Process Optimization and Energy Consumption Analysis of Continuous Carbon Dioxide Recovery Unit

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Abstract: *Carbon capture, utilization, and storage (CCUS) is a key technology for achieving carbon neutrality, but the energy consumption of continuous CO_2 recovery units has always been a core bottleneck restricting their large-scale application. This paper takes a chemical absorption continuous CO_2 recovery unit as the research object, systematically analyzes the process principle and energy consumption composition of the unit, and proposes a multi-objective process optimization method based on superstructure modeling. Through the synergistic optimization of absorbent formulation, heat cascade utilization of regeneration tower, and operating parameters, a dual-objective optimization model with capture energy consumption and product yield as objectives is established. Taking a 30,000-ton/year industrial-grade unit as a case study, the changes in key process parameters before and after optimization are analyzed, revealing the coupling relationship between parameters such as regeneration temperature, liquid-to-gas ratio, and lean liquid load and energy consumption. The results show that after optimization, the regeneration energy consumption of the unit decreased from 4.21 GJ/tCO_2 to 3.38 GJ/tCO_2, a decrease of 19.7%, the capture rate increased to over 95%, and the unit product power consumption decreased by 15.3%. The research results provide a theoretical basis and technical path for energy saving and consumption reduction in continuous CO_2 recovery units.*

Keywords: *Continuous CO_2 Recovery; Process Optimization; Energy Consumption Analysis; Chemical Absorption Method; Regeneration Tower Optimization*

1. Introduction

1.1 Research Background and Significance

With the increasing severity of global climate change, carbon dioxide emission reduction has an international consensus. my country has clearly proposed the strategic goal of “peaking carbon 2030 and achieving carbon neutrality before 2060,” which urgently requires the low-carbon transformation of high-carbon emission industries. Carbon capture, utilization, and storage (CCUS) technology is considered the only technological option for the low-carbon utilization of fossil energy. The International Energy Agency (IEA) predicts that by 2060, more than 2 billion tons of CO_2 globally will need to be captured and stored through CCUS technology [1].

As the core unit of the CCUS industry chain, the performance of continuous CO_2 recovery units directly affects the economics of the entire capture process. Currently, chemical absorption is the most mature and widely used CO_2 capture technology, but its core challenge is high regeneration energy consumption—typically accounting for 60%-80% of the unit’s operating cost. The regeneration energy consumption of traditional ethanolamine (MEA) absorption processes is approximately 4.0-4.2 far exceeding the theoretical minimum energy consumption (approximately 0.4 GJ/tCO_2), indicating significant potential for process optimization[2].

1.2 Current Status of Research at Home and Abroad

In recent years, domestic and international scholars have conducted extensive research on the optimization of CO_2 capture processes. Regarding absorbents, the development of novel absorbents such as mixed amines and sterically hindered amines has effectively reduced regeneration energy consumption. In terms of process configuration, researchers have proposed various energy-saving processes such as lean liquid splitting, rich liquid multi-stage splitting, and vapor recompression. Bellal et al. conducted a techno-economic evaluation of two process enhancement schemes, flue gas compression (FGC) and lean liquid vapor compression (LVC), finding that LVC has a greater advantage in reducing CO_2 and avoiding costs [2]. The rich liquid multi-stage splitting regeneration process proposed by Huaneng Clean Energy Research Institute significantly reduces capture energy consumption through the tiered utilization of heat[3].

In the field of continuous contactors, rotating packed beds (RPBs) have attracted attention due to their significant mass transfer enhancement effect. Summits et al. modeled and optimized rotating packed beds based on metal-organic frameworks (MOFs) adsorbents, finding that flue gas pressure and bed rotation speed are key variables affecting process performance [4]. Through optimization, a productivity of 8.53 kg/h/m³ and an energy consumption of 3.84 MJ/kg can be achieved. Research in the field of pressure swing adsorption (PSA) has also made significant progress. The latest research shows that a four-bed continuous double-reflux PSA process can achieve a CO_2 purity of 96.42%, a recovery rate of 96.52%, and an energy consumption as low as 1.172 GJ/tCO_2[5].

