Parameters Optimization of Post Combustion CO_2 Capture Demonstration Plant Using New Ternary Amines at Natural Gas Power Station

Zhongyuan Huang[*], Xuliang Jin[a], Fanqin Meng[b], Aiming Yin[c]

[*]406485892@qq.com, [a]19547871@qq.com, [b]1574949513@qq.com, [c]137117503@qq.com

China Datang Corporation Science and Technology General Research Institute Ltd., North China Electric Power Test and Research Institute, Beijing 100040, China

Abstract. Post-combustion chemical decarbonization process is one of the important technology options for the low-carbon development of natural gas power plants. In this paper, the operating parameters of CO2 capture using new ternary amines are studied in a 1800t/y demonstration plant at Beijing Gaojing Thermal Power Station. The influence of main operating parameters on the CO2 capture efficiency and specific heat consumption is investigated. The test results show that the optimum operating conditions are flue gas flow rate (V_{fg}) 3000Nm^3/h, flue gas temperature (T_{fg}) 40°C, reboiler steam flow rate (Q_{reb}) 367kg/h, desorber operating pressure (P_{des}) 10kPa, solvent circulating flow rate (f_{sol}) 4.0m^3/h. Under optimum operating conditions, the average CO_2 capture efficiency capture is 90.6%, and the specific heat consumption is 3.29 GJ/tCO_2.

Keywords. Post-combustion CO_2 capture, Capture efficiency, Natural gas power plant, Specific heat consumption, Operating parameter

1 Introduction

According to the Chinese government's low-carbon development goal, fossil fuel power plants, which are the main source of CO_2 emissions, are under increasing pressure to reduce emission [1]. Post combustion using chemical absorption is currently one of the most mature technologies for CO_2 capture from flue gas [2]. The high energy consumption for CO_2 desorption is hindering its large-scale commercial application [3]. Process improvement is one of the effective ways to reduce the energy consumption of the CO_2 capture system [4]. In general, post combustion CO_2 capture integration with fossil fuel power plants will reduce the efficiency of power generation by 8% to 13%, and increase the cost of power generation by about 30% [5,6]. Therefore, for the post-combustion CO_2 capture power plant, it is important to optimize the combination of various energy-saving processes and build a low-energy CO_2 capture system to reduce the overall system energy consumption and operating costs.

In this paper, a 1800 t/y demonstration project of post combustion chemical absorption CO_2 capture using novel ternary amines is researched. The influence of flue gas flow rate, flue gas temperature, absorbent circulation flow rate, tower operating pressure and steam flow rate on carbon dioxide capture efficiency and energy consumption is investigated. The research results define the optimal operating range of the CO_2 capture system, and provide a reference for the future design of CO_2 capture systems in natural gas power plants.

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2 CO_2 capture process description

The CO_2 capture demonstration project was constructed at the Datang Beijing Gaojing Thermal Power Plant, which is a 3×470MW gas-fired cogeneration heating, cooling and power. The design capacity of the flue gas is 3200 Nm^3/h, liquid CO_2 production (2.5~2.8M Pa.g,-15~-20℃) is 1800 t/y. The CO_2 capture plant is schematically shown in Figure 1.

