Conference Paper

Research on Energy Utilization in Recovery of CO$_2$ from Boiler Flue Gas

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Abstract
To the 2×40 t/h heating boiler flue gas, ethanolamine was used for absorption, carbamate – for desorption. The waste heated boiler flue gas was used to heat the absorption and the desorption; the pump was driven by the solar energy. The results showed that the best absorption rate was 82.28%, when the ethanolamine concentration was 40% and the temperature was 40°C; the energy consumption was 59.82 KJ/mol. The best desorption temperature was 115°C, the desorption rate was 55%, and its energy consumption was 694.30 KJ/mol. The pump needed 1.49 KJ/h, reduced 42.8 t/year of CO$_2$ and regenerated 23.54 t/year of CO$_2$.

Keywords: CO$_2$ absorption rate, CO$_2$ desorption rate, CO$_2$ regeneration rate, energy conservation, emission reduction

1. Introduction
In recent years, the concentration of CO$_2$ in the atmosphere has increased yearly. Before the Industrial Revolution, the concentration of CO$_2$ in the atmosphere was 280 ppm. In 2016, the World Meteorological Organization (WMO) announced that the concentration of CO$_2$ in the global atmosphere exceeded 400 ppm for the first time. The total CO$_2$ emission in 2016 of China is about 8 billion tons, provided that about more than 60% of CO$_2$ comes from the power and heat industries [1]. CO$_2$ in the atmosphere is one of the main culprits of global warming. If industrial CO$_2$ is collected, it can be used to make industrial products such as dry ice, soda ash, and urea. Therefore, research on CO$_2$ recovery and utilization in boiler flue gas has become an important topic for Chinese researchers.

At present, the CO$_2$ capture of boilers mainly utilizes the chemical absorption method, because this method has high decarburization rate, low decarburization cost, and remarkable effect. In this article, for the flue gas of 2×40 t/h coal-fired boiler, CO$_2$ is captured by ethanalamine and sodium hydroxide under experimental conditions.
The parameters of the flue gas of 2x40 t/h coal-fired boiler are shown in Table 1. The volume concentration of CO$_2$ gas is about 13%. In order to facilitate the reading of the rotameter, the volume concentration of simulated CO$_2$ gas is 14%.

### Table 1: Flue gas parameters of 40 t/h coal fired boiler.

| Heading         | Flue Gas Temperature (°C) | Pressure (MPa) | Exhaust Flow Rate (m/s) | Exhaust Flow (m$^3$/h) | Standard Dry Exhaust Flow (m$^3$/h) |
|-----------------|---------------------------|----------------|-------------------------|------------------------|-------------------------------------|
| Average value   | 135                       | 0.098066       | 3.99                    | 129361.40              | 92070.46                            |
| Maximum         | 168                       | 0.098120       | 4.05                    | 131283.70              | 96577.34                            |
| Minimum         | 95                        | 0.097983       | 3.74                    | 121168.00              | 56276.74                            |
| Number of samples | 30                        | 30             | 30                      | 30                     | 30                                  |

### 2. Experiment

The CO$_2$ trap consists of a gas cylinder, a rotameter, a pressure reducing valve, a mixing buffer, an electrothermal thermostatic water bath, a thermometer, and a three-necked flask (Figure 1). First, the absorbent is heated in the constant temperature water bath to the experimental temperature. Then, using the CO$_2$ cylinder and the N$_2$ cylinder, the pressure is adjusted by reducing valve to obtain the experimental condition flow. Finally, the gas is mixed by the mixing buffer and flows to the absorbent.

![Figure 1: Schematic diagram of absorption experiment: 1 – CO$_2$ cylinder; 2 – N$_2$ cylinder; 3, 4 – pressure-reducing valves; 5 – mixing buffer device; 6 – rotameter; 7 – thermometer; 8 – absorbent; 9 – constant temperature water bath; 10 – first-level NaOH solution; 11 – second-level NaOH solution; 12 – third-level NaOH solution.](image)

