

Article

Techno-Energy Optimization of Carbon Capture Process in MDEA Blended Amines for Flue Gas Difficult to Reduce: A Case Study on Coal-Fired Power Plant

Tianjiao Zhang ^{1,*}, Hu Qu ¹, Xin Liu ¹ and Hanyong Li ²¹ China Petroleum Engineering & Construction Corporation (CPECC) North Branch, Renqiu 062550, China² Beijing Institute of Petrochemical Technology (BIPT), School of Mechanical Engineering, Beijing 102600, China

* Correspondence: ztj201307@126.com

Abstract

Chemical absorption is currently the most mature technology for carbon capture from flue gas in coal-fired power plants. The selection of the amine solution system and process optimization directly determine the energy consumption of carbon capture and are critical to the large-scale implementation of the amine process. In this study, a composite amine solution of N-methyl-diethanolamine-piperazine-water (MDEA-PZ-H₂O) was selected as the CO₂ absorbent. Aspen HYSYS (14.0) software was used to establish a typical process model for CO₂ capture from flue gas in coal-fired power plants. Using single-factor sensitivity analysis, key process parameters in the typical carbon capture process—including amine solution composition, flue gas inlet temperature, lean liquid temperature, and gas-to-liquid ratio—were optimized. Based on the process optimization, this study conducted integrated energy-saving optimization by optimizing the temperature distribution in the absorption tower (achieved through the integration of inter-stage cooling in the absorption tower) and regeneration energy savings (achieved through the coupling of the Mechanical Vapor Recompression (MVR) process). The results indicate that the carbon capture system integrating the inter-stage cooling process with the MVR energy-saving process reduces the energy consumption per unit of carbon captured by 15.15% compared to a typical process system. This demonstrates that the integration of multiple energy-saving processes with the recovery of flue gas and CO₂ waste heat recovery within the system is an effective approach to reducing the energy consumption per unit of carbon capture.

Keywords: N-methyl diethanolamine; piperazine-activated; flue gas carbon capture; amine solution system; single-factor sensitivity analysis; energy consumption; optimization



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1. Introduction

Excessive emissions of greenhouse gases such as carbon dioxide are the primary drivers of a range of environmental issues, including global warming and ecological degradation. Therefore, reducing emissions of greenhouse gases such as carbon dioxide is crucial to addressing climate challenges. This has also become a critical issue for the sustainable development of human society [1–3]. Currently, carbon dioxide, as the primary greenhouse gas, has become the focus of attention, and countries around the world have reached a consensus on the necessity of implementing carbon dioxide emission reductions to address climate change. As the world's second-largest economy and the largest carbon emitter, China has proposed the “dual carbon” goals of “striving to reach a carbon peak by

2030 and achieve carbon neutrality by 2060.” [4–6]. According to relevant data, the primary source of carbon dioxide within China is industrial flue gas generated by the combustion of fossil fuels such as coal, with low-concentration carbon dioxide in flue gas emitted by coal-fired power plants accounting for the majority [7–10]. Therefore, the efficient and energy-saving capture of low-concentration, low-partial-pressure carbon dioxide from coal-fired power plant flue gas has become a top priority for China in achieving “dual carbon” goals.

At present, the amine-based chemical absorption method is the most mature and widely used technology for capturing low-concentration carbon dioxide from industrial flue gas. However, the traditional MEA (monoethanolamide) carbon capture process suffers from high energy consumption during regeneration and high capture costs, which have become key constraints to the large-scale industrial application of this technology. To address these issues, researchers both domestically and internationally have conducted extensive studies on carbon capture processes using blended amine solutions [11–13]. Existing research findings [14–17] indicate that the MDEA blended amine system offers better energy-saving performance than traditional MEA single-amine solutions, making it a chemical absorbent with significant development potential. Pilot tests [14] indicate that the CO₂ absorption capacity is significantly enhanced after mixing MDEA with PZ, effectively reducing regeneration energy consumption. However, the current depth of process system research on the MDEA blended system still falls short of meeting the requirements for large-scale industrial application [18–20]. This study takes the typical flue gas composition of a certain thermal power plant as its research subject. Based on the reaction mechanism between the MDEA blended system and CO₂, the Aspen HYSYS (14.0) simulation software was used to establish a process system model for flue gas carbon capture using MDEA-PZ-H₂O composite amine solution. This study analyzes the key influencing factors of the classic carbon capture process flow for flue gas in a typical coal-fired power plant. Building upon the analysis and optimization of the classic process, the study conducts integrated optimization analyses for absorption tower temperature distribution and regeneration energy savings. This research will provide an efficient, low-energy-consumption solution for the engineering application of low-concentration CO₂ capture from flue gas in coal-fired power plants.

2. Methodology

2.1. Organic Alcohol Amine Solutions [21–23]

Organic amine solutions are currently the most extensively studied and widely used chemical absorbents. Organic amine-based chemical absorbents include monoethanolamine (MEA), 2-amino-2-methyl-1-propanol (AMP), methyl ethanolamine (MMEA), diethylamine (DEA), and N-methyl-diethylamine (MDEA). A comparison of commonly used organic amine chemical absorbent solutions and their advantages and disadvantages is shown in Table 1.

