and coal consumption rate of power plant [7].

In this paper, carbon capture turbine is proposed to improve the performance of thermal system for secondary reheat unit. Several scheme that steam extracted from different pumping points simulated by EBSILON, and analyzed getting the best pumping point by using the unit consumption method.

2. Carbon capture system

At present, the carbon capture technology is divided into four categories: post-combustion CO₂ capture, pre-combustion CO₂ capture, oxygen-enriched CO₂ combustion, and chemical chain combustion. The post-combustion CO₂ capture equipment is mainly used for the separation of carbon dioxide in the tail smoke of the power plant. The main characteristics of this method are that the carbon capture equipment is independent of the existence of the power plant in the power plant, and it can be more flexible choice to integrate into the thermal power plant location.

As for the post-combustion CO₂ capture the alcohol amine method (MEA chemical absorption method) technology is the most mature. Alcohol amine method uses MEA as its circulating working fluid, with a small molecular weight, strong absorption of acid gas characteristics, for the capture of low concentrations of carbon dioxide in the performance of good.

Figure 1 shows the carbon capture using alcohol amine [8]. MEA solution in the absorption tower absorbs carbon dioxide in the flue gas, the rich liquid is pumped into the rich and poor liquid heat exchanger and then into the analytical tower, absorbs heat from the thermal system extracted steam, then high concentrations of carbon dioxide is separated out. Rich liquid turns into lean liquid back to the absorption tower recycle and precipitated carbon dioxide enters the tower top condenser from tower top, water vapor separated out from the fluid, and then the rest fluid go through multistage compressor to reach the storage temperature and pressure, and finally turn into liquid carbon dioxide in the refrigeration machine.

In this system, the large amount of steam required by the reboiler is derived from the extraction of the thermal system. At present, generally using gas exhausted from intermediate pressure cylinder to supply the carbon capture system heating, but the pumping temperature and pressure are higher than the reboiler required, so it was proposed to lead the intermediate pressure cylinder’s exhaust gas to the diminutive steam turbine to decline its pressure and decompression. However, due to pressure limit by intermediate pressure cylinder, diminutive steam turbine has less stages so that do a small quantity work, the unit efficiency is not significantly improved. In this paper, the concept of carbon capture turbine is proposed. The steam exhaust port is not limited to the intermediate pressure cylinder exhaust.
port and the reboiler can be supplied by super high pressure cylinder and high pressure cylinder’s exhaust steam.

![Diagram of alcohol amine carbon capture system](image)

**Figure 1.** Alcohol amine carbon capture system.

### 3. Carbon capture turbine

#### 3.1. Carbon capture turbine

The large amount of extracted steam required for carbon capture can only be extracted from the connection between medium and low pressure cylinders, where the pressure is low, resulting in the diminutive steam turbine stages is less, therefore the energy lost. Therefore, this paper presents a new type of carbon capture steam turbine, extract the ultra-high pressure, high pressure cylinder exhaust. The more stages it has, the less of loss energy, thereby enhancing the efficiency of the whole plant.

#### 3.2. Simulation and comparison of steam supply points

With carbon capture turbines, the steam supply points of the carbon capture system is no longer limited to the connecting pipes between the medium and low pressure cylinders. As shown in Figure 2, we can extract steam from the ultra-high pressure cylinder, high pressure cylinder supply the reboiler. And the most efficient point still need EBSILON simulation to determine.

Figure 2 shows the thermal system of a late-model post-combustion carbon capture unit. The extraction steam position can be: ultra-high pressure cylinder exhaust, high pressure cylinder extrance, high pressure cylinder exhaust and medium pressure cylinder extrance. In the reboiler, the MEA is separated from the rich solution, and the MEA is sensitive to the temperature’s change, when its temperature is higher than 122 degree Celsius. This paper set the heat transfer temperature difference 10 degree Celsius, the required steam temperature is 132 degree Celsius. According to EBSILON simulation, ultra-high pressure cylinder exhaust steam do work in carbon capture turbine, the exhaust pressure is 0.287MP and temperature reached 132 degree Celsius, conform to the reboiler requirement. Reboiler drainage can choose the appropriate location inject to low-temperature heating system. And other locations exhaust after going through the carbon capture turbine, its temperature is higher than the reboiler temperature requirement, need to reduce the pressure first. As shown in Figure 2, the reboiler condensate is injected to the steam cooler while the steam is subjected to water spray temperature...
reduction before the reboiler. After two stages of thermoregulation, the steam that conforms to the requirements enters the reboiler for heat transfer.

Carbon capture systems with different steam locations, the units’ indicators diverse. Table 1 compares the six different carbon capture schemes. Table 1 reveals that the highest efficiency of extraction point’s, which attached to the steam entrance of high-pressure cylinder. This scheme shows the lowest coal consumption rate, carbon dioxide emissions rate is also the lowest, which is determined the best scheme. Secondly, the supply steam from intermediate pressure cylinder’s entrance renders unit efficiency splendid; Super high pressure cylinder exhaust steam and high-pressure cylinder exhaust steam emerge similar thermal efficiencies. The existing medium-pressure cylinder steam extraction scheme which supply the reboiler directly has the lowest thermal efficiency, which is 2.34% lower than the optimal scheme.

