A New Ternary Amines Absorbent Apply to Post-combustion Chemical Decarbonization in Natural Gas Power Plant

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Abstract. In this paper, a ternary amine absorbent(2-(2-Aminoethylamino) ethanol, Monoethanolamine, Piperazine, AEEA-MEA-PZ) named DT06 is selected by basic properties and physicochemical properties tests. The main performance is further verified by the 2Nm^3/h testing device and 3000Nm^3/h industrial demonstration system. Compare to 30%MEA, the laboratory research results of DT06 show that, the absorption load, regeneration rate and circulation capacity reached 1.39 times, 2.31 times and 1.43 times of MEA, respectively. The viscosity, surface tension, density and other physical-chemical properties are similar to MEA, and the stability is increased by 36.84%. In the case of approximate capture efficiency, the DT06 regeneration energy consumption is only 84.16% of MEA. Industrial demonstration system test shows that, compared with MEA, DT06 reduces the regeneration heat consumption by 34.19%, the electric power consumption for CO_2 capture by 13.24%, the degradation rate by 37.8%, and the comprehensive operating cost by 27.37%, which has certain degree of commercial application potential.

Key words. Natural gas power plant, CO_2 capture, Capture efficiency, Regenerati heat consumption, Ternary amine absorbent

1 Introduction

For the power generation industry using fossil fuel, chemical absorption method is the closest method for commercialized in the technologies of post-combustion decarbonization [1,2]. The main challenge for CO_2 capture from flue gas is the enormous energy consumption for solvent regeneration, which accounts for 70%-80% of the overall process [3]. The energy consumption of solvent regeneration is composed of three parts: sensible heat of rich absorbent, latent heat of absorbent vaporization and desorption reaction heat [4]. Usually, the proportion of desorption reaction heat in the total energy consumption can reach more than 40% [5].

At present, there are few researches on carbon capture engineering of gas turbines power plant, especially the lack of high-performance absorbent for flue gas characteristics [6]. The objective of this study is to developed a new solvent which apply to post-combustion chemical decarbonization in natural gas power plant.

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2 Basic performance test

In this paper, organic amines such as MEA, EMEA, MDEA, AMP, AEEA,DEEA, DETA, and PZ are selected. According to the volume content of Natural gas power plant flue gas. Referring to other scholars' research results on the properties of organic amines [7,8], four binary and terpolymer combination absorbents were formed, named DT05, DT06, DT07 and DT08 respectively, and their absorption performance, desorption performance, cycle capacity and physical and chemical property were tested. The tests method and data processing method refer to other studies [9,10].

(1) Absorption properties

With a mass concentration of 30% 100g of DT05, DT06, DT07, DT08 absorbent absorption test, examined the change rule of the absorbent load with the test time, as shown in Figure 1. Absorption reaction rate with the change rule of the load is shown in Figure 2.

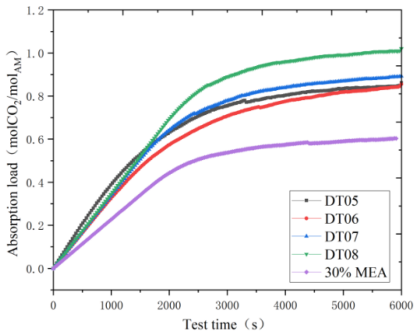

Figure 1. The change rule of DT05~DT08 absorption load with test time

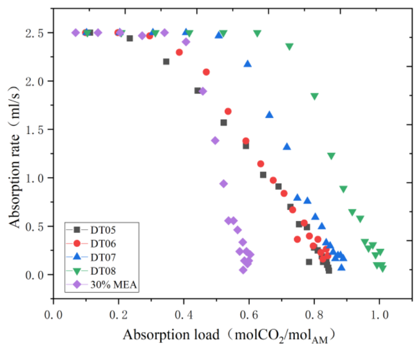

Figure 2. The change rule of absorption rate with absorption load of DT05~DT08

From Fig. 1, the loading of MEA was 0.61 $molCO_2/mol_{AM}$, DT05, DT06, DT07, DT08 were 0.86 $molCO_2/mol_{AM}$, 0.85 $molCO_2/mol_{AM}$, 0.89 $molCO_2/mol_{AM}$, 1.02 $molCO_2/\ mol_{AM}$, which were 1.41, 1.39, 1.46, and 1.67 times that of MEA, respectively.The absorption rate changes were further compared by Fig. 2: DT05 can only have high capture efficiency at low lean loads, DT06's capture performance is close to that of the MEA, and DT07 and DT08 are more applicable to lean loads.