The pressure reducing valves of the CO$_2$ and N$_2$ cylinders can be adjusted to obtain flow rates of 0.8 and 4.8 L/min. The volume concentration of CO$_2$ gas in the mixed gas was 14.28%, which was very close to the volume concentration of CO$_2$ gas in the...
coal-fired boiler. The flow was maintained for 5 minutes, the total mass of CO\(_2\) during the time was M. In this experiment, to obtain an optimal absorption coefficient, we used different concentrations of ethanolamine solution to absorb CO\(_2\) under different temperature conditions. Given the rate of absorption of ethanolamine could not be directly measured, so the three-necked flask in Figure 1 was used to capture CO\(_2\) that was not absorbed by ethanolamine. By the use of a three-stage absorption device, we could absorb more than 97% of CO\(_2\), and the experimental error has greatly reduced [2]. The absorbent was sodium hydroxide solution, and the product was Na\(_2\)CO\(_3\), which continuously reacted with BaCl\(_2\) to form BaCO\(_3\) precipitate:

\[
\text{BaCl}_2 + \text{Na}_2\text{CO}_3 = \text{BaCO}_3 \downarrow + 2\text{NaCl}
\]  

(1)

We filtered, dried, and weighed the BaCO\(_3\) precipitate to obtain its mass. By the way, the Na\(_2\)CO\(_3\) mass was also calculated.

Experimental instruments and reagents used are presented in Table 2.

| Instrument/Reagents          | Model/Manufacturer                                      |
|------------------------------|---------------------------------------------------------|
| Electric thermostatic water bath | Model 8002, Beijing Huabolian Medical Equipment Co., Ltd. |
| Magnetic stirrer             | EMS-4A type, Shanghai Yingdi Instrument Equipment Co., Ltd. |
| Heating CO\(_2\) decompression flow vessel | YQT-341, Qingdao Yulongyuan Welding & Cutting Equipment Co., Ltd. |
| Nitrogen pressure reducing flow device | YQA-731L, Qingdao Yulongyuan Welding & Cutting Equipment Co., Ltd. |
| Electronic balance           | JA1003, Shanghai Shunyuhengping Scientific Instrument Co., Ltd. |
| Electric blast drying oven   | CS101-2A, China Chongqingyinghe Test Instrument Co., Ltd. |
| Ethanolamine                 | Tianjin Kemiou Chemical Reagent Co., Ltd.               |
| Sodium hydroxide             | Tianjin Hedong District Hongyan Reagent Factory         |
| Ammonia with a mass fraction of 25% to 27% | Xi'an Jianxiang Chemical Co., Ltd. |
| Barium chloride              | Zhengzhou Zhiyuan Chemical Products Co., Ltd.           |

The sodium hydroxide solution was used as an absorbent, which absorbed CO\(_2\) to form Na\(_2\)CO\(_3\).

\[
2\text{NaOH} + \text{CO}_2 = \text{Na}_2\text{CO}_3 + \text{H}_2\text{O}, \Delta H = -171.8 \text{KJ/mol}.
\]  

(2)

The ethanolamine reacted with CO\(_2\) to form a carbamate, and the carbamate was pyrolyzed to ethanolamine and CO\(_2\) by the following reaction:

\[
\text{CO}_2 + 2\text{HOC}_2\text{H}_4\text{NH}_2 \rightleftharpoons \text{HOC}_2\text{H}_4\text{NH}_3\text{COONHC}_2\text{H}_4\text{OH}, \Delta H = +72.7 \text{KJ/mol}.
\]  

(3)
Carbamate desorption device diagram is presented in Figure 2. Thermal analysis of the absorption reactions is presented in Table 3.

**Table 3: Thermal analysis of the absorption reactions.**

| Physical Properties                  | Ethanolamine |
|--------------------------------------|--------------|
| Reaction heat (KJ/mol)               | -36.35       |
| Dissolve heat (KJ/mol)               | 0            |
| Specific heat capacity (kJ/(kg·°C))  | 3.4          |
| Energy consumption (KJ/mol)          | 191.44       |

The absorption rate of the ethanolamine absorbent is calculated as follows:

\[ \eta = \frac{M - M_1}{M} \times 100\% \]  \hspace{1cm} (4)

In the formula, \( M_1 \) is the mass of \( \text{CO}_2 \) absorbed by the tertiary absorption device, \( M \) is the total mass of \( \text{CO}_2 \) after 5 minutes of cylinder aeration.

### 3. Results and Discussion

As shown in Figure 3, the highest absorption rate is at 40°C, and the temperature in the absorption tower of industrial decarbonization system is 30~60°C [3]. The optimum temperature for absorption of \( \text{CO}_2 \) by ethanolamine is 40°C, the concentration is 40%, and the absorption rate is 82.28%.
Figure 3: Effect of temperature on ethanol amine absorption.

It can be seen from Figure 4 that as the temperature increases, the desorption rate of the carbamate solution also becomes larger, and the desorption rate is the lowest at 100°C. From 110 to 115°C, the fold line is the steepest and the desorption rate is the highest, indicating that desorption is the best in this temperature range. The carbamate has the highest desorption rate at around 115°C, with a value of 55%, and then tends to be gentle with increasing temperature.