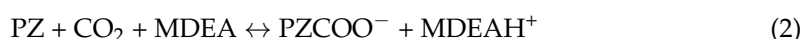
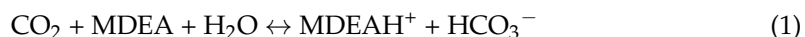
As shown in Table 1, Monoamine solution systems have inherent limitations. The most widely used MEA exhibits fast reaction kinetics, but they are characterized by high regeneration energy consumption, high corrosion potential, and low cycle capacity. Steric-hindered amine AMP offers high CO₂ cycle capacity and low regeneration energy consumption, but its slow reaction rates limit its standalone application. Amines such as MDEA and PZ face a difficult trade-off between reaction rate and regeneration energy consumption. Therefore, mixed amine solutions offer a synergistic balance between reaction rate and energy consumption during regeneration, making them the current focus of research and development. In this study, an MDEA-based mixed amine solution (MDEA-PZ-H₂O) was selected as the absorbent.

Table 1. Comparative analysis of the advantages and disadvantages of organic alcoholamine solvents.

Organic Alcohol Amine Solvents	Advantages	Disadvantages
MEA	High CO ₂ capture efficiency, rapid CO ₂ absorption rate, and widespread industrial applications.	High energy consumption during regeneration, low CO ₂ loading capacity, and susceptibility to degradation and foaming can reduce decarbonization efficiency.
MDEA	Excellent chemical stability, resistant to degradation and spoilage.	React with CO ₂ at a low rate. A catalyst is needed to accelerate the reaction rate with CO ₂ .
PZ	High CO ₂ absorption capacity and fast absorption rate	Low solubility; commonly used as an activator
AMP	High absorption capacity per unit mass, low energy consumption during regeneration, and minimal corrosion of equipment	Expensive and prone to significant evaporation loss

2.2. Mechanism

The primary components of the MDEA-PZ-H₂O composite amine solution are N-Methyldiethanolamine (MDEA), piperazine (PZ), and water (H₂O), blended in specific proportions to serve as a carbon dioxide absorbent. The MDEA-PZ-H₂O composite amine solution fully leverages MDEA's high CO₂ absorption capacity and low regeneration energy consumption. Simultaneously, the addition of PZ enhances the absorption reaction rate, ultimately forming a composite amine solution characterized by rapid reaction speed, high absorption capacity, and low regeneration energy consumption. Regarding the reaction mechanism between the MDEA-PZ-H₂O composite system and CO₂, the prevailing view among domestic and international scholars is explained by the “shuttle mechanism” [12]. The molecular dynamics reaction can be represented by Equations (1)–(3),



Equation (1) is the main reaction for the absorption of CO₂ by an aqueous MDEA solution. There is no active N-H group in the MDEA molecule, which bonds directly with CO₂. It relies on the hydration of CO₂ to form MDEAH⁺ ions and HCO₃[−] ions. It describes the rapid salt formation reaction after adding PZ alkanolamine to the MDEA solution in Equation (2). PZ acts as an activator, rapidly capturing CO₂ and then transferring it to MDEA to form PZCOO[−] and MDEAH⁺. Equation (3) describes the PZ regeneration cycle reaction. PZCOO[−] hydrolysis while CO₂ is transferred in the form of HCO₃[−], simultaneously generating MDEAH⁺, and PZ is regenerated.

2.3. Typical Process

The typical process flow for chemical absorption-based carbon capture from flue gas in coal-fired power plants using an MDEA-PZ-H₂O alcohol amine solution as the absorbent is shown in Figure 1. High-temperature, low-pressure flue gas containing impurities enters the carbon capture process system from the wet desulfurization unit of the coal-fired power plant. After being pressurized by a blower, the flue gas undergoes pretreatment in the pretreatment tower. The primary purpose of pretreatment is to remove impurities from the flue gas to prevent interference with the subsequent reaction between the alcohol amine solution and CO₂. Simultaneously, pretreatment reduces the flue gas temperature through low-temperature water washing or low-temperature alkali washing, which helps improve carbon dioxide capture efficiency. The pretreated flue gas enters

the absorption tower through the bottom inlet. MDEA-PZ-H₂O amine solution enters the tower from the top and flows downward through the tower plates, reacting with the flue gas flowing upward through the plates to absorb and capture the majority of CO₂ components. The purified flue gas exits from the top of the absorption tower, while the CO₂-rich solution exits from the bottom. The rich liquid exchanges heat with the regenerated high-temperature lean liquid in the lean-rich heat exchanger. After heating, the rich liquid enters the regeneration tower. Within the regeneration tower, CO₂ is desorbed from the rich liquid through flash evaporation and high-temperature steam stripping, transforming it into high-temperature lean liquid. The high-temperature lean liquid sequentially passes through the lean-rich heat exchanger to recover heat, is boosted by the lean liquid pump, cooled in the lean liquid cooler, and then returns to the absorption tower, completing one cycle. The high-concentration CO₂ tail gas separated in the regeneration tower is typically routed downstream through compression, drying, cooling, and other process units before being delivered to downstream users.

