Research on Integration of a New Carbon Capture System and Steam Cycle in Power Plant

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Abstract: The paper simulate the traditional and the new technologies of carbon capture on the basis of the 330 MW power plant unit by using Aspen plus. Meanwhile, by checking linear relationship between load and steam flow rate, the model of the unit steam cycle is set up, verifying the accuracy of the model. And put the two kinds of process equipment into the unit steam cycle, to analyze the factors affecting the steam cycle of the two technologies. The main conclusions are drawn as follows: The new technology has lower heat consumption than the traditional technology as well as the extent of the impact of the unit output power. So the new technology has advantages on energy saving. Also, the study of the characteristics of the integrated system is conducted, obtaining that it has different impacts on the unit output power when extracting from different steam turbine pressure ports to heat the carbon capture system, which will give a reference for units operation with the new carbon capture system.

1 Introduction
Because of the overuse of fossil fuels, global carbon dioxide emissions are becoming more and more serious. The goal of the Paris Agreement is that the global average temperature must be controlled within 2 °C in this century[1]. In order to fulfill emission reduction obligations in the Paris Agreement, the key is to control the emission of greenhouse gas in power industry. In all CO2 emission reduction technologies, chemical absorption is the most recognized and most feasible method. And ammonia method has its unique advantages on other alcohol amine methods[2]. For example, compared with the conventional MEA method, the removal efficiency of ammonia method is 5%-8% higher than the MEA method[3]. In the aspect of carbon capture and utilization by ammonia, Zhao[4], Qing[5], Barzagli[6], Zhang[7] et al have done the research about the influence of reaction conditions like pressure, temperature, flow rate, flow gas composition and reactor type on the absorption and regeneration process. Yu et al proposed a new carbon capture technology which saves the energy consume and also improves the carbon capture efficiency. Nowadays, there are a series of carbon capture pilot equipment in all over the world, such as Power span company[8], Munmorah plant in Australia[9] and Alstom company in America[10].

Traditional ammonia method for carbon capture has its inherent difficulties including: ammonia escape[11]; low utilization of absorbent[12]; the reaction rate slowing down in late stage reaction[13]; regeneration energy consumption is too high[14]. Zheng et al researched on a new technology in carbon capture by ammonia with reinforced crystallization[15], and already proved that this technology has high utilization of absorbent and quick reaction rate. Compared with traditional technology, the regeneration of carbon capture of the new technology increased by 3 times and the
regeneration energy consume reduced by 50%. The energy consume also reduced by 30% compared with the phase change absorption method which is also an area of focus. The process is shown in Figure 1.

Compared with the traditional (or the old) technology, the new technology does not let the rich solution flow into the regeneration tower, while being reinforced crystallization in the crystallizer using the ethyl-alcohol as salting-out agent when it is in low carbonization degree, and then flow into solid-liquid separator. Finally, put the crystal into the regeneration tower to be heated. Nowadays, the study on carbon capture by ammonia with crystallization becomes more and more in the academic field. Chen et al[16] studied on the reaction temperature and absorbent concentration, and found that: the reaction temperature has very small effect on absorption of CO2; the removal efficiency is 90% when the ammonia concentration is high(10%) while 83% when it is low(5%). Yu et al[17] take 6% as the maximum ammonia concentration value, and test the CO2 regeneration process, obtaining that Main components of crystallized product is NH4HCO3. Theoretically and practically, these researches above prove the rationality of the technology of carbon capture by ammonia with reinforced crystallization.

Most of the CO2 capture systems are still remain in the laboratory stage, Zhang[18] optimized the carbon capture process by ammonia using the method of system simulation, while integrated the carbon capture system and unit steam circulation. This paper simulate the model of traditional and new CO2 capture technology as well as the steam cycle of 330MW coal-fires unit by using the software Aspen plus, and put these models into CO2 capture platform for coal-fired unit. We study the effect of different operating conditions on the energy consume and efficiency and so on, as well as the effect of the two kinds of technologies on the unit output power by using the platform above, which will verify the feasibility of the new technology.