(2) Desorption performance

The change rule of the desorption rate with the load as shown in Figure 3.

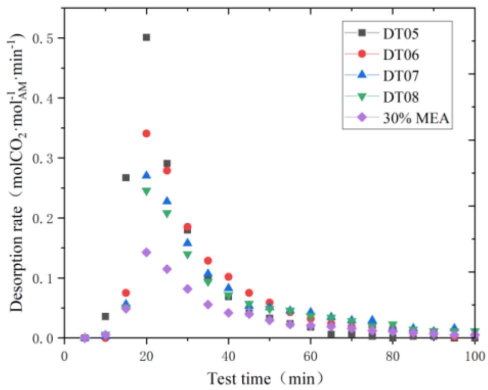

Figure 3. The change rule of DT05~DT08 desorption rate with test time

From Fig. 5, the maximum desorption rates of DT05, DT06, DT07, and DT08 systems can reach 3.3, 2.3, 1.86, and 1.66 times of MEA, respectively.

(3) Cycle capacity

The average value of CO_2 desorption under different cycles was calculated to examine the change of its cycle capacity, and the results are shown in Figure 4.

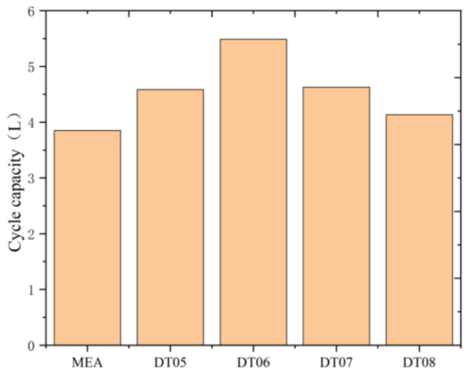

Figure 4. Comparison of the average desorption volume of multiple cycles of DT05~DT08

As shown in Fig. 4, the desorption capacity of DT06 was 5.49L, which was 1.43 times of that of MEA. Under multiple cycles, the CO_2 cycling capacity of DT06 was higher than that of DT05,DT07,DT08, and the basic performance had the conditions to establish continuous cycle of absorption-desorption.

(4) Physical and chemical property test

The indexes and corresponding methods for testing the physicochemical properties ofDT05, DT06, DT07, DT08 are shown in Table 1.

Table 1. DT05~ DT08 physical and chemical properties test results

Test metrics	unit (of measure)	Test results				
		30% MEA	DT05	DT06	DT07	DT08
stickiness	Viscometer /$mm^2 \cdot s^{-1}$	1.42	2.08	1.98	3.62	2.52
surface tension	Hanging piece method/$mN \cdot m^{-1}$	63.31	54.56	54.03	68.79	55.93
foaminess	Foam tube method/mm/mm	195	200	175	185	190
volatility	Saturated vapor pressure method/kPa.A	4.7	4.7	5.5	5.8	4.9
pH		12.98	12.36	10.26	11.28	10.89
degradability	Cyclic capacity attenuation /L	-1.71	-1.02	-1.08	-1.31	-1.15

The test results show that the viscosity, surface tension, density, foaming, volatility and other basic physical parameters of DT06 is similar to those of 30% MEA, and 30% MEA has been fully verified in several demonstration projects. Therefore, it can be considered that the solvent formulations designed in this paper can satisfy the hydrodynamic conditions of absorption-desorption mass transfer in packed towers and have the feasibility of further evaluating the solvent performance through the joint operation of multiple towers.

Based on the results of absorption, desorption, cycle capacity, physical and chemical properties tests, and considering that the capture object is low CO_2 partial pressure flue gas of natural gas power plant, the comprehensive performance of DT06 is more excellent, and thus it is the preferred formulation for subsequent small pilot continuous operation verification.