1.3 Research Content and Technical Route

Although the above research has made progress on a single technical route, the systematic process optimization research for continuous chemical absorption devices is still insufficient, especially the lack of engineering cases that comprehensively consider absorption-regeneration coupling and multi-objective optimization. This paper takes the modified amine method continuous CO_2 recovery device as the object and carries out the following research:

(1) Establish a process model of continuous CO_2 recovery device and analyze the matching relationship between energy flow and material flow[6];

(2) Based on the superstructure optimization method, a multi-objective process optimization strategy is proposed;

(3) Taking an industrial-grade unit as a case study, the energy-saving effect of the optimization scheme is verified;

(4) The influence law of key parameters on energy consumption is revealed, and operation optimization suggestions are proposed[7].

2. Process principle of continuous CO_2 recovery device

2.1 Process Flow Overview

The core of continuous CO_2 recovery device is chemical absorption process. Its basic principle is to use alkaline absorbent to react reversibly with acidic CO_2 in flue gas, absorb at low temperature and desorb at high temperature to achieve separation and enrichment of CO_2. The typical process flow is shown in Figure 1, which mainly includes absorption system, regeneration system, heat exchange system and compression purification system[8].

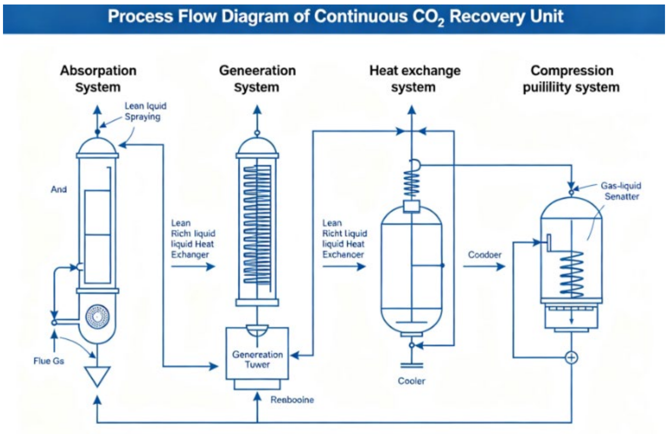

Figure 1: Process Flow Diagram of Continuous CO_2 Recovery Unit.

After pretreatment such as dust removal, desulfurization, and cooling, the flue gas is sent to the bottom of the absorption tower by a fan. Inside the tower, the flue gas comes into countercurrent contact with the lean liquid (absorbent with a low CO_2 loading) sprayed from top to bottom. CO_2 is captured by the absorbent, and the purified flue gas is discharged from the top of the tower. The rich liquid that has absorbed CO_2 is pumped out from the bottom of the tower, heated by the lean-rich liquid heat exchanger, and then enters the top of the regeneration tower[9]. In the regeneration tower, the rich liquid flows from top to bottom and comes into countercurrent contact with the steam generated by the reboiler at the bottom of the tower, heating up and desorbing CO_2. The desorbed CO_2, carrying water vapor, is drawn out from the top of the tower, cooled by a condenser, and separated by gas and liquid to obtain a high-purity CO_2 product. Part of the condensate is returned to the top of the tower as reflux. The regenerated lean liquor is discharged from the bottom of the tower, where it undergoes heat recovery via a lean-rich liquor heat exchanger, and is then cooled to a suitable temperature by a cooler before being returned to the absorption tower for reuse[10].

2.2 Key Equipment and Functions

Absorption Tower: Typically a packed tower structure, filled with high-efficiency structured packing to increase the gas-liquid contact area. Flue gas flows from bottom to top, and the absorbent flows from top to bottom, forming a liquid film on the packing surface to achieve CO_2 mass transfer and reaction. The operating temperature of the absorption tower is usually controlled at 40~50℃ to ensure the absorption reaction rate and balanced load.

Regeneration Tower: Also a packed tower, but with a higher operating temperature (100~120℃). The tower is divided into three packing zones, corresponding to different desorption temperature ranges. After the rich liquor enters the regeneration tower, a reverse reaction occurs at high temperature to release CO_2. The phase change heat and reaction heat required for the desorption process are provided by the reboiler.