2 Process description

2.1 Steam cycle of coal-fired unit

The model of steam cycle of coal-fired unit is shown in Figure 2. Boiler heats the feed water to make it steam. The steam passes through high pressure cylinder of steam turbine to promote the steam turbine work. The wet steam enters the reheater to be heat into reheat steam after doing work and then work in turbine medium pressure cylinder and low pressure cylinder. After the exhaust steam enters the condenser, it is heated by the feed water heater and pressurized by the water pump. Finally, the exhaust steam is re-fed into the boiler and recycled. The model uses the real data of the power plant, such as the parameters of boiler feed water heater, pump, steam turbine and the flow parameters of water and steam.
2.2 Traditional technology
As shown in Figure 3, the flue gas is introduced from the bottom of the absorption tower, and the absorbent is sprayed downward from the top of the absorption tower. The flue gas contacts with the absorbent in the absorption tower, and the absorbent absorbs the CO$_2$ in the flue gas and becomes rich liquid. The pressurized rich liquid and the lean liquid from the regeneration tower conduct heat exchange in heat exchanger, and then passed into the middle of the regeneration tower for thermal regeneration after heated to a certain temperature.

2.3 New technology
As shown in Figure 4, the system platform for the steam cycle of the unit and the new ammonia process for carbon capture is merged. In the process of regeneration, the rich liquid flows out from the bottom of the absorber and enters the regenerator, where it crystallizes when it meets the dissolvent. Then, a two-stage separator is introduced for solid-liquid separation, and the dried crystal is obtained, which is then heated in the regenerator for regeneration. After regenerated, the CO$_2$ gas with higher purity is obtained by component separation.
3 Model settings and regulations

3.1 settings and regulations of steam cycle model
When using Aspen to simulate the steam process, the two most commonly used methods of physical properties were STEAM-TA and STEAMNAS. It is found that STEAM-TA is more reasonable to use as the physical property method of steam model, so another method is set as an alternative. As to material flow, boiler feed water is the only parameter that needs to be set up. The regulations include flow rate, pressure and temperature. The temperature and pressure values are determined according to the feed water temperature and pressure of 330MW typical coal-fired boiler. The initial value of the flow rate is the flow rate value under the rated load, which is adjusted accordingly with the change of the load. Material flow regulation is provided in Table 1.

| Parameter   | Value  |
|-------------|--------|
| Pressure    | MPa    |
| Temperature | °C     |
| Flow rate   | Kmol/hr|

The main modules are set out in Table 2:

| Modules                  | User models | Function               |
|--------------------------|-------------|------------------------|
| BOIL                     | HEATER      | Boiler                 |
| RHEAT                    | HEATER      | Reboiler               |
| HPSP, IPSP, LPSP         | Turbine     | Steam turbine          |
| COMPR                    | Turbine     | Small steam turbine    |
| CONMIX                   | MIXER       | Deaerator              |
| H1-H82                   | HEATER      | Boiler feed water heater|
| CONDENSE                 | HEATER      | Condenser              |

3.2 settings and regulations of traditional technology model
With more and more research on ammonia decarbonization, the physical properties of Aspen plus are gradually increasing, including ENRTL-HF model, UNIQUAC model, Edwards model and Pitzer model. According to my previous research[15], we adopt the ELECNRTL model. Henry component uses N2, NH3 and CO2 given by the system. All the reaction groups were H2O, N2, CO2 and NH3. N2 is not involved in the reaction, and the remaining 3 components constitute NH3-CO2-H2O system. The main reactions in the NH3-CO2-H2O system are shown in Table 3.
Table 3. Main reactions of the NH₃-H₂O-CO₂ system

| reaction ID | reaction type | chemical equation |
|-------------|---------------|-------------------|
| 1           | Equilibrium   | NH₃ + H₂O $\leftrightarrow$ OH⁻ + NH₄⁺ |
| 2           | Equilibrium   | H₂O + HCO₃⁻ $\leftrightarrow$ CO₃²⁻ + H₃O⁺ |
| 3           | Equilibrium   | NH₃ + HCO₃⁻ $\leftrightarrow$ H₂O + NH₂COO⁻ |
| 4           | Equilibrium   | 2H₂O + CO₂ $\leftrightarrow$ HCO₃⁻ + H₃O⁺ |
| 5           | Equilibrium   | 2H₂O $\leftrightarrow$ OH⁻ + H₃O⁺ |

The initial parameters of the traditional process are set out in Table 4.