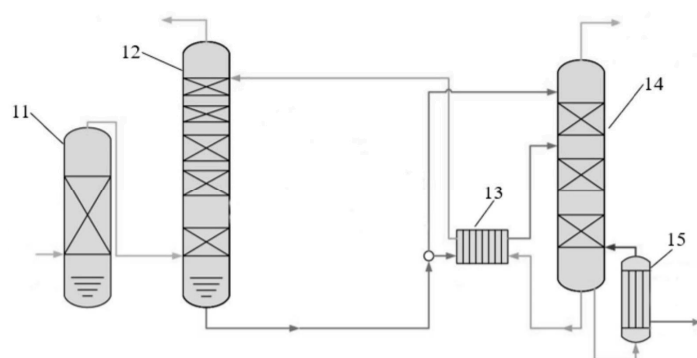


Figure 1. Typical process for low-concentration CO₂ capture from flue gas. 11-Pretreatment tower; 12-Absorption tower; 13-Concentrate-product heat exchanger; 14-Regeneration tower; 15-Reboiler.

3. Simulation

3.1. Input

Flue gas from the outlet of a desulfurization unit at the coal-fired power plant was selected as the feed gas input. The flue gas composition originating from the actual coal-fired power plant by volume is shown in Table 2. The composite amine solution of MDEA-PZ-H₂O was selected as the absorbent input. The total amine mass fraction of the composite amine solution is 42%, with MDEA accounting for 32%, PZ for 10%, and water for 58%. The initial process parameters for the composite amine solution are shown in Table 3.

Table 2. Components of flue gas.

Component	Concentration (vol%)
N ₂	74.08
CO ₂	11.74
O ₂	6.53
H ₂ O	7.65

Table 3. Components of the composite amine solution.

Component	Concentration (wt%)
MDEA	32
PZ	10
H ₂ O	58

Table 4. Initial inlet parameters of the process model.

Initial Inlet Parameters	Value
Inlet temperature of flue gas to the blower (°C)	50
Inlet pressure of flue gas to the blower (kPa)	15
outlet pressure of flue gas from blower (kPa)	80
Flue gas flow ($10^4 \text{ m}^3 \cdot \text{d}^{-1}$)	276
Theoretical tray of the absorption tower	25
Inlet pressure of flue gas to the absorption tower (kPa)	78
Temperature of flue gas to the absorber (°C)	50
Temperature of the lean stream to the absorber (°C)	45
Temperature of the feed solution entering the regeneration tower (°C)	88
Pressure at the top of the regeneration tower (kPa)	30
Theoretical Trays for Regeneration Tower	20
Regeneration tower top reflux	100%
Regeneration Temperature (°C)	110

3.5. Verification

As shown in Table 5, the simulation results obtained using the HYSYS model based on the initial input parameters meet the specified requirements when compared with the required purification standards and pilot test results. This indicates that the model can effectively simulate the flue gas carbon capture process.

Table 5. Comparison of key data and simulation data.

Parameter	Key Data	Simulation Data
CO ₂ capture rate (%)	92	90.03
CO ₂ Purity (mass fraction, %)	95	95.01
Temperature of flue gas to the absorber (°C)	46	50
Regeneration Temperature (°C)	110	110
Energy consumption per unit of CO ₂ (GJ/t – 1)	3.8	3.89

4. Results and Discussion

4.1. Analysis and Optimization of a Typical Process

4.1.1. Analysis and Optimization of Amine Solution Formulations

For the MDEA-PZ-H₂O composite amine absorbent, the mass percentage ratio of MDEA to PZ is one of the most critical process parameters affecting carbon capture efficiency. Therefore, the primary objective of the analysis and optimization in this section is to determine the optimal mass percentage ratio of MDEA to PZ in the amine solution. Based on the aforementioned process model, the mass fraction of PZ was fixed at 10%, and the mass fraction of water in the amine solution changes with the mass fraction of MDEA, keeping the solution components at 100%. Using a single-factor sensitivity analysis method, while maintaining a carbon capture rate of no less than 90%, the changes in amine solution circulation volume and CO₂ loading in the rich stream as a function of the MDEA mass fraction were examined by continuously varying the MDEA mass fraction, as shown in Figure 3. When the MDEA mass fraction increased from 25% to 31%, the amine solution circulation volume required to achieve a carbon capture rate of over 90% gradually decreased, while the CO₂ loading in the rich solution gradually increased; when the MDEA mass fraction reached 30%, the amine solution circulation volume was at its lowest, and the CO₂ loading in the rich solution was at its highest, proving that at this mass fraction, the amine solution exhibits the best CO₂ capture performance; Further increasing the MDEA mass fraction causes the amine solution circulation rate to rise gradually, while the CO₂ loading in the rich solution decreases. This indicates that an excessively high MDEA mass fraction leads to increased amine solution viscosity, which in turn increases mass

transfer resistance between the gas and liquid phases and reduces the amine solution's CO₂ absorption efficiency. Therefore, the optimal MDEA mass fraction is 30%.