3 2Nm^3/h small pilot plant test

3.1 Test methods for small pilot devices

In order to verify the capture efficiency and operational energy consumption of DT06 on flue gas from natural gas power plants under the operating conditions of the absorption-desorption cycle, this paper firstly uses a small test simulation device to evaluate the operational performance of DT06 for 168 hours, and compares it with the results of MEA operation under the same test conditions.

The process flow of the small pilot plant is shown in Figure 5.

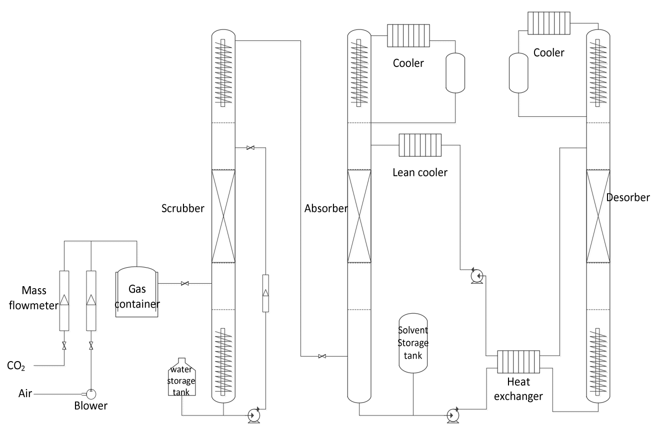

Figure 5. Process flow of the pilot plant

As shown in Figure 5, the pilot plant is mainly composed of gas distribution system, CO_2 separation system, cooling water circulation system, data acquisition and control system, thermal oil heating system. Among them, the CO_2 separation system includes: water washing tower, absorption tower, desorption tower, solution pump, poor-rich liquid plate heat exchanger, poor-liquid cooling plate heat exchanger, gas-liquid separator, and absorption liquid storage tank. The system is designed with flue gas flow rate of 2.0Nm^3/h, solvent flow rate of 0.05m^3/h, absorption temperature of 25℃-50℃, regeneration tower pressure of 0-20kPa, regeneration temperature of 100-110℃ .

3.2 Test results of small pilot plant

During the operation of the small pilot plant, the absorption and regeneration towers were filled with 350 m^2/m^3 and 250 m^2/m^3 metal corrugated plate gauge packing, respectively, and the system inlet flow rate was 1.8 Nm^3/h, the CO_2 volumetric content was 5%, and the solvent cycle was 0.02 m^3/h, with an absorption temperature of 40°C and a regeneration temperature of 101°C. The results of the 168-h operation of MEA and DT06 are shown in Figure 6.

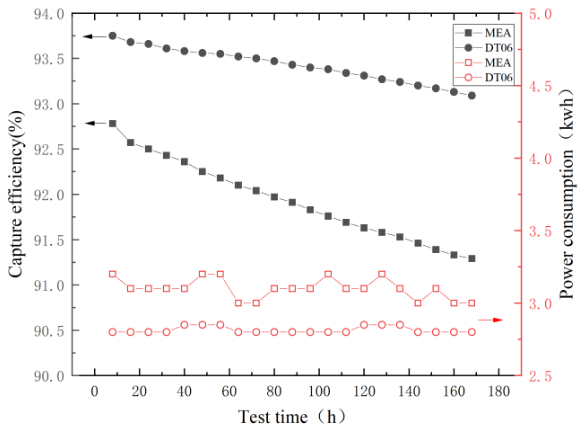

Figure 6. Results of MEA and DT06 168h small trial run

The average capture efficiencies of DT06 and MEA were 93.6% and 91.8%, respectively. The energy consumption of DT06 and MEA heat transfer oil regeneration system is 2.71 kWh and 3.22kWh, respectively, and the energy-saving effect of DT06 is more than 15%. The results of the 168 hours of operation show that: DT06 can ensure the capture efficiency of 90% of the flue gas of the low CO_2 partial pressure, and at the same time, it has a lower energy consumption of regeneration and a higher degree of stability.