Table 4. The setting of initial parameters for the traditional technology

| initial parameters                      | value | initial parameters                      | value |
|-----------------------------------------|-------|-----------------------------------------|-------|
| ammonia concentration/\%               | 5     | absorber(regeneration)tower pressure/Bar| 1.2   |
| absorbent temperature/°C               | 20    | reflux ratio                            | 0.2   |
| Absorber tower temperature/°C          | 20    | Outlet steam rate/ kmol/hr              | 4000  |

The specific module settings are shown in Table 5:

Table 5. The model setting for the traditional technology

| Modules   | user models | function       |
|-----------|-------------|----------------|
| STRIPPER  | RadFrac     | Strict distillation |
| PUMP      | PUMP        | Solution pressure |
| HEATEXC   | Heatx       | Heat exchange   |
| ABSORBER  | RadFrac     | Strict distillation |

3.3 settings and regulations of new technology model

According to my previous research[15], in the Aspen system, the new technology has one more reaction than the traditional technology.

AMMON-01$\leftrightarrow$HCO₃⁻+NH₄⁺  (1)

The reaction temperature is 20 °C, the crystallization pressure is 1200kPa, and the reaction direction is the reverse of the reaction equation (1). The initial regeneration temperature is 80 °C and the reactant is ammonium bicarbonate crystal. The products are NH₃, CO₂ and H₂O. The reaction heat is 64 kJ / mol (at 25 °C standard condition).

Table 6 describes the model settings in the new process simulation.

Table 6. The model setting for the new technology

| Modules | user models | function       |
|---------|-------------|----------------|
| STRIPPER| RadFrac     | Strict distillation |
| PUMP    | PUMP        | Solution pressure |
4 Comparative study of two process systems

4.1 Validation of model accuracy
The accuracy of the new process model and the traditional process model has been demonstrated in my previous research [15]. Therefore, it is necessary to verify the steam model of the unit. There are many steam extraction points, including the inlet and outlet positions of high pressure (HP), medium pressure (IP) and low pressure (LP) cylinders of steam turbines and the steam extraction points of feed water heaters (A, B, C, D, E, F, G, H). The unit load rate is defined by setting the boiler feed water rate. The boiler feed water rate is 908192 kmol/hr when it at 100% rated load. The boiler feed water rate is set for other load according to the linear relationship. Figure 5 shows the variation of the flow rate of each steam extraction point as the unit load changes. The selected load rates are 50%, 75%, 100% and 110% respectively. It can be seen that the flow rate of each steam extraction point increases linearly with the increase of load rate. This is consistent with the actual power plant condition, and the accuracy of the model is verified.

![Figure 5. The effect of load on the flow rate in different extraction points](image)

4.2 Integration of steam cycle and carbon capture system
The essence of integrating the carbon capture system into the steam cycle of the unit is to use a certain proportion of steam extracted from the steam extraction point of the unit to provide the heat consumption needed for the thermal regeneration of the carbon capture system. The steam extracted must satisfy the following conditions: First, the temperature of the steam extracted must reach a certain level to ensure the continuous regeneration reaction. As far as the traditional process is concerned, the regeneration temperature of carbon capture by ammonia is 120 ºC, and the extraction temperature for thermal regeneration should be more than 130 ºC after deducting the temperature difference of equipment. Second, the flow rate of the steam extraction point should be large enough to meet the enthalpy required for thermal regeneration. Table 7 shows the temperature and flow rate of each steam extraction point. The steam extraction points selected according to the above two conditions are E point and LP point.
Table 7. The temperature and flow rate of all steam extraction points

| Extraction point | Temperature (°C) | Flow rate (kg/hr) |
|------------------|------------------|-------------------|
| HP               | 483              | 908192            |
| A                | 380.4            | 63294.17          |
| B                | 314.8            | 69998.8           |
| IP               | 535              | 774899            |
| C                | 436.5            | 34386.15          |
| LP               | 339.9            | 678893.7          |
| D                | 339.9            | 61619.2           |
| E                | 240.1            | 36203.05          |
| F                | 149.5            | 20033.71          |
| G                | 99               | 29272.82          |
| H                | 60.5             | 18236.44          |
| CNDR             | 32.5             | 575147.7          |

Figure 6 shows the steam system drawing from LP point in traditional process, and Figure 7 shows the steam system drawing from E point in new process.