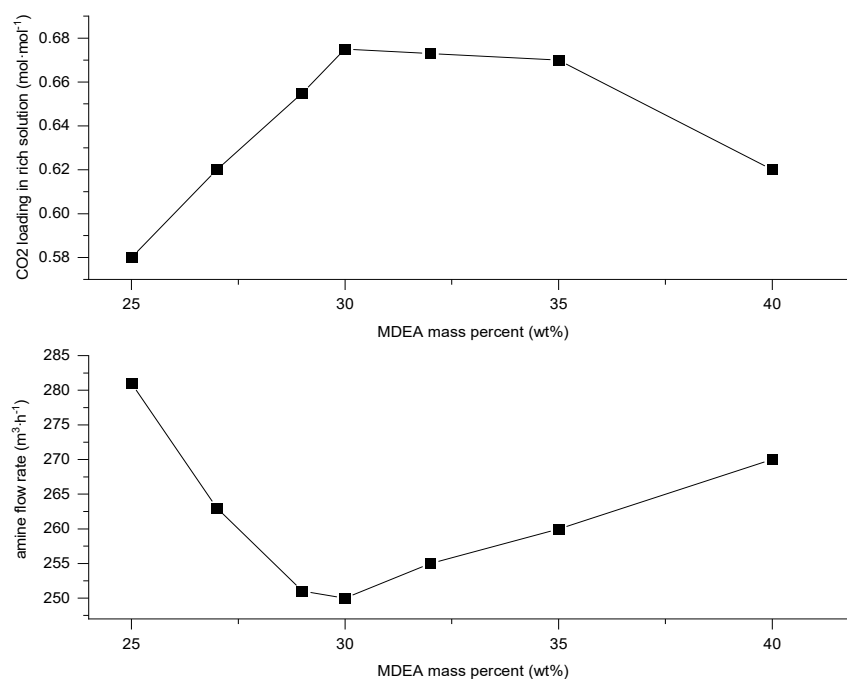


Figure 3. Effect of MDEA on CO₂ loading in rich solution and amine flow rate.

In the process model, the mass fraction of MDEA was fixed at 30.03%. While ensuring that the CO₂ capture rate remained no less than 90%, the mass fraction of PZ in the amine solution was continuously varied to examine the trends in amine circulation rate and CO₂ loading in the rich stream, as shown in Figure 4.

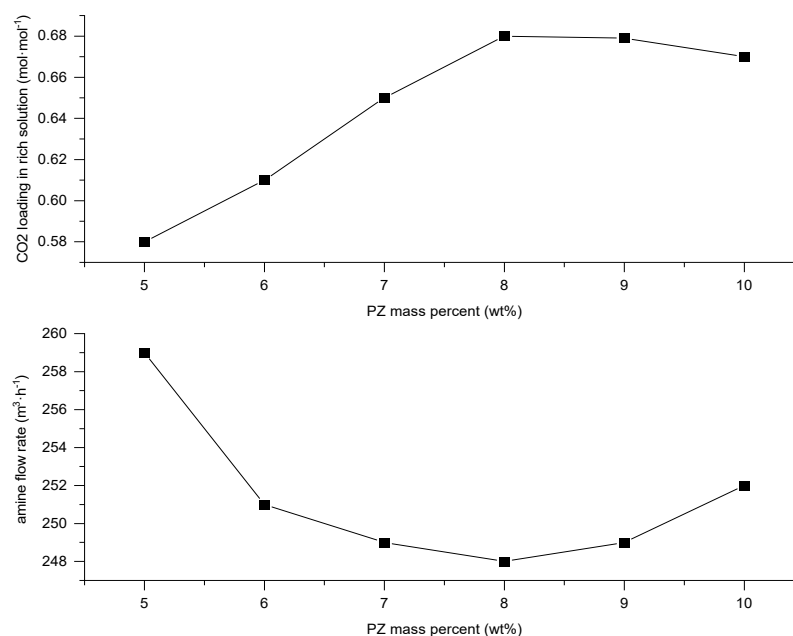


Figure 4. Effect of PZ on CO₂ loading in rich solution and amine flow rate.

As the PZ mass fraction gradually increased from 4% to 8%, the mass fraction of water in the amine solution changed with the mass fraction of MDEA, keeping the solution components at 100%. The amine circulation rate curve showed a significant decrease, while

the CO₂ loading in the rich liquid increased substantially. This indicates that within this mass fraction range, the activator PZ significantly enhances the performance of the MDEA solution. However, when the PZ mass fraction reached 8%, the CO₂ loading in the rich liquid reached its upper limit; further increasing the PZ mass fraction, the amine solution circulation rate actually increases, and the CO₂ load in the rich solution gradually decreases. This is because there is an upper limit to the MDEA mass fraction in the amine solution, and consequently, there is also an upper limit to the PZ mass fraction. Therefore, the PZ mass fraction of 8% is preferred. The mass percentages of MDEA and PZ in the polyamine solution were set at 30% and 8%, respectively.

4.1.2. Analysis and Optimization of the Gas-to-Liquid Ratio

The gas-to-liquid ratio is the ratio of the volumetric flow rate of flue gas entering the carbon capture unit to the volumetric flow rate of lean amine liquid. The gas-to-liquid ratio is primarily used to characterize the variation in the circulation volume of the amine solution required to achieve a certain capture efficiency at a given flue gas flow rate. The gas-to-liquid ratio has a significant impact on the CO₂ capture efficiency of carbon capture systems. When the flue gas flow rate is fixed, the gas-to-liquid ratio primarily determines the circulation volume of the amine solution. Therefore, it is a key factor influencing the energy consumption of the carbon capture system during regeneration. Consequently, a single-factor sensitivity analysis was employed to investigate the effects of variations in the gas-to-liquid ratio on CO₂ capture efficiency and energy consumption during regeneration.