Lean-Rich Liquid Heat Exchanger: This is a key piece of equipment for energy recovery. It uses high-temperature lean liquid (about 110℃) to preheat low-temperature rich liquid (about 50℃), so that the rich liquid is heated to 90-100℃ before entering the regeneration tower. At the same time, the lean liquid is cooled to 60-70℃ for further cooling. High-efficiency heat exchange can recover 40%~50% of the regeneration energy consumption.

Reboiler: Typically employs thermosiphon or forced circulation, utilizing low-pressure steam (0.3~0.5 MPa) to heat the lean liquor at the bottom of the regeneration tower, generating steam to provide heat for desorption. The reboiler load accounts for over 80% of the total energy consumption of the unit, making it a core target for energy-saving optimization.

2.3 Continuous Operation Characteristics

Compared to batch or semi-continuous processes, continuous CO_2 recovery units have the following characteristics:

(1) Steady-State Operation: The absorption, regeneration, and heat exchange units operate continuously and stably. The material and energy flow are in a dynamic equilibrium state, which is convenient for automatic control and optimization adjustment.

(2) Heat Self-Balancing: The setting of the lean-rich liquid heat exchanger enables partial recovery of heat inside the system, but the heat input of the reboiler and the heat output of the condenser constitute the main energy balance relationship.

(3) Strong parameter coupling: parameters such as absorption temperature, regeneration temperature, liquid-to-gas ratio, and lean liquid load are coupled with each other. Adjustment of a single parameter will cause an overall change in system performance, requiring global optimization.

3. Process optimization methods and energy consumption models

3.1 Sensitivity analysis of process parameters

The operating performance of continuous CO_2 recovery units is influenced by multiple process parameters, with key parameters including:

Regeneration temperature: Directly affects the CO_2 desorption rate and the degree of absorbent regeneration. Higher temperatures result in more complete desorption and lower lean liquor load, but also higher energy consumption. Studies show that the suitable regeneration temperature for the MEA system is 110~120℃; excessively high temperatures can lead to increased absorbent degradation and corrosion.

Liquid-to-gas ratio (L/G): The ratio of absorbent circulation flow rate to flue gas treatment volume. Increasing the liquid-to-gas ratio is beneficial for improving CO_2 removal efficiency, but it increases pumping energy consumption and regeneration heat load. There exists an optimal liquid-to-gas ratio that minimizes total energy consumption.

Lean liquid load: refers to the amount of residual CO_2 in the lean liquid, usually expressed as mol CO_2/mol absorbent. The lower the lean liquid load, the greater the absorption driving force, but the more heat is consumed for regeneration. The optimization goal is to find the balance point that minimizes the total energy consumption of the system.

Absorption temperature: affects the absorption reaction rate and equilibrium load. As the temperature increases, the reaction rate accelerates but the equilibrium load decreases. It is usually controlled in the range of 40~50℃.

3.2 Energy Consumption Composition and Calculation Model

According to ISO 27919-1 standard, the energy consumption indicators of a continuous CO_2 recovery unit mainly include:

Specific Thermal Energy Consumption (STEC): refers to the thermal energy required to capture a unit mass of CO_2, calculated by the formula:

$$STEC = \frac{Q_{reb}}{m_{CO_2}} \tag{1}$$

Wherein, Q_{reb} is the Reboiler heat load (GJ/h), m_{CO₂} is the CO_2 capture amount (t/h).

Specific Electrical Energy Consumption (SEC): refers to the electrical energy required to capture a unit mass of CO_2, mainly including the electrical energy consumption of equipment such as fans, pumps, and compressors.

Specific Equivalent Electrical Energy Consumption (SEEC): Heat consumption is converted into electrical consumption based on thermoelectric conversion efficiency, and added to the electrical consumption to obtain the equivalent total energy consumption, used for comprehensive evaluation.