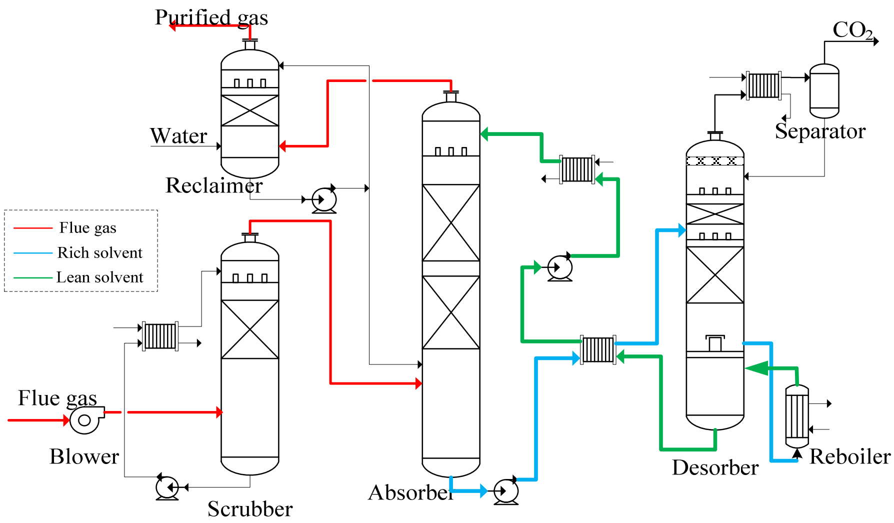

Figure 1. CO_2 capture process flow rate sheet in Gaojing thermal power plant

The flue gas is extracted after the HRSG low temperature economizer, and cooled to 40℃ in the scrubber to meet the mass transfer requirements of the absorber. The flue gas and lean solvent are contacted by a counter flow, which captures the CO_2 in the flue gas. Decarbonized flue gas is washed again in the reclaimer to reduce absorbent leakage. The rich solvent is extracted from absorber and heated to 95-105℃ by the lean solvent in the lean-rich heat exchange. Subsequently, the rich solvent is heated close to 110-115℃ in the desorber and CO_2 is released. The rebioler installed at the bottom of the desorber, provides heat for the whole desorption process. The low-pressure saturated steam used in the reboiler is extracted from low pressure drum of HRSG. The lean solvent is cooled to 40℃, and pumped back to the absorber. The CO_2 gas enters a subsequent process where it is compressed and liquefied into a product.

The CO_2 capture plant consists of a scrubber, an absorber and a desorber. The other equipment such as the blower, the reboiler,the reclaimer, pumps, heat exchangers, coolers are shown in Figure 2.The main facility parameters of the CO_2 capture system are shown in Table 1.

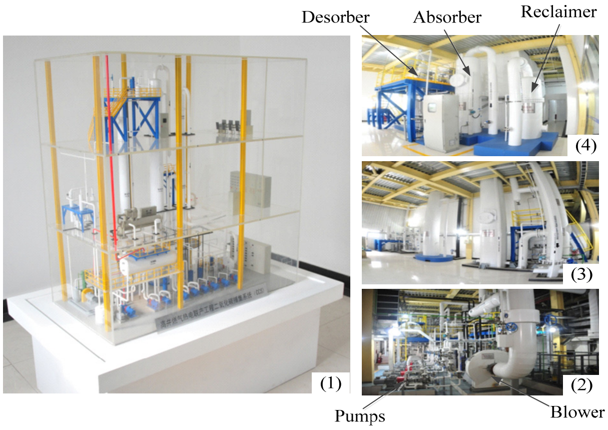

Figure 2. The CO_2 capture plant model and facilities(1.Plant model;2.1st floor;3.2nd floor;4.3rd floor)

Table 1. Facility parameters of the CO_2 capture plant

Blower	Flue gas flux:0~3200 Nm^3/h Outlet pressure:0~20.0 kPa.g Motor power:30kW
Scrubber and reclaimer	Packing type:125Y Material:304 stainless steel Packing size:Ø800×8000mm
Absorber	Packing type:250Y Material:304 stainless steel Packing size:Ø1000×17000 mm
Desorber	Packing type:125Y Material:304 stainless steel Packing size:Ø600×12000 mm
Reboiler	Type:shell-and-tube heat exchanger Material:304 stainless steel
Gas-water separator	Type:flash tank Material:304 stainless steel Size:Ø400×1500 mm
Washing water cooler,Lean cooler, Regenerating gas cooler,Lean-rich heat exchanger	Type:plate heat exchanger Material:304 stainless steel
Rich pump Lean pump Scrubbing pump Recovery pump	Type:variable frequency pump Material:304 stainless steel Flux:0~12 m^3/h Motor power:1.1-5.5kW

3 Plant operation and test method

3.1 Plant operating parameter

This CO_2 capture plant is controlled by a programmable logic controller, which runs on an industrial PC installed in the control cabinet of the plant. The operator can continuously monitor the operating status of main facilities and streams. The main operating parameters, which need operators adjust at any time according to the running status shows are shown in Table 2. The feature of new the ternary amines is reported, and the data have been reported in the reference [7,8].