As shown in Figure 5, for the flue gas components listed in Table 2 and the flue gas flow rates in Table 4, a gradual increase in the gas-to-liquid ratio results in a gradual decrease in the alcohol amine solution circulation rate, a corresponding gradual increase in the carbon capture rate, and a significant reduction in the energy consumption for regeneration of the carbon capture system. Therefore, by comprehensively considering the carbon capture rate going to 90% and the least regeneration energy consumption, the optimal gas-to-liquid ratio is determined to be 369. Compared to the typical process adopted in the literature [24], which achieves a 90% CO₂ capture rate with a gas–liquid ratio of 236, the results of this study significantly increase the gas–liquid ratio, thereby reducing the amine solution circulation rate and significantly lowering the regeneration energy consumption.

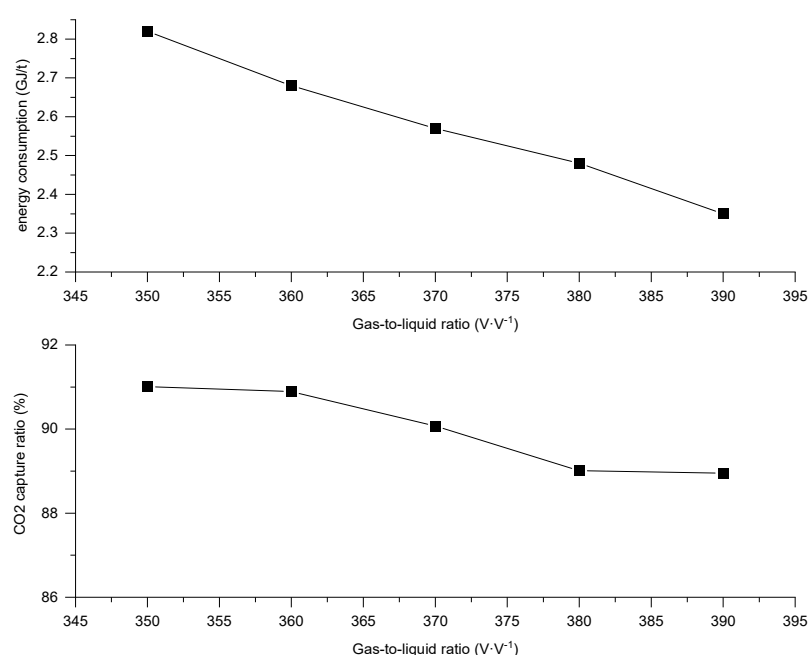


Figure 5. Effect of gas-to-liquid ratio on CO₂ capture ratio and energy consumption.

4.1.3. Analysis and Optimization of Reaction Temperature

The absorption temperature is the temperature at which the reaction between the mixed amine solution in the absorption tower and the CO₂ in the flue gas occurs. It is determined by both the temperature of the lean solution entering the tower and the temperature of the flue gas entering the tower. The absorption temperature affects the carbon capture rate and the energy consumption for regeneration in the carbon capture system. In this section, a single-factor sensitivity analysis is employed to first examine the effect of the flue gas inlet temperature on the amine solution circulation rate and the energy consumption for regeneration. With the lean solution inlet temperature fixed at 45 °C, the flue gas inlet temperature was continuously adjusted to ensure that the carbon capture efficiency remained no less than 90%. The relationship between the amine solution circulation rate and regeneration energy consumption as a function of flue gas inlet temperature was investigated, and the results are shown in Figure 6. As shown in Figure 6, as the flue gas inlet temperature to the tower decreases, the amine circulation rate required to maintain a carbon capture rate of at least 90% gradually decreases, and the regeneration energy consumption also decreases accordingly. This indicates that a lower flue gas temperature is conducive to the absorption reaction; however, the flue gas inlet temperature range of 40–55 °C must also be considered. Therefore, the flue gas inlet temperature to the absorption tower is selected as 40 °C.

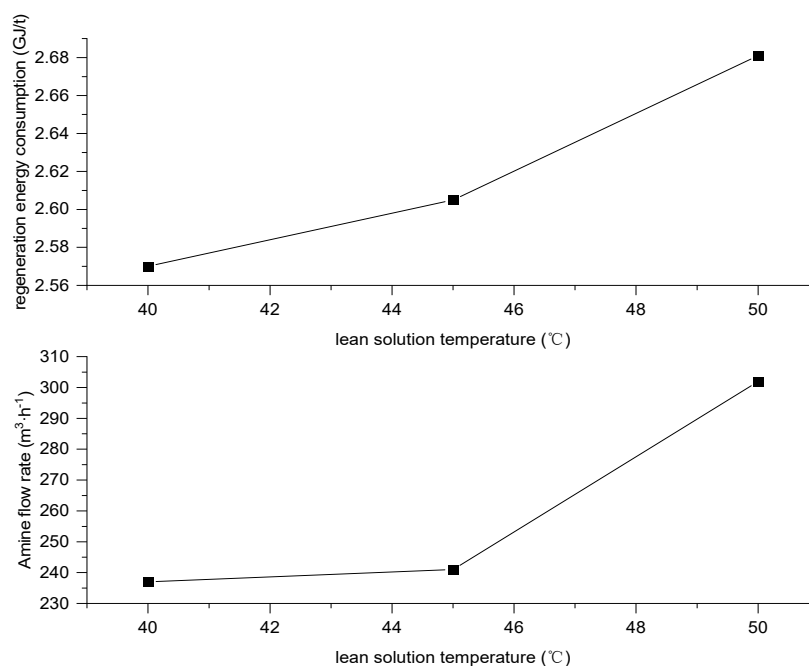


Figure 6. Effect of lean solution temperature on amine flowrate and energy consumption.