4. Energy Source of Boiler Flue Gas CO₂ Capture System

According to the experimental results, the CO₂ absorption-desorption device is applied to a 2×40 t/h coal-fired boiler. The waste heat of flue gas is used to heat the system. The design calculation and schematic of the device are as follows.
4.1. Energy balance

The ethanolamine absorbent absorbs CO$_2$ under heating conditions, and the different components result in different specific heat capacities, so the absorbed heat is different.

\[
Q_{\text{solution}} = (W_1 C_{P1} + W_2 C_{P2})(t_b - t_a) - (\Delta H_S)_{t_a} + (\Delta H_S)_{t_b}
\]  

(5)

The general equation is:

\[
Q_{\text{In}} = Q_{\text{solution}} + \Delta H
\]

(6)

The energy flow diagram of the CO$_2$ capture system is shown in Figure 5.

4.2. Calculation of flue gas waste heat utilization system

The nominal dry exhaust flow rate is $9.20 \times 10^4$ m$^3$/h as shown in Table 1, and the average temperature is 135°C. CO$_2$ flow: $q_3$ is $6.75 \times 10^3$ mol/min. The amount of CO$_2$ that can be absorbed $q_{2a} = 5.55 \times 10^3$ mol/min; the amount of ethanolamine $Q_3 = 1.11 \times 10^4$ mol; the quality of the solution is $1.69 \times 10^3$ kg. According to the relevant literature [4], the solubility of CO$_2$ in 40% ethanolamine solution is 2.94 mol/L at 40°C under
Figure 5: Energy flows in the CO₂ capture system.

atmospheric pressure. The volumetric flow rate of ethanolamine is required every minute: \( Q_3 = 1.89 \times 10^3 \) L/min. The transfer rate of carbamate between the absorption-desorption devices \( q_4 = 92.52 \) mol/s. According to the concentration of ethanolamine, the concentration of the carbamate solution is 54.40%, the flow rate of the carbamate solution \( q_{\text{solution}} = 28.24 \) kg/s. According to the literature \( [5] \), the carbamate density is \( 7.46 \times 10^2 \) kg/m³, which is obtained from the binary organic solution density formula: \( \rho_{\text{solution}} = 0.86 \times 10^3 \) kg/m³. Therefore, the volumetric flow rate of the solution in pipeline 1 \( Q_{\text{solution}} = 2.43 \times 10^4 \) cm³/s.

4.3. Energy calculation of the heat exchange system

As can be seen from Table 1, the average temperature of the boiler flue gas outlet is 135°C, and it can be seen from Figure 4 that the optimum temperature of the carbamate desorption process is 115°C. The waste heat of the flue gas is used to heat the carbamate solution to achieve the energy saving effect of the desorption device.

The temperature change of flue gas is \( \Delta t_{fg} \), the physical property of the flue gas at 135°C are found in the Industrial Furnace Design Manual: the density of the flow gas \( \rho_{fg} = 88 \) kg/m³, the specific heat capacity of the flow gas \( c_{fg} = 1.08 \) kJ/kg·K, the density of the solution is \( 0.86 \times 10^3 \) kg/m³, the flow rate of the solution is \( 2.43 \times 10^2 \)
m³/s. According to the literature [5], the specific heat capacity of carbamate $c_a = 2.00 \times 10^2 J/(kg \cdot K)$. Calculated according to the specific heat capacity definition, $c_{solution} = 2.31 \times 10^3 J/(kg \cdot K)$.

Heat exchange rate:

$$Q = c_{fg} \times L \times \rho_{fg} \times \Delta t_{fg} = c_{solution} \times q_{solution} \times \rho_{solution} \times \Delta t_{solution}$$

Substituting data, we get the temperature change of the flue gas 63.2°C and the temperature change of the solution 31.8°C. The solution can be heated to 71.8°C by flue gas waste heat. In order to achieve the optimum desorption temperature, steam can be used in the desorption column, $\Delta_{steam} = 43.2°C$.

4.4. Packing tower design calculation

The schematic diagram of CO₂ absorption–desorption device design is presented in Figure 6. The ethanolamine solution storage tank volume is designed to be 2.5 m³, which is used to store the ethanolamine solution required for the reaction. The absorption–desorption device is designed as a packed tower. The tower diameter is set to 2.0 m, and the tower height $Z$ is calculated as follows.