Table 2. Operating parameter of the CO2 capture system

Parameters	Unit	Range
Flue gas flow rate	Nm^3/h	2000-3200
CO_2 content of scrubber inlet gas	vol%	4.2-4.6
Temperature of scrubber inlet gas	℃	80-105
Pressure of scrubber inlet gas	KPa,g	3.0-5.0
Temperature of absorber inlet gas	℃	40±2
Temperature of absorber outlet gas	℃	50±2
Low pressure steam flow rate of reboiler	kg/h	200-500
Low pressure steam pressure of reboiler	MPa,g	0.37-0.39
Low pressure steam temperature of reboiler	℃	148-150
Solvent circulating flow rate	m^3/h	3.0-6.5
Desorber operating pressure	kPa,g	3.0-50.0
Desorber temperature	℃	101-106

3.2 Parameter test method

In the performance test of the CO_2 capture system, the main test parameters include: CO_2 content in flue gas, steam content in the flue gas, volume flow rate of the flue gas, steam flow rate, temperature and pressure of the absorbent and the flue gas.

The following conditions are required during the test:

1) The gas turbine load is maintained between 250-300MW;

2) The steam power auxiliary system operates stably;

3) The CO_2 capture system operates continuously;

4) The CO_2 capture system operates stably;

5) Data collection should be performed at least 2 hours after the change of operating conditions..

6) The range of varied parameter and constant parameters is shown in Table 3.

Table 3. Varied parameter. range of variation and constant parameters in the plant test

Varied parameter	Range	Constant parameters
V_{fg}	2000Nm^3/h,2500Nm^3/h, 3000Nm^3/h	T_{fg} , Q_{reb} , P_{des} , f_{sol}
T_{fg}	30°C,32°C,34°C,40°C,45°C	V_{fg} , Q_{reb} , P_{des} , f_{sol}
Q_{reb}	200kg/h,300kg/h,400kg/h	V_{fg} , T_{fg} , P_{des} , f_{sol}
P_{des}	5kPa,10kPa,15kPa,20kPa, 25kPa,30kPa,40kPa	V_{fg} , T_{fg} , Q_{reb} , f_{sol}
f_{sol}	4.0m^3/h,4.5m^3/h,5.0m^3/h, 5.5m^3/h,6.0m^3/h	V_{fg} , T_{fg} , Q_{reb} , P_{des}

V_{fg}: flue gas standard volume flow rate (Nm^3/h).
T_{fg}: flue gas temperature(°C).
Q_{reb}: low pressure steam flow rate of reboiler(kg/h).
P_{des}: desorber operating pressure(kPa,g).
f_{sol}: solvent circulating flow rate(m^3/h).

3.3 Calculation method of performance indicators

(1) CO_2 mass flow rate in flue gas

$$m_{CO2-fg} = 1.964 V_{fg} C_{CO2-fg} \left(1-\varphi_{fg}\right) \tag{1}$$

Where V_{fg} is the flue gas standard volume flow rate rate(Nm^3/h) $C_{CO2\text{-}fg}$ is CO_2 content in flue gas(standard,dry basis,%); φ_{fg} is vapor content in flue gas(%).

(2)Captured CO_2 mass flow rate

$$Q_{CO2} = m_{CO2-fg} - m_{CO2-tg} \tag{2}$$

Where $m_{CO2\text{-}fg}$ is the CO_2 mass flow rate of raw flue gas(t/h); $m_{CO2\text{-}tg}$ is the CO_2 mass flow rate of treated flue gas(t/h).

(3)CO_2 capture efficiency

$$\eta_{CO2} = Q_{CO2} / m_{CO2-fg} \tag{3}$$

(4)Specific steam consumption

$$E_s = Q_{reb} / Q_{CO2} \tag{4}$$

Where Q_{reb} low pressure steam flow rate of reboiler(kg/h);

(5) Specific heat consumption

$$E_h = E_s \cdot \left(H_{ste} - H_{cond}\right) \tag{5}$$

Where H_{ste} enthalpy value of reboiler inlet steam (GJ/t); H_{cond} enthalpy value of reboiler condensate (GJ/t).