Based on the optimization results, the flue gas inlet temperature to the tower was set at 40 °C. A single-factor sensitivity analysis was conducted to investigate the effects of the lean liquid inlet temperature on the amine circulation rate and regeneration energy consumption, as shown in Figure 7. While ensuring a carbon capture rate of no less than 90%, a decrease in the lean liquid absorption temperature leads to a corresponding reduction in the amine circulation rate, accompanied by a decrease in regeneration energy consumption. This further demonstrates that lowering the temperature facilitates the absorption reaction. The absorption reaction between MDEA-PZ-H₂O and CO₂ is an exothermic reaction, and a low-temperature environment promotes the reaction. Therefore, reducing both the lean liquid inlet temperature and the flue gas inlet temperature aids the chemical reaction.

Furthermore, an excessive temperature difference between the lean and rich liquids is not conducive to energy conservation. Thus, the lean liquid inlet temperature to the absorption tower is set at 40 °C.

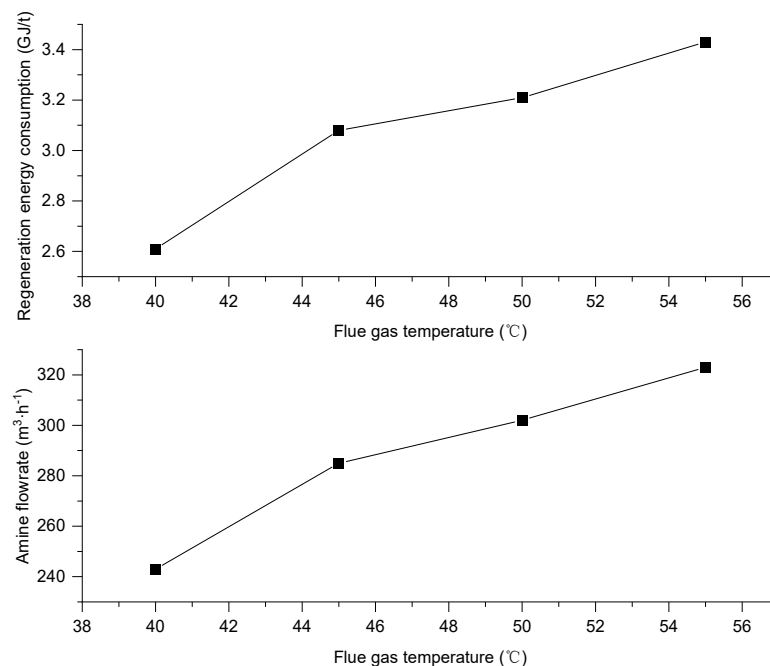


Figure 7. Effect of flue gas temperature on amine flowrate and energy consumption.

Based on the above analysis and optimization results, the optimized key parameters for the typical carbon capture process using the MDEA-PZ blended system are selected as follows: Blended amine solution ratio of 30% MDEA + 8% PZ + 62% H₂O, gas-to-liquid ratio of 369, lean liquid inlet temperature of 40 °C, flue gas inlet temperature of 40 °C, and regeneration temperature of 110 °C. When the carbon capture rate of the optimized process system reaches 90.07%, the system energy consumption is 3.3 GJ/t. Compared with the existing literature [24] research results, the reaction temperature of this study is optimized to 40 °C. Meanwhile, considering the higher gas–liquid ratio in this study, the energy consumption index of this study is significantly lower than the 3.89 GJ/t reported in the literature.

4.2. Optimization of Integrated Energy-Saving Processes

4.2.1. Optimization of Temperature Distribution in the Absorber

The absorption reaction between the MDEA-PZ-H₂O amine solution and CO₂ primarily takes place in the absorption tower. The reaction kinetics within the absorption tower are governed primarily by chemical equilibrium and molecular kinetic equilibrium. First, from the perspective of chemical equilibrium, since the absorption reaction is exothermic, lowering the reaction temperature within the absorption tower promotes the reaction. From a molecular kinetic perspective, higher temperatures facilitate molecular motion; thus, an increase in temperature enhances molecular movement. This section focuses on optimizing the temperature distribution within the absorption tower to promote the reaction between MDEA-PZ-H₂O and CO₂. Typically, the optimal temperature range for the reaction between the MDEA-PZ-H₂O amine mixture and CO₂ is 40–65 °C [13].

The temperature distribution across the absorption tower trays is shown in Figure 8. The peak temperature within the tower occurs between the 4th and 10th trays, with the highest temperature reaching 74.5 °C, which is detrimental to the absorption reaction. Therefore, a forced circulation cooling process is implemented between the 4th and 10th trays. Hot

amine solution is withdrawn from the absorption tower, cooled, and then pumped back into the tower via a circulation pump. This reduces the maximum temperature to a reasonable range, thereby optimizing the temperature distribution within the absorption tower. The integrated inter-tray cooling process model is shown in Figure 9.