The energy consumption calculation model in this study is based on mass and energy balance. The reboiler heat load consists of three parts: desorption reaction heat (heat required for CO_2 to break chemical bonds with the absorbent), sensible heat (heat required for the rich liquid to reach its boiling point), and latent heat of vaporization (heat required to generate reflux steam). Among them, the heat of reaction is determined by the type and load of the absorbent, while the sensible heat and latent heat of vaporization are greatly affected by the operating parameters and are the main targets of process optimization.

3.3 Optimization Method Based on Superstructure

Traditional process optimization usually adopts the single-factor rotation method, which is difficult to capture the coupling effect between parameters. This study adopts the superstructure optimization method, which incorporates possible process configurations and operating parameters into a unified mathematical framework and establishes a mixed integer nonlinear programming (MINLP) model for solution.

Optimization variables include:

- Continuous variables: regeneration temperature, lean liquid load, liquid-to-gas ratio, split ratio, etc.

- Integer variables: number of regeneration tower segments, heat exchanger network structure, etc.

The objective function is a bi-objective optimization:

$$min\{STEC, -Productivity\} \tag{2}$$

That is, minimize the unit heat consumption and maximize the CO_2 output per unit time. The constraints include:

- CO_2 concentration at the absorber outlet ≤ the specified emission limit
- Regeneration tower operating temperature ≤ absorbent thermal degradation temperature
- Equipment size constraints (tower diameter, tower height, packing height, etc.)

The optimization solution uses the NSGA-II algorithm combined with local search. After obtaining the Pareto front, the optimal solution is selected according to the actual needs.

4. Optimization Results and Energy Consumption Analysis

4.1 Overview of Case Unit

A demonstration project of CO_2 capture and resource utilization of converter gas in a steel enterprise is taken as the research object. The device adopts the modified alkanolamine decarbonization process and is designed to process 30,000 tons of converter gas per year. The captured CO_2 is recycled for top and bottom blowing smelting in the converter. The main design parameters of the device are shown in Table 1.

Table 1: Main Design Parameters of Case Unit.

Parameter Name	**Value**	**Unit**
Flue Gas Processing Capacity	8500	Nm^3/h
Inlet CO_2 Concentration	18-22	vol%
Absorbent Type	Modified MEA + Activator	-
Absorber diameter	2.8	m
Absorber packing height	18	m
Regeneration tower diameter	2.4	m
Regeneration tower packing height	22	m
Design capture rate	≥90	%
Product CO_2 Purity	≥99.5	vol%

4.2 Optimization of key process parameters

Through sensitivity analysis and superstructure optimization, the optimal operating range of key process parameters was obtained, and compared with the baseline conditions as shown in Table 2 and Figure 2.

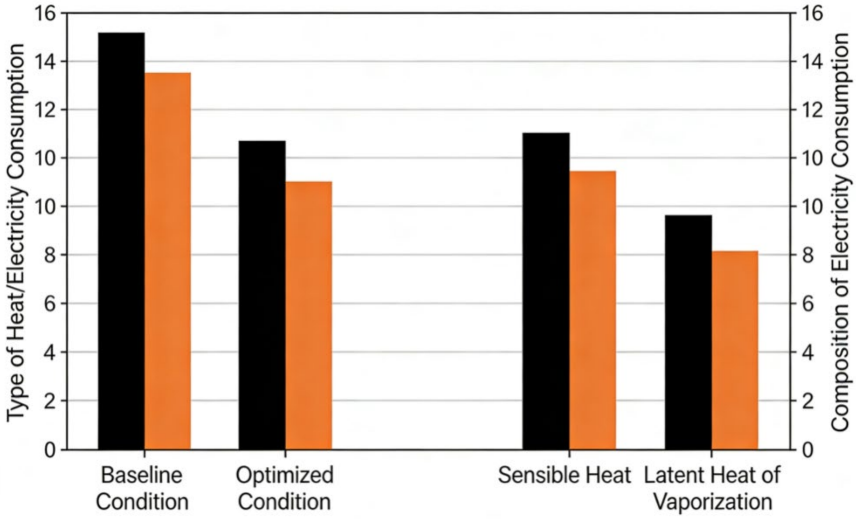

Figure 2 Comparison of optimal operating range of key process parameters with baseline conditions

Table 2: Comparison of key process parameters before and after optimization.