4 Results and discussion

4.1 Variation of flue gas flow rate

In order to study the influence of the flue gas flow rate on CO2 capture efficiency and specific heat consumption. Under the operating conditions of T_{fg}40°C, Q_{reb}395kg/h, P_{des}10kPa, f_{sol}4.0m^3/h, the V_{fg} is varied at 2000Nm^3/h, 2500Nm^3/h, 3000Nm^3/h, the test result is shown in Figure 3.

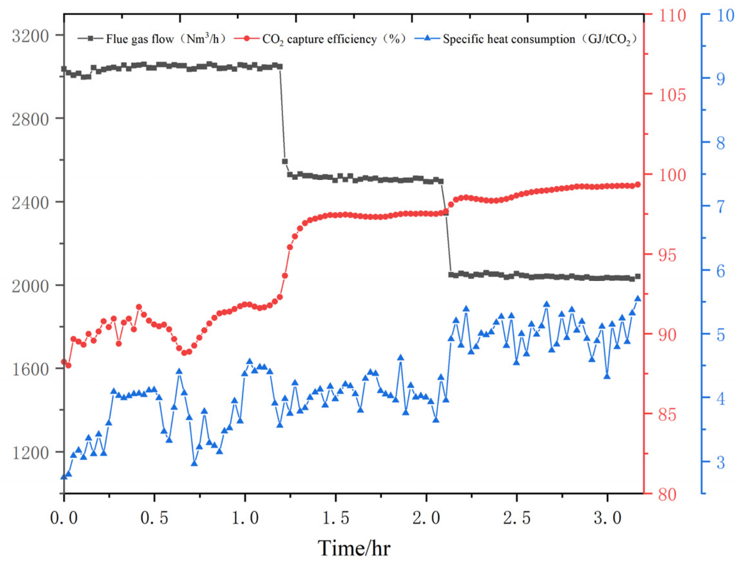

Figure 3. Influence of V_{fg} on the CO_2 capture efficiency and specific heat consumption

When the flue gas flow rate is 2050Nm^3/h, 2513Nm^3/h, 3041Nm^3/h respectively, the CO_2 capture efficiency is 99.8%,97.1%,91.6%, and the specific heat consumption is 4.98GJ/tCO_2, 4.05GJ/tCO_2, 3.71GJ/tCO_2 accordingly. When the other operating conditions are maintained, the CO_2 capture efficiency and specific heat consumption are significantly negatively correlated with the flue gas flow rate. During the experiment, the capture efficiency can respond to the change of flue gas flow rate very quickly, which further verifies that the mass transfer condition of the flue gas phase in the absorber is the main factor affecting the chemical absorption reaction.

4.2 Variation of flue gas temperature

To study the influence of the flue gas temperature on CO_2 capture efficiency and specific heat consumption. The absorber inlet flue gas temperature is adjusted to 30°C, 32°C, 34°C, 40°C, 45°C respectively by change the cooling water recirculation flow rate of scrubber. Other operating parameters are: V_{fg}3000Nm^3/h,Q_{reb}395kg/h, P_{des}10kPa, f_{sol}4.0m^3/h, the test result is shown in Figure 4.

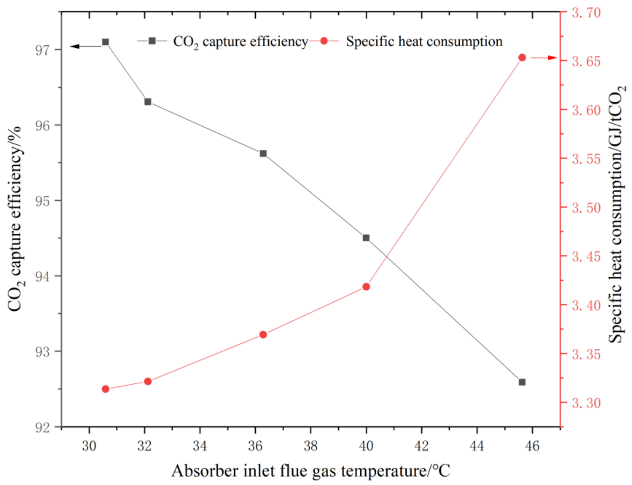

Figure 4. Influence of the flue gas temperature on the CO_2 capture efficiency and specific heat consumption