By the same token, we can draw steam from point E in the traditional process and from point LP in the new process. The heat of the steam is transferred to the regenerator of the carbon capture system through the heat exchanger of the HEATX model. The amount of steam is determined by the heat consumption of the regenerator. After steam heat exchange, the pressure remains constant and becomes saturated steam.
4.3 Consumption analysis and influence on output power

By comparing the effects of different steam extraction points and steam extraction ratios on the output heat, the external supplementary heat needed for regeneration and the output power, the advantages and disadvantages of the two processes in energy saving are studied. In the carbon capture system, as shown in Figure 8, with the change of the steam extraction ratio at LP point, the steam provides heat and needs additional heat. As shown in Figure 9, the relationship between the ratio of steam extracted from LP point and the heat supplied by the steam and the output power of the unit is shown.

Figure 9 also shows that when the steam extraction ratio increases, the heat supplied by the steam increases linearly, and the additional heat required and the output power of the unit decreases linearly. In traditional process, the system calculates that the regeneration heat consumption of reheater is 160MW. If the steam with 30% flow rate is extracted from LP point, 149.5MW is supplied by steam system and 10MW is supplied with external heat. At this time, the unit load of 300MW is reduced to 253.5MW. For the new process, the regeneration heat consumption calculated by the system is 55 MW. When the steam extraction ratio is 12%, the steam heating is 60.5 MW, which meets the heat consumption demand of the new process. At this time, the unit output power still remains 280 WM. Therefore, it can be concluded that the new technology in carbon capture by ammonia with reinforced crystallization has lower heat consumption than the traditional process, less impact on the output power of the unit, greatly saving the energy consumption and cost of decarbonization.

In addition, by comparing the steam curves drawn from E point and LP point, it is found that the effect of extracting steam from E point is less than that from LP point on the output power. For example, when 30% steam is extracted from both E and LP points simultaneously, the output power is 289 MW and 253.5 MW, respectively. Therefore, it is more reasonable to set the extraction point near the position of the low pressure cylinder of the steam turbine. The reason is that the closer to the low pressure cylinder, the lower the steam superheat, the lower the energy quality of the steam, and the smaller the impact on the thermal efficiency of the steam cycle.

5 Conclusion

In this paper, the energy efficiency of the new and traditional ammonia carbon capture process is analyzed. The steam cycle model of a typical 330 MW unit, the model of new technology in carbon
capture by ammonia with reinforced crystallization and the traditional ammonia carbon capture are simulated by Aspen plus software. The steam model of the unit and the two ammonia carbon removal process models are combined to analyze the steam extraction points. Suitable steam extraction points are selected by analyzing the temperature and flow rate of each extraction point, and steam is extracted from each extraction point to provide the heat needed for thermal regeneration of decarbonization system.

On the one hand, the advantages of the new process over the traditional process in energy saving are compared; on the other hand, the performance characteristics of the two processes combined with the unit are analyzed. At the same steam extraction point (e.g. LP point), the traditional process requires a steam heat exchanger with a flow rate of more than 30% for CO\textsubscript{2} heating and regeneration, and the output power of the 300 MW unit is reduced to 253.5 MW. The new process only needs 12% steam and the output power of the unit is maintained at 289 MW. Therefore, the reduction of output power by traditional method is four times of that by new process, and the energy consumption of new process is lower than that of traditional process, which has a great advantage in energy saving. On the other hand, after incorporating the decarbonization system, in order to reduce the impact on the output process, the steam extract point should be selected near the steam turbine low pressure cylinder under the premise of satisfying the heat consumption of the decarbonization system.

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