![Figure 2. Extraction of steam location.](image)

| Project        | Cycle Thermal Efficiency/% | Standard coal consumption rate/kJ·(kw·h)⁻¹ | Turbine heat rate/kJ·(kw·h)⁻¹ | Unit heat consumption rate/kJ·(kw·h)⁻¹ | Heat consumption of the whole plant generation/kJ·(kw·h)⁻¹ | Carbon dioxide emission rate/g·(kw·h)⁻¹ |
|----------------|---------------------------|------------------------------------------|-------------------------------|----------------------------------------|-------------------------------------------------|-----------------------------------|
| VHP exhaust    | 44.05                     | 315.73                                   | 8341.53                       | 8510.90                                | 9240.81                                         | 122.08                            |
| HP entrance    | 44.96                     | 309.32                                   | 8172.35                       | 8338.28                                | 9053.39                                         | 119.60                            |
| HP exhaust     | 44.08                     | 315.50                                   | 8335.53                       | 8504.78                                | 9234.16                                         | 122.00                            |
| IP entrance    | 44.55                     | 312.20                                   | 8248.31                       | 8415.79                                | 9137.55                                         | 120.71                            |
| IP exhaust     | 43.49                     | 319.78                                   | 8448.66                       | 8620.20                                | 9359.49                                         | 123.65                            |
| IP exhaust without CCT | 42.62                 | 326.31                                   | 8621.01                       | 8796.05                                | 9550.42                                         | 126.17                            |
4. Unit consumption analysis
The unit consumption analysis is a kind of system energy analysis method based on exergy analysis and economic analysis and the product consumption is taken as the measure. In accordance with the method, energy consumption can be reduced. Based on the second law of thermodynamics, it reflects the loss of exergy due to equipments’ irreversible factors. The unit consumption analysis can clearly show the distribution of the total system consumption in each device, it can also show the impact of the transformation of the system components in the system transformation, so as to more clearly determine the direction of transformation. It can be seen from Table 2 that the steam extraction position has little effect on the unit consumption of steam turbine, condenser, pump and diminutive turbine which supply the pump and has obvious effect on the unit consumption of carbon capture system. However, there is no obvious effect on the boiler unit consumption.

Table 2. Comparison of six kinds of consumption schemes for steam supply

| Project                      | VHP exhaust | HP entrance | IP exhaust | IP entrance | IP exhaust | IP without CCT |
|------------------------------|-------------|-------------|------------|-------------|------------|----------------|
| Boiler                       | 141.50      | 137.04      | 139.97     | 137.72      | 140.97     | 143.85         |
| VHP                          | 1.59        | 1.36        | 1.39       | 1.28        | 1.33       | 1.35           |
| HP                           | 0.43        | 0.38        | 1.06       | 0.99        | 0.96       | 0.97           |
| IP                           | 0.54        | 0.59        | 0.53       | 0.53        | 1.33       | 1.35           |
| LP                           | 1.75        | 2.00        | 1.78       | 2.01        | 1.55       | 1.88           |
| CCT                          | 2.69        | 2.32        | 1.64       | 1.41        | 0.48       | -              |

In intermediate pressure cylinder followed by diminutive steam turbine scheme, the unit consumption was significantly lower than the traditional intermediate pressure cylinder directly supply steam to the reboiler. This is because the introduction of carbon capture steam turbine, the boiler unit consumption reduced by 2.88, carbon capture system unit consumption reduced 3.75, proved that in...
the same extraction position, the carbon capture turbine is beneficial to reduce the unit consumption. Ultra-high pressure cylinder exhaust scheme and high-pressure cylinder exhaust scheme’s whole unit consumption quite similar; In the case of intermediate pressure cylinder exhaust scheme, due to the low extraction pressure, the carbon capture turbine has lesser stages, resulting in the exhaust steam temperature up to 280 degree Celsius, after going through the temperature reduction process to 132 degree Celsius, steam is injected to reboiler. Temperature process energy severe loss, so this location of the carbon capture system unit consumption is significantly higher than other cases. High-pressure cylinder entrance extraction scheme’s boiler unit consumption is the lowest of all schemes, carbon capture system consumption and the whole unit consumption are also the lowest cost, so it is the optimal scheme.

Figure 3 shows comparison of total unit consumption; Figure 4 shows comparison of boiler and carbon capture total unit consumption.

![Figure 3: Comparison of total unit consumption (g/kw·h).](image1)

![Figure 4: Comparison of boiler and carbon capture total unit consumption (g/kw·h).](image2)
5. Conclusions
In this paper, we use EBSILON to simulate six schemes of a 660MW secondary reheat fossil fuel-fired unit, and use the unit consumption analysis method to obtain the optimal integration method. The conclusions are: The effect of steam extraction on the unit consumption of steam turbine, pump and diminutive turbine and condenser is small, but has obvious effect on the unit consumption of carbon capture system. There is no obvious effect on the boiler unit consumption; The introduction of carbon capture turbines significantly reduces the unit consumption of the carbon capture system. In the same extract position, the exhaust heat which go in the auxiliary steam turbine cycle heat efficiency is higher than the case without auxiliary turbine; In the case of stable CO₂ emission rate, considering the cycle thermal efficiency and the heat rate, the high-pressure cylinder exhaust steam is the best choice for carbon capture capture turbines; Six schemes’ cycle thermal efficiency: HP entrance>IP entrance>HP exhaust>VHP exhaust>IP exhaust>IP without CCT; The heat rate and unit consumption: HP entrance<IP entrance<HP exhaust<VHP exhaust<IP exhaust<IP without CCT. So HP entrance is the best position to extract steam to carbon capture turbine.

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