The CO_2 capture efficiency gradually reduced from 97.1% to 92.6% with the flue gas temperature increased.. Because of the exothermic reaction between amine and CO_2, when the flue gas temperature is low, the operating temperature of the whole absorber is at a lower level, which is conducive to the forward absorption reaction due to reaction thermodynamics enhanced.

In addition, there is another mechanism for the effect of flue gas temperature on capture efficiency: when the temperature is at a low level, the molecular thermal motion of CO_2 in the flue gas is weakened, and the diffusion coefficient is reduced, which is not conducive to gas mass transfer. For the low CO_2 partial pressure gas of the gas-fired power plant, the concentration gradient between the gas phase body and the gas film in the absorber is low, and the driving force of CO_2 diffusion is insufficient. Therefore, the temperature of the absorber gas should not be too low.

4.3 Variation of Reboiler steam flow rate

In order to study the influence of reboiler steam flow rate on CO_2 capture efficiency and specific heat consumption. The reboiler steam flow rate is controlled at 200kg/h, 300kg/h, 400kg/h, respectively, and V_{fg}3000Nm^3/h, T_{fg}40°C, P_{des}10kPa, f_{sol}4.0m^3/h, The test results are shown in Table 4.

Table 4. The influence of the Reboiler steam flow rate on CO_2 capture plant performance.

Q_{reb}(kg/h)	199.74	295.72	382.7
V_{fg}(Nm^3/h)	3007.85	2992.54	2947
$C_{CO2\text{-}fg}$(%)	4.457	4.481	4.426
$C_{CO2\text{-}tg}$(%)	1.857	1.315	0.262
η_{CO2}(%)	59.61	71.69	93.57
Q_{CO2}(kg/h)	144.71	174.09	225.2
E_s(t/tCO_2)	1.38	1.706	1.7
E_h(GJ/tCO_2)	2.828	3.495	3.87

Table 4 shows that, when the steam flow rate is 200kg/h, 300kg/h, 400kg/h, the CO_2 capture efficiency is 59.87%, 71.7% and 93.57%, respectively, the specific heat consumption is 2.796GJ/tCO_2, 3.127GJ/tCO_2, 3.87GJ/tCO_2. According to the test results in Table 4, there is a positive correlation between the unit capture energy consumption and capture efficiency when the steam flow rate is between 200-400kg/h; however, when the steam flow rate is above 300kg/h, the change rate of the renewable energy consumption is significantly higher than that of capture efficiency. Theoretically, when the operating conditions of the system are stable, especially when the circulation flow rate of the absorber is unchanged and the capture efficiency reaches a certain value (the chemical absorption rate based on the amine solvent is usually more than 80%), the energy consumption cost of further improving the capture efficiency will be significantly increased. mainly because of the difficult by-product formed by the reaction of amine and CO_2, which only increases the steam consumption. The regeneration rate of the rich liquid is difficult to achieve the expected effect. The main reason is that the by-product formed by the reaction of the alcohol amine and CO_2 is difficult to regenerate, and the regeneration rate of the rich liquid is difficult to achieve the desired effect by simply increasing the steam consumption.

4.4 Variation of desorber operating pressure

In order to study the influence of the desorber operating pressure on CO_2 capture efficiency and specific heat consumption. The desorber operating pressure is adjusted to 5kPa, 10kPa, 15kPa, 20kPa, 25kPa, 30kPa, 40kPa respectively. The other operating parameters are V_{fg} 3000Nm^3/h, T_{fg}40°C, Q_{reb}367kg/h, f_{sol} 4.0m^3/h, the test result is shown in Figure 5.