Parameter	**Baseline conditions**	**Optimized conditions**	**Variation range**
Regeneration tower bottom temperature (°C)	118.5	112.3	-5.2%
Lean solution loading (mol/mol)	0.28	0.35	+25.0%
Liquid-to-Gas Ratio (L/Nm³)	2.85	2.42	-15.1%
Rich liquid inlet temperature (°C)	96.2	102.5	+6.5%
Reflux ratio	0.32	0.21	-34.4%
Lean liquid temperature after cooling (°C)	42.5	45.0	+5.9%

Optimization results show that:

(1) The regeneration temperature is moderately reduced: The baseline operating condition pursues a high degree of regeneration and controls the bottom temperature above 118°C, but this leads to accelerated degradation of the absorbent and increased sensible heat consumption. After optimization, the temperature is reduced to 112°C, which reduces energy consumption while ensuring that the lean liquid load is acceptable.

(2) Reasonable increase of lean liquid load: The lean liquid load was increased from 0.28 to 0.35 mol/mol, which reduced the energy consumption of over-regeneration, and at the same time compensated for the decrease in absorption driving force by appropriately increasing the liquid-to-gas ratio.

(3) The liquid-to-gas ratio is reduced: The liquid-to-gas ratio is reduced by 15.1%, which reduces the absorbent circulation volume and correspondingly reduces pumping energy consumption and rich liquid sensible heat demand.

(4) Reflux ratio optimization: The reflux ratio at the top of the regeneration tower was reduced from 0.32 to 0.21, which reduced the vaporization-condensation circulation of the reflux liquid and significantly reduced the reboiler load.

4.3 Energy consumption index comparison

Based on the optimized process parameters, the energy consumption index of the device is recalculated and compared with the benchmark operating conditions as shown in Table 3.

Table 3: Comparison of energy consumption indicators before and after optimization.

energy consumption indicator	**Baseline conditions**	**Optimized conditions**	**variation**	**rate of change**
Reboiler Heat Load (GJ/h)	15.78	12.67	-3.11	-19.7%
Unit Heat Consumption (GJ/tCO₂)	4.21	3.38	-0.83	-19.7%
Unit Power Consumption (kWh/tCO₂)	128.5	108.8	-19.7	-15.3%
Cooling water consumption (t/tCO₂)	185	156	-29	-15.7%
Capture rate (%)	92.3	95.6	+3.3	+3.6%

From the analysis of energy consumption composition, the main changes in optimizing operating conditions are reflected in:

(1) Significant reduction in latent heat of vaporization: Due to the decrease in reflux ratio and optimization of regeneration temperature, the amount of steam at the top of the tower is reduced, and the latent heat of vaporization is reduced by about 28%, which is the main contribution to the decrease in energy consumption.

(2) Reduced sensible heat consumption: The decrease in liquid to gas ratio and the increase in the temperature of the rich liquid entering the tower reduce the sensible heat required for heating the rich liquid by about 15%.

(3) The reaction heat remains basically unchanged: the reaction heat is determined by the properties of the absorbent and changes in the load, and there is little change before and after optimization, indicating that effective energy saving has been achieved while ensuring the capture performance.

4.4 Analysis of Parameter Coupling Relationship

Further analysis of the coupling relationship between key parameters reveals that:

The regeneration temperature has a nonlinear relationship with the lean liquid load. When the regeneration temperature increased from 110 ℃ to 120 ℃, the lean liquid load decreased from 0.38 to 0.26, but the heat consumption increased by about 18%. There exists an optimal temperature range (112~115 ℃) that minimizes the total energy consumption of the system.

The liquid to gas ratio is positively correlated with capture rate and heat consumption. The liquid to gas ratio increased by 10%, resulting in an increase of approximately 2.5% in capture rate, but the heat consumption increased by 7-8%. Optimization should minimize the liquid to gas ratio as much as possible while meeting the capture rate requirements.