4 3000 Nm^3/h industrial-scale demonstration plant test

4.1 Demonstration plant

On the basis of completing the laboratory evaluation of DT06 absorbent, it was applied in the 1800-ton CCS project of Datang International Beijing Gaoging Cogeneration Branch. The system was built in 2014 following the 9F-NGCC unit, and is the first industrial demonstration system of post-combustion chemical absorption and capture in natural gas power plant in China. The rated flue gas intake of the capture system is 3200 Nm^3/h, the designed output is 5 tons/day, and the end product is 2.5~2.8MPa, -15~-20℃ liquid CO_2 (purity>99.9%), and the flow of the capture process section is shown in Figure 7.

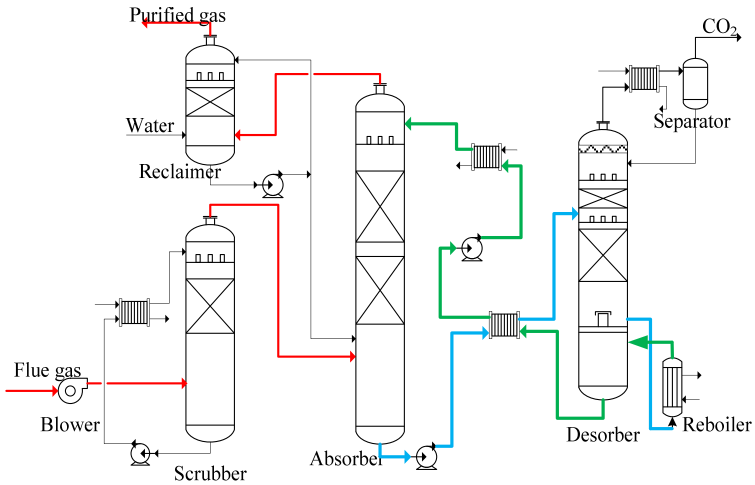

Figure 7. CO_2 Capture process for Gaojing Thermal Power

4.2 DT06 Operating Parameters and Results

According to the design information of the carbon capture device, and the steady state condition was gradually established by adjusting the main parameters such as flue gas flow rate, absorber inlet flue gas temperature, solvent circulation flow rate, regeneration tower operation pressure, steam flow rate and so on with the goal of maintaining 90% of the capture efficiency, and the range of adjustment of the system parameters is shown in Table 2.

Table 2. Main parameters and adjustment range of demonstration plant

parameters	realm
Flue gas flow	1500-3200Nm^3/h
Scrubber inlet flue gas CO_2concentration	4.2 to 4.4% (vol%)
Scrubber inlet flue gas temperature	~100.0°C
Scrubber inlet flue gas pressure	4.0-5.0 KPa(g)
Absorption tower inlet flue gas temperature	30-50°C
Regeneration tower operating pressure	3.0-50kPa
Reboiler Low Pressure Steam Flow	<370kg/h
Reboiler Low Pressure Steam Pressure	0.3-0.4MPa(g)
Reboiler low pressure steam temperature	145-150°C
Absorbent circulation flow	3.0-6.5m^3/h

The total operation time was 312 hours, and the data recorded by the on-site PLC system was used for analysis. In order to improve the recognition of the data curves, the trend of the average value of flue gas flow rate, capture efficiency, and heat consumption of the capture per 100 data (per 1000 seconds) with the operation time was examined, as shown in Figure 8.