![Figure 6: Schematic diagram of CO₂ absorption–desorption device design.](image)

According to mass transfer theory, we can get:

$$Z = H_{OV} N_{OV} = H_{OL} N_{OL},$$

where $H_{OV}$, $H_{OL}$ – height of the total mass transfer unit of gas and liquid phase; $N_{OV}$, $N_{OL}$ – the total mass transfer unit of gas and liquid phase.
We use Dg38 metal Pall ring for packing and after calculation we get $Z = 12.44$ m.

4.5. Pipeline design calculation

Pipeline 1 represents a stainless steel pipe transfer solution of model DN80 and length 5 m: the diameter $d_1$ of the pipeline 1 is 80 mm. The flow rate $v_1$ inside the tube is 4.83 m/s. The volume flow of ethanolamine $q_{\text{3solution}}$ from the desorption unit to the ethanolamine storage tank and the absorption unit is $2.43 \times 10^4$ cm$^3$/s. The diameter of the line 2 is the same as that of the line 1, and the length is 2 m. The pipeline 3 uses 30 stainless steel tubes covered by fins and the model number is DN30 and the length is 5 m. The flow rate $v_2$ inside the tube is 1.15 m/s.

4.6. Calculation of resistance loss

Since the solution component is mostly water, the physical properties of solution can be approximately calculated as those the water. At $40^\circ$C, the density of the water is $9.92 \times 10^2$ kg/m$^3$, and the viscosity $\mu$ is $0.656 \times 10^{-3}$ N.s.m$^{-2}$, $Re$ is $6.8 \times 10^4$. Therefore, the flow state in the pipes 1 and 2 is turbulent. For line 3, $Re$ is $5.22 \times 10^4$. Therefore, the flow state in the pipeline 3 is turbulent. The resistance loss along the path is 8.44 m, the local resistance loss is 0.998 m, the pressure drop is $9.25 \times 10^4$ Pa, and the pump work is $2.85 \times 10^3$ at the effectiveness of 0.78. According to the existing motor selection, two pump motors with a power of 1.5 kW were selected.

4.7. Calculation of the solar energy systems

The design power of the solar system should satisfy the total power of the motor 3 kW.

12 Yingli YL270P-29b photovoltaic panels were used to construct the photovoltaic array. The maximum output power was 270 W, the open circuit voltage was 37.9 V, the short circuit current was 9.35 A, the maximum working voltage was 31 V, the maximum working current was 8.9 A, and the size was $1650 \times 992 \times 35$ mm$^3$. We chose 16 HGY6037 batteries to store the excess energy.

Taking Xi’an as an example, the installation inclination of the photovoltaic (PV) model is designed to be 45°, and priority should be given to guarantee the use of electricity in winter. The PV model’s wiring design uses a series of 2-way parallel
connections. Through simulation, the expected power generation of the system is as follows.

As can be seen, the PV system’s annual power generation is $1.20 \times 10^3$ kWh. The generating capacity is maximal in August, reaching 135 kWh monthly, which can ensure the load operating 4.0 h daily. While the generating capacity is minimal in December, reaching 73.70 kWh monthly, it can ensure the load operating 2.0 h daily. Expected generation capacity of designed PV system is presented in Table 4.

| Month  | Horizontal Radiation kWh/m² | Expected Generation kWh |
|--------|-----------------------------|-------------------------|
| January | 63.9                        | 82.3                    |
| February | 72.2                        | 80.9                    |
| March   | 98.9                        | 97.6                    |
| April   | 122.3                       | 105.4                   |
| May     | 145.7                       | 120.9                   |
| June    | 151.5                       | 120.0                   |
| July    | 153.7                       | 125.5                   |
| August  | 149.4                       | 135.1                   |
| September | 100.8                      | 96.8                    |
| October | 82.3                        | 88.3                    |
| November | 63.3                        | 77.5                    |
| December | 57.7                        | 73.7                    |
| Year    | 1261.7                      | 1203.8                  |

5. Conclusion

Under the optimal experimental conditions, the ethanolamine concentration is 40%, and the absorption rate at the temperature of 40°C is 82.28%. The designed 2×40 t/h civil heating boiler flue gas absorption and desorption device has a diameter of 2.0 m and a tower height of 12.44 m. The filler is a Dg38 metal Pall ring. The system reduces CO₂ emissions by 42.8 t/year and regenerates CO₂ by 23.54 t/year. The system uses boiler flue gas to provide heats, accounting to $1.2 \times 10^7$ MJ/year for the absorption and desorption devices, and the energy provided by the solar energy system is $1.08 \times 10^3$ kWh/year.
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