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Capture of CO_2 from coal-fired power plant with NaOH solution in a continuous pilot-scale bubble-column scrubber

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Abstract

A continuous pilot-scale bubble-column scrubber with NaOH as the absorbent was used to explore the capture of CO_2 gas from a coal-fired power plant. The experimental design was based on the results of previous study. The diameter of the column was 20 cm and the height of the column was 2.4 m. According to the S/N ratio, parameters, including absorption rate (R_A), absorption efficiency (E), overall mass-transfer coefficient (K_Ga) and ratio of the gas-liquid flow rate (R), were selected for Taguchi analysis to obtain optimum conditions. A total of eleven experiments were carried out to verify the optimum conditions here. The range of the gas-flow rate (Q_g) and liquid-flow rate (Q_{LT}) conducted in this work were 48-192 L/min and 1.6-10 L/min, respectively. The input gas concentrations were 9-12.2%. Using a steady-state material balance with a two-film model, R_A and K_Ga could be determined. The results showed that E, R_A and K_Ga were in the range of 30-98%, $1.03x10^{-4}$-$11.48x10^{-4}$ mol/s-L and 0.018-0.058 1/s, respectively. The obtained scrubbing factors (φ) were 0.00285-0.146 mol/mol-L, while R was in the range of 0.23-24.14. The dynamic behavior of the scrubber was also discussed in this study. The results could be used as a basis for commercial scale operation for the carbon capture at a power plant as well as microalgae cultivation.

Keywords: Taguchi Method, overall mass-transfer coefficient, two-film model, carbon capture

1. Introduction

Carbon dioxide capture is a topical subject for many countries, and considerable investments have been made on its research. Many strategies have been developed, such as CCS and CCU; among these, absorption technology is the most mature method that can meet the urgent needs [1]. Such technology uses solvents, including MEA, ammonia and alkaline, as absorbents [2-5]. The use of MEA, ammonia and other solvents has problems of solvent regeneration, CO_2 transport and storage, thus, increasing the operating costs. Using the absorption solution as the base material to support algae can sequester carbon while recycling resources, providing dual benefits. In view of this, this study used NaOH as an absorbent. As CO_2 is ionized after being absorbed by the NaOH solution, its pH value has a considerable influence on $H_2CO_3^*$, HCO_3^- and CO_3^{2-} [6, 7]. The solution, after absorbing CO_2, can be used as the nutrient for algae under the condition of pH=10, in order to reach the effect of carbon sequestration by algae. This research project of "CO_2 sequestration and reduction by microalgae" takes advantage of Taiwan's subtropical environment, thermal power plants and microalgae cultivation technology. The carbon reduction by microalgae cultivation produces microalgae plastids and releases oxygen by using water, CO_2 and sunlight through photosynthesis [8]. In theory, each kilogram of CO_2 can cultivate 0.57 kg blue-green algae and release 0.73 kg oxygen, indicating that the microalgae have a very high ability to utilize CO_2. On the other hand, carbon generated from 1 kg of CO_2 can produce about 25 to 44 kg algae and 32 to 44 kg O_2 without additional costs or risks for recycling, separation and compression. Since the cultivation of microalgae requires bicarbonate, using NaOH as the absorbent to absorb the CO_2 in the flue gas can achieve a carbon sequestration effect, as well as raise the algae and capture carbon. Hence, the purposes of this study are: (1) to find conditions of on-site operations by using the results of the Taguchi experimental design and (2) to

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conduct on-site operations and obtain the E, R_A, K_Ga, R and φ.

2. Experimental Section

2.1. Experimental Design

Relevant on-site operation conditions were designed according to the conditions of un-manipulated tests by following the optimal operational conditions of the Taguchi design. Our previous lab study found that Q_g=3-12 L/min and Q_{LT}=104-613 mL/min. As the column diameter and height of the on-site operation are 20 cm and 2.4 m, respectively, the tower sectional area of the on-site operation was 16 times that of the Taguchi experiment (d=5 cm); hence, the on-site operation Q_g and Q_{LT} were 48-192 L/min and 1.6-10 L/min, respectively under the condition of the same mass flux. As the on-site operating conditions were based on E, R_A, K_Ga, R and φ, as shown in Table 1, 6 groups of experiments were expected to be conducted. However, since the conditions of NO. 18 and NO. 19 were the same, only 5 groups of experiments were required to be conducted. To understand the reproducibility, at least 2 experiments had to be conducted for each group of experiments. For NO. 21, 3 experiments were conducted, and thus, overall 11 groups of experiments had to be conducted for the on-site operations. Experimental conditions was listed in Table 1.

2.2. Experimental Procedure

The on-site equipment was as shown in Fig. 1. First, we verified whether the flue gas was normally discharged by checking the blower, voltage, inlet concentration (y_1), temperature and water vapor. After ensuring normal operation, the flue gas was input at the column bottom and then the prepared NaOH absorbent was pumped into the column to the overflow height. The well-calibrated pH electrodes were put in the column to record the changes in pH values, and the thermometer was inserted to record changes in temperature. Meanwhile, the prepared NaOH solution was continuously pumped and the mixed solution was output in the way of overflow. The Q_g and the Q_{LT} of the operation were 20~300 L/min and 1~10 L/min respectively. In the operation, the CO_2 analyzer (Gas Data PCO2 meter) was used to measure the CO_2 concentration. When the outlet CO_2(y_2) was detected at a certain level, it meant that the steady state had been reached. In the steady state, taking the material balance of CO_2 can determine the R_A and K_Ga [2, 6]. The variations in pH, temperature of the liquid (T), y_2 and inlet gas pressure (P) were recorded every 5 min during operation.