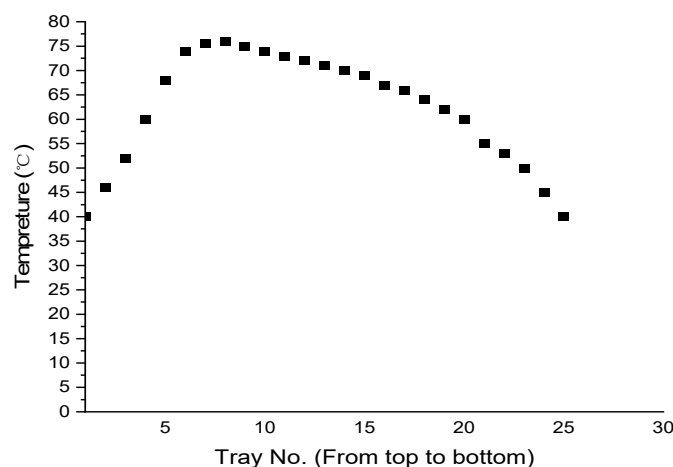


Figure 8. Temperature distribution of each tray in the absorption tower.

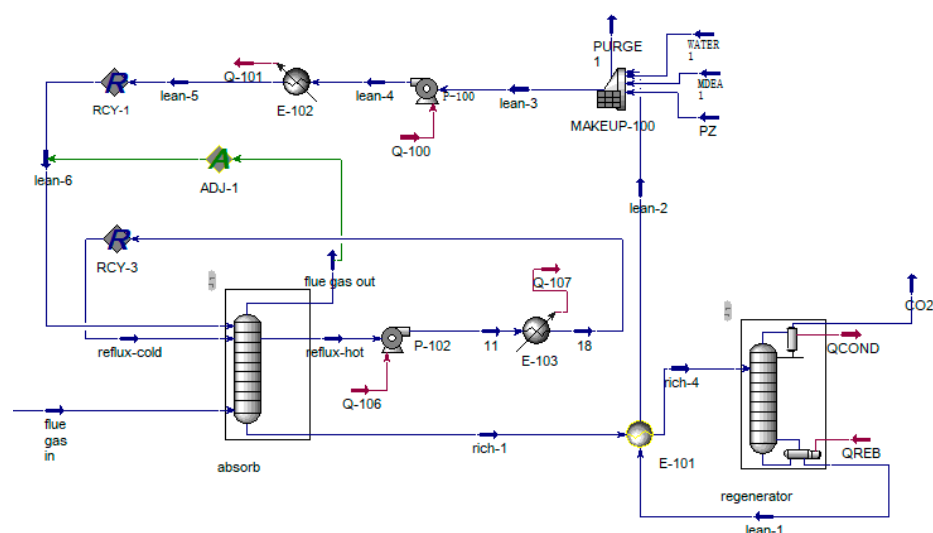


Figure 9. Optimization of the inter-stage cooling process to improve temperature distribution in the absorption tower.

After optimizing the temperature within the absorption tower, a comprehensive analysis was conducted that took into account the distribution of CO₂ and the absorbent within the tower, as well as the energy consumption associated with regeneration. The integration of the inter-stage cooling energy-saving process improves the temperature distribution within the absorption tower, which aids in the absorption of CO₂ by the amine solution. However, it also requires the addition of energy-consuming equipment such as circulation pumps and coolers. The energy consumption of the carbon capture system after integrating the inter-stage cooling process is 3.05 GJ/t, representing a slight decrease compared to that of a typical process system. This demonstrates that the process can achieve energy-saving effects; however, the energy-saving benefits are limited when this process is implemented in isolation.

4.2.2. Optimization of Renewable Energy Consumption

The energy consumption of the regeneration stage directly affects the economic viability and feasibility of the entire carbon capture system. Reducing the energy consumption of the regeneration tower, optimizing process parameters, and improving absorption and desorption processes are key to enhancing the efficiency of carbon capture technology and reducing costs. To reduce energy consumption in the regeneration section, the Mechanical Vapor Recompression (MVR) process is integrated into the regeneration tower process flow to recover thermal energy from the lean liquid and reduce regeneration energy consumption. Figure 10 shows the energy-saving carbon capture process model that integrates the absorption tower temperature distribution optimization process with the MVR regeneration energy-saving process.