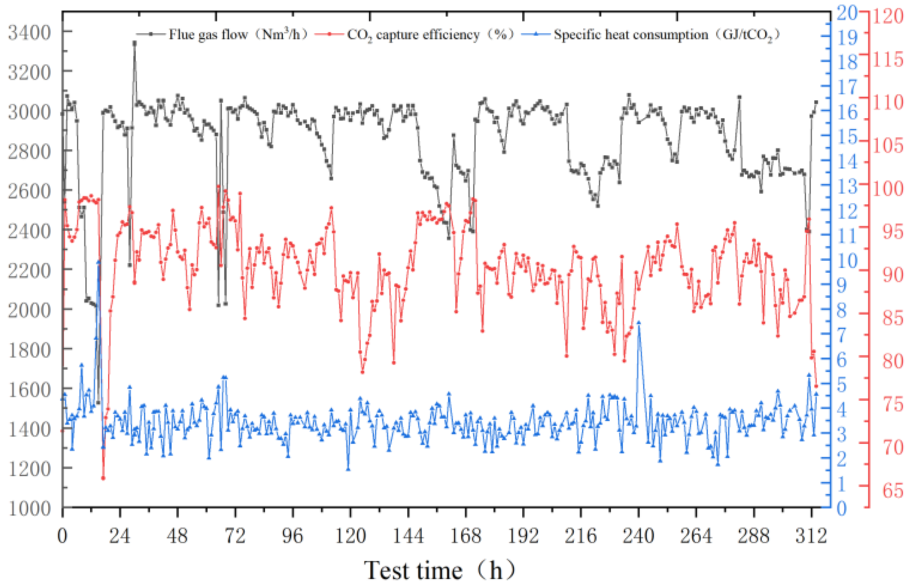

Figure 8. Results of the DT06 in the industrial demonstration plant

The data were further statistically organized, and the results are shown in Table 3.

Table 3. Operational performance of DT06 and MEA

Operational Pharmaceuticals	DT06	MEA
Flue gas flow rate (Nm^3/h)	2857	2893
Inlet tower CO_2 concentration (%)	4.493	4.55
Steam flow rate (kg/h)	369.06	578
Capture rate (%)	90.98	91.2
Steam consumption (t/t)	1.75	2.65
Energy consumption (GJ/tCO_2)	3.58	5.44
Power consumption (kWh/tCO_2)	84.76	97.75
Desalination water consumption (t/tCO_2)	0.341	0.514
Sorbent consumption (kg/tCO_2)	1.2	1.93
Cooling water usage (t/tCO_2)	210	247

The inlet flue gas flow rate of the system is 2857 Nm^3/h, which is somewhat different from the data of the initial commissioning period of the system in 2014 (3100 m^3/h), mainly because the solvent used in this operation is a new type of compound alcohol amine, and there is a certain difference in absorption and desorption with the original design agent MEA. However, the system capture efficiency and capture volume are basically at the same level with MEA, which verifies the reliability of the absorption performance of DT06. The regeneration steam consumption of DT06 is 1.749 t/tCO_2, and the converted regeneration heat consumption is 3.58 GJ/tCO_2, which is a decrease of 34.19% compared with 5.44 GJ/tCO_2. In addition, the unit capture power consumption is 84.76 kWh/tCO_2, which is better than MEA's 97.7 kWh/tCO2, and close to the average of 70-100 kWh/tCO_2 of the similar technology (coal-fired power plant CCS). The unit capture consumption of DT06 is 1.2kg/tCO_2, which is 37.8% lower than that of MEA, obtained from the change of amine content. The operating cost was measured based on the carbon capture system unit consumption, and the results are shown in Table 4. The operating cost of DT06 is 309.03 CNY/t, which is 27.37% lower compared with MEA.

Table 4. Operating cost comparison of MEA and DT06

Item	Price	DT06	MEA
Vapor	107.58 CNY/t	188.27	285.09
Electrical power	0.604 CNY/kWh	51.19	59.04
Demineralized water	23.68 CNY/t	8.07	12.17
Circulating cooling water	0.03 CNY/t	6.3	7.41
Solvent	46000 (DT06), CNY/t 32000(MEA), CNY/t	55.20	61.76
Total		309.03	425.47

According to the above operation test and technical and economic analysis, the performance of DT06 under industrial operation is significantly better than that of MEA, and it has the technical conditions for commercial application.

5 Conclusions

In this paper, a high-performance ternary absorbent(AEEA-MEA-PZ) named DT06 has been obtained from the research on the formulation design, basic performance test, physical and chemical property test, small pilot plant validation, and the operation and evaluation of the industrial demonstration system.

According to the 3000Nm^3/h industrial tests: the regeneration heat consumption of DT06 is 3.58 GJ/tCO_2, which is 34.19% lower compared with that of MEA, the power consumption of the unit of capture is 84.76kWh/tCO_2, which is a relative reduction of 13.24%, degradation reduces by 37.8%, and the comprehensive operation cost is decreased by 27.37%.

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