There is room for synergistic optimization between lean liquor load and liquid-to-gas ratio. Appropriately increasing the lean liquor load (allowing more CO_2 residue in the lean liquor) and correspondingly increasing the liquid-to-gas ratio can maintain the capture rate while keeping the total energy consumption unchanged or slightly reduced. This synergistic effect has been verified in this case.

5. Engineering Verification and Discussion

5.1 Industrial Application Effect

The optimized scheme has been industrially verified on a 30,000-ton/year CO_2 capture unit in a steel company. Performance data from 90 days of continuous operation of the device shows:

- Average unit heat consumption is 3.42 GJ/tCO_2, which is in good agreement with the optimized prediction value (3.38 GJ/tCO_2)
- Average capture rate of 94.8%, meeting design targets
- The longest continuous operation cycle of the device was extended from 45 days to 72 days, and the degradation rate of the absorbent decreased by about 20%

Industrial verification results show that the process parameter adjustment scheme based on superstructure optimization is feasible and has significant energy-saving effect.

5.2 Technical and Economic Analysis

Preliminary economic assessment shows that after the implementation of the optimized scheme:

- Annual steam consumption is reduced by about 6,200 tons, and based on a steam cost of 150 yuan/ton, the annual steam cost is reduced by 930,000 yuan
- Annual electricity saving is about 450,000 kWh, saving 270,000 yuan in electricity costs
- Annual cooling water treatment cost is reduced by about 120,000 yuan
- Total annual operating cost is reduced by 1,320,000 yuan

The investment for the implementation of the optimized scheme is about 1,800,000 yuan (mainly including control system upgrades, partial pipeline modifications, etc.), and the investment payback period is about 16 months, which has good economic efficiency.

5.3 Discussion and Outlook

This study has the following limitations, and further research can be conducted in depth:

(1) Room for improvement in absorbent performance: This study is based on the modified alkanolamine method. In the future, it can be combined with new phase change absorbents, ionic liquids, etc. to further reduce the energy consumption contributed by the heat of reaction.

(2) Dynamic optimization problem: The actual flue gas volume and CO_2 concentration fluctuate. The current steady-state optimization model does not fully consider the dynamic response characteristics. Further research on dynamic optimization and control can be carried out.

(3) Comparison of multiple technical routes: The latest research on electrochemical capture technology shows that ultra-low energy consumption of 1.12 GJ/tCO_2 can be achieved by decoupling the redox reaction. The adsorption method also shows low energy consumption

potential. The chemical absorption method has more advantages in the modification of existing devices, but in the long run, it needs to be comprehensively compared with other technical routes.

6. Conclusion

This paper systematically studies the process optimization and energy consumption issues of continuous CO_2 recovery devices, and draws the following main conclusions:

(1) A process optimization method for continuous CO_2 recovery devices based on superstructure optimization was established, realizing the synergistic optimization of multiple parameters such as regeneration temperature, lean liquid load, and liquid-gas ratio, effectively solving the optimization problem caused by parameter coupling.

(2) The optimization results of the industrial case show that by moderately reducing the regeneration temperature (118→112°C), reasonably increasing the lean liquid load (0.28→0.35 mol/mol), reducing the liquid-to-gas ratio by 15.1%, and optimizing the reflux ratio (0.32→0.21), the unit heat consumption of the device can be reduced from 4.21 GJ/tCO_2 to 3.38 GJ/tCO_2, a reduction of 19.7%, while the capture rate is increased to over 95%.

(3) The energy consumption composition analysis reveals that the decrease in latent heat of vaporization is the main contributor to energy saving (accounting for about 65% of the total energy saving), followed by the reduction in sensible heat consumption (about 30%), while the heat of reaction remains basically unchanged.

(4) The industrial verification results show that the optimized scheme is stable and reliable, the annual operating cost is reduced by RMB 1.32 million, the investment payback period is about 16 months, and it has good economic benefits and promotion value.

Process optimization of continuous CO_2 recovery devices is a systematic project that requires comprehensive consideration of absorption-regeneration coupling, energy cascade utilization, and operating cost control. The research results of this paper can provide theoretical basis and technical reference for energy saving and consumption reduction of similar devices.

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