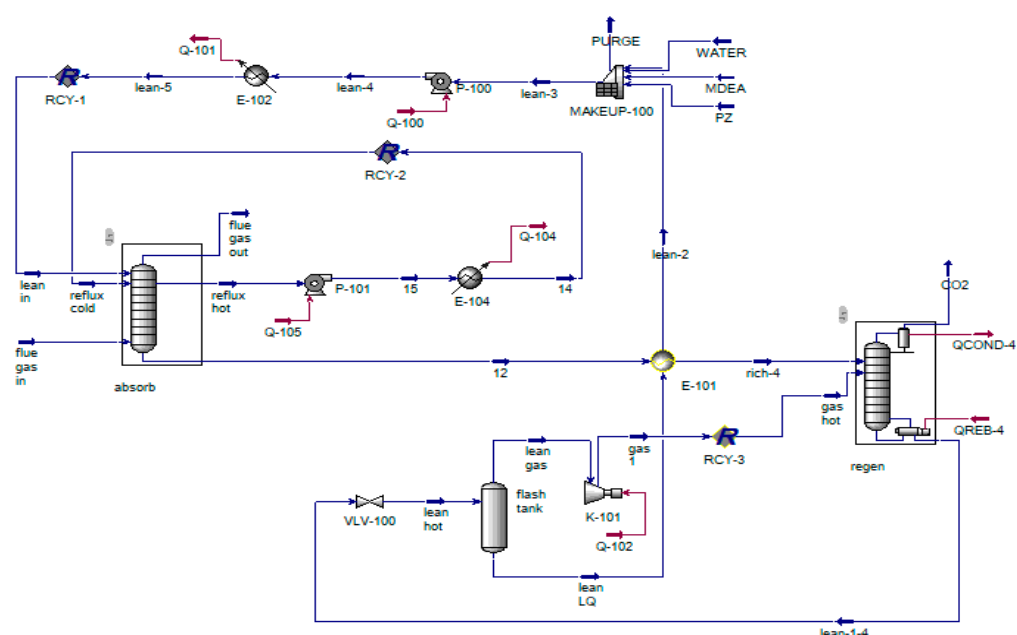


Figure 10. Energy-saving process integrating inter-stage cooling for the absorption tower with MVR regeneration.

The MVR process works by first directing the lean amine solution from the bottom of the stripping tower into a flash tank for low-pressure flash evaporation. The resulting vapor is then pressurized and heated by a compressor before being returned to the stripping tower, thereby reducing the thermal load on the reboiler. Thus, the MVR process achieves the goal of reducing regeneration energy consumption by recovering the thermal energy from the secondary vapor generated during the flash evaporation of the lean solution.

In summary, the comprehensive energy consumption of the carbon capture system, which integrates the optimized temperature distribution process for the absorption tower stage with the MVR regeneration energy-saving process, is 2.8 GJ/t.

4.3. Results

According to Table 6, the results of the optimization of the typical carbon capture process indicate that the optimized composition of the MDEA-PZ-H₂O amine solution is 30% MDEA + 8% PZ + 62% H₂O. The feed temperature is 40 °C. The flue gas inlet temperature is 40 °C. Moreover, the regeneration temperature is 110 °C. When the carbon capture rate of the optimized process system reaches 90.07%, the gas-to-liquid ratio is 369, and the system energy consumption is 3.3 GJ/t.

Table 6. Optimization of key parameters for the typical carbon capture process.

Item	MDEA Mass Fraction (wt%)	PZ Mass Fraction (wt%)	Water Mass Fraction (wt%)	Temperature of Lean Stream (°C)	Temperature of Flue Gas (°C)
Initial value	32%	10%	58%	45	50
Optimized value	30%	8%	62%	40	40

As shown in Table 7, based on the optimization of the standard process, this study examined the energy-saving effects of optimizing the temperature distribution in the integrated absorption tower and of the MVR regeneration energy-saving process, respectively. When the inter-stage cooling process for absorption towers was implemented alone to optimize the temperature distribution within the absorption towers, the energy consumption per ton of the carbon capture system was 3.05 GJ/t. This represents a 7.58% reduction compared to the typical process. Therefore, the energy-saving effect of this process when used alone is limited. When the inter-stage cooling process for absorption towers was integrated with the MVR regeneration energy-saving process, the energy consumption per ton of the carbon capture system was 2.8 GJ/t. This represents a 15.15% reduction compared to the initial process. Energy consumption includes reboiler heat duty, electricity consumption of pumps, fans, and compressors.

Table 7. Optimization of key parameters for a typical carbon capture process.

Item	Typical Process of Carbon Capture	Optimization of Temperature Distribution in the Absorber	MVR Regeneration Energy Consumption
Energy Consumption (GJ/t)	3.3	3.05	2.8

5. Conclusions

Based on the reaction mechanism between MDEA-PZ-H₂O composite amine solution and CO₂, a process model for CO₂ capture using the composite amine solution was established using the flue gas composition of a specific coal-fired power plant as design input. Single-factor sensitivity analysis was employed to optimize the process parameters of the conventional process and to analyze the impact of key influencing factors on the CO₂ capture process. Based on the optimization results, Aspen HYSYS simulation was used to evaluate the energy-saving effects of the integrated inter-stage cooling process and the MVR energy-saving regeneration process, respectively. The study leads to the following conclusions:

- For the CO₂ capture system using an MDEA-PZ-H₂O composite amine solution, the amine solution ratio, flue gas inlet temperature, lean solution inlet temperature, and gas-to-liquid ratio are the key factors affecting the carbon capture process and regeneration energy consumption.
- For the CO₂ capture system using MDEA-PZ-H₂O composite amine solution, the inter-stage cooling energy-saving process can improve the temperature distribution within the absorption tower, thereby promoting CO₂ absorption by the amine solution; however, the energy-saving effect is limited when inter-stage cooling is used alone.
- The integration of multiple energy-saving processes, specifically the absorption tower inter-stage cooling process combined with the MVR regeneration energy-saving process, can significantly reduce system energy consumption, achieving energy conservation and reduced consumption. The optimized integrated energy-saving process reduces energy consumption by 15.15% compared to the initial process.

- (d) **Methodological Limitation.** This article focuses on studying key process parameters using a single-factor sensitivity analysis, and the next step will be to carry out a multi-objective optimization algorithm, taking into account the interactions and synergies between various process parameters.

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