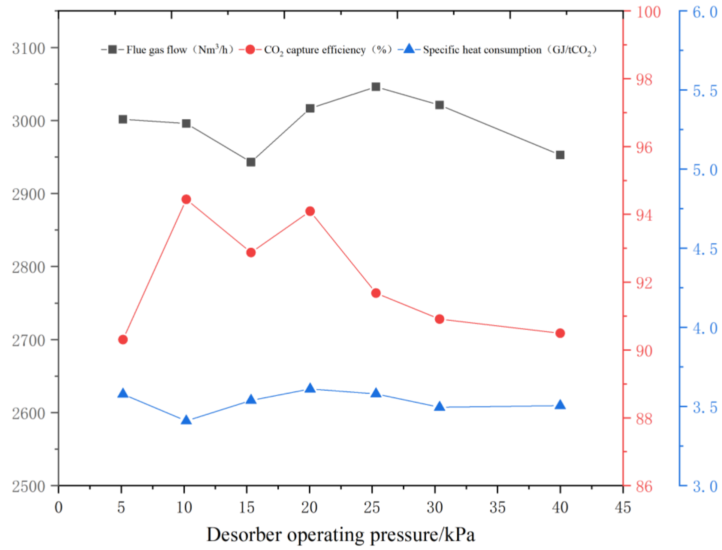

Figure 5. Influence of the desorber operating pressure on the CO_2 capture efficiency and specific heat consumption

Figure 5 shows that with the pressure of the desorber increased from 5kPa to 40kPa, the capture efficiencies are 90.3%, 94.4%, 92.9%, 94.1%, 91.7%, 90% and 90.5%, respectively. The overall trend is first rising and then falling, and the optimal operating pressure was 10kPa.

The operating pressure of the desorber is the key factor affecting the regeneration rate, especially when the solvent recirculation flow rate and the steam flow rate of the reboiler is stable. When the desorber operating pressure is low, the proportion of water vapor in the regeneration gas is larger than CO_2, the concentration difference of CO_2 on the mass transfer interface is relatively larger, and the driving force of mass transfer is strengthened, which is conducive to the solvent regeneration. However, the lean liquid temperature at the bottom of the desorber is relatively low when the desorber operating pressure is low. For example, when the desorber operating pressure is 5kPa, the lean liquid temperature is only about 102℃ (the optimum regeneration temperature is usually above 110 °C). The regeneration rate decreases significantly at low temperatures, resulting in an increase in the lean CO_2 load of the absorption tower, and then reduces the capture efficiency.

4.5 Variation of the solvent recirculation flow rate

In this test, the solvent circulating flow rate is adjusted to 4.0m^3/h, 4.5m^3/h, 5.0m^3/h, 5.5m^3/h, 6.0m^3/h. The other operating parameters are V_{fg} 3000Nm^3/h, T_{fg}40℃, Q_{reb}367kg/h, P_{des}10kPa, f_{sol}4.0m^3/h, the test result is shown in Figure 6.

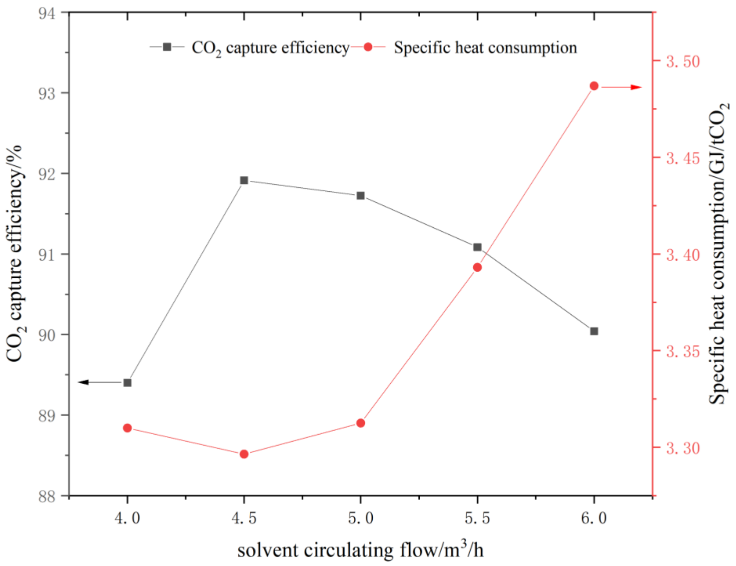

Figure 6. Influence of the solvent recirculation flow rate on the CO_2 capture efficiency and specific heat consumption

Figure 6 shows that, when the solvent circulating flow rate is 4.0m^3/h, 4.5m^3/h, 5.5m^3/h, 6.0m^3/h, the capture efficiency is 89.4%, 91.9%, 91.7%, 91.1% and 90.1%, and the specific heat consumption is 3.31GJ/tCO_2, 3.29GJ/tCO_2, 3.32GJ/tCO_2, 3.39GJ/tCO_2, 3.49GJ/tCO_2 respectively. For this CO_2 capture plant, with the increase of solvent circulating flow rate, the CO_2 capture efficiency generally increased first and then decreased. Under the condition of maintaining the flue gas flow rate, with the increase of the solvent circulating flow rate, the absorber liquid holdup of the packing increases, and the absorption capacity is improved.. At the same time, the absorbent flow rate increases, the surface fluidity of the filler layer increases, and the liquid phase mass transfer conditions are improved. With the further increase of the solvent circulating flow rate, the solvent regeneration rate decreases, which affects the forward progress of the absorption reaction, and further aggravates the decline of the capture efficiency , leading to the increase of the specific heat consumption.

4.6 Optimize operation results

According to the parameter test results, the optimum operating conditions are V_{fg} 3000Nm^3/h,T_{fg}40°C, Q_{reb}367kg/h, P_{des}10kPa, f_{sol}4.0m^3/h, Figure 7 shows the results of 4 hours of continuous operation under optimum operating conditions. The average CO_2 capture efficiency capture is 90.6%, and the specific heat consumption is 3.29GJ/tCO_2.

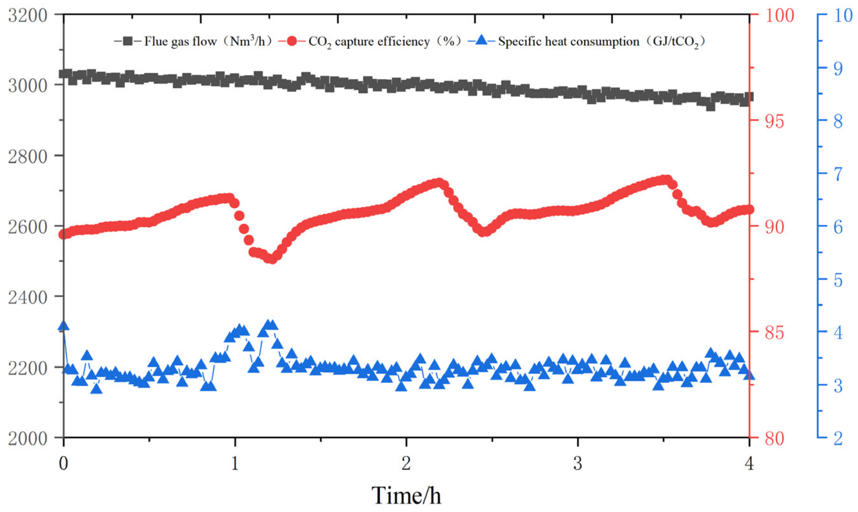

Figure 7. Performance of the CO_2 capture plant under optimal operating conditions

5 Conclusions

The operation parameters of CO_2 capture using new ternary amines are studied in a 1800t/y demonstration plant at Beijing Gaojing Thermal Power Station.. The influence of flue gas flow rate, flue gas temperature , reboiler steam flow rate, desorber operating pressure, solvent circulating flow rate on the CO_2 capture efficiency and specific heat consumption is investigated. The tests show that the optimum operating conditions are flue gas flow rate 3000Nm^3/h, flue gas temperature 40°C, reboiler steam flow rate 367kg/h, desorber operating pressure 10kPa, solvent circulating flow rate 4.0m^3/h. Under optimum operating conditions, the average CO_2 capture efficiency capture is 90.6% ,and the specific heat consumption is 3.29GJ/tCO_2.

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