3. Results and Discussion

3.1. Dynamic and Steady-State Operations

With NO.18 as an example, Figs. 2(a)-(d) includes the recorded data of CO_2 concentration (y_2), pH, T and P. Fig. 2 (a) illustrates the relationship between outlet concentration of CO_2 and time. As indicated in Fig. 2(a), initially, the y_2 dropped to a low value and then increased with time further until the time was 50 min. After 50 min, the y_2 remained nearly unchanged at about 4.2%. However, the y_2 in the two groups of experiments had no significant differences as the inlet concentrations were close. Fig. 2(b) illustrates the trends of pH values recorded under different conditions over time. The changes in values can be regarded as a reference to the operation in the steady state condition or not. Initially, the pH value from 13.2 decreased to around 12.5 and then showed only slight changes. Overall, after 50 min of operation, the changes in pH were insignificant and tended to be at a steady state. This is similar to changes in the y_2. The variations of T and P are similar to those in Figs. (a) and (b). The temperature inside the column was 35°C. The measurement readings of P were in the range of 2.5-2.7 psi, and the pressure was reduced to 1.14-1.23 psi/m by the division of the column height. The above data show that on-site operations in this research are reproducible.

3.2. Experimental Data of the Pilot Study

The data of groups of experiments are as shown in Table 2. The inlet CO_2 concentration was mostly in the range of 10%-12%. Meanwhile, the air was filled with water and fly ash. The water was filtered and removed by bag filters, and the operation took at least 70 min. The E was in the range of 30~98%. The R_A and the K_Ga could be obtained by the material balance at the steady state. The obtained R_A was in the range of 2.37x10^{-3}~ 11.1x10^{-3} mol/s · L; the obtained K_Ga was in the range of 0.018~0.058 l/s; the obtained R was in the range of 0.23-24.14 and the φ was in the range of 0.0002~0.0135 mol/mol · L. The value of R is defined as the ratio of molar rate F_G/F_L, which can be estimated by $F_G(=Q_GP/RT)$ and $F_L(=Q_{LT}C_L)$. The ratio R was significant for equipment design. On the other hand, the value φ is defined as $(F_Gy_1E)/(F_LV_L)$ (mol-CO_2/mol-NaOH · L), which describes the absorption capacity of NaOH solution in the bubble-column scrubber. In addition, the last two columns of Table 2 illustrate the mean residence times of gas ($\bar{t}_G$) and liquid ($\bar{t}_L$). The $\bar{t}_G$ was in the range of 25.6-102.4 s and the $\bar{t}_L$ was in the range of 502-3075 s. Compared to the $\bar{t}_G$ and $\bar{t}_L$ using Taguchi experiments of 4.41-17.6s and 166-1000s, it was found that the $\bar{t}_G$ and $\bar{t}_L$ were longer than those of Taguchi experiments, since the height of pilot-scrubber is longer than that in lab-scale. Hence, the E and R_A of the on-site operations were inevitably higher than those of the Taguchi experiments [9].

Conclusion

The optimal operating parameters of the Taguchi experiments can be converted into on-site operating conditions. This study successfully used the pilot-scale bubble column as the scrubber and NaOH as the absorbent to capture the CO_2 in the flue gas of the Lin-kou power plant. The test results show that y_2, pH, T and P were at constant levels after 50-60 min without controlling the pH value and temperature. Under the conditions of the steady state, we can obtain data for the E, R_A, K_Ga, R and φ. For the solutions required for algae cultivation in the future, the pH value of the required absorption liquid should be around 10. The R_{max}, Q_g and Q_{LT} should be 192 L/min and 1.6 L/min, and the C_L should be 0.3 M. According to φ, the Q_g and Q_{LT} are 144 L/min and 1.6 L/min, and the C_L is 0.173 M. However, the E of the two is about 35%. Hence, it is suggested that operations can be combined with the conditions of high pH values (No. 17 and 21) and low pH values (No. 20 and 22) to obtain the desired pH values for algae cultivation. The data obtained in this research can be used as a basis for further large-scale operations.

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Table 1: Operating conditions conducted at Lin-Kou power plant

		Target pH	Q_g(L/min)	Q_{LT} (L/min)	C_L (M)
NO.17	E(Larger is better)	13	48	9.8	0.15
NO.18	R_A (Larger is better)	13	192	5.1	0.3
NO.19	K_Ga(Larger is better)	13	192	5.1	0.3
NO.20	R_{max}(Larger is better)	10	192	1.6	0.3
NO.21	R_{min}(Smaller is better)	13	48	7.2	1.36
NO.22	ϕ (Larger is better)	10	144	1.6	0.173

Table 2: Experimental data obtained at Lin-Kou power plant

	C_L	E	y_1	y_2	$R_A(10^3)$	$K_Ga(10^2)$	R	φ	$\bar{t}_G$	$\bar{t}_L$
	M	%	%	%	mole/s · L	1/s	-	mol/mol · L	s	s
NO.17-1	0.15	90.2	12.2	1.2	3.59	2.8	1.58	0.0021	102.4	502.0
NO.17-2	0.15	87.5	11.2	1.4	3.20	2.5	1.58	0.0019	102.4	502.0
NO.18-1	0.3	65.6	12.2	4.2	11.1	5.8	5.98	0.0058	25.6	964.7
NO.18-2	0.3	63.2	11.4	4.2	10.3	5.7	5.94	0.0052	25.6	964.7
NO.19-1	0.3	65.6	12.2	4.2	11.1	5.8	5.98	0.0058	25.6	964.7
NO.19-2	0.3	63.2	11.4	4.2	10.3	5.7	5.94	0.0052	25.6	964.7
NO.20-1	0.3	37.7	12.2	7.6	6.87	3.26	18.70	0.0103	25.6	3075.0
NO.20-2	0.3	33.9	11.2	7.4	5.41	2.77	18.70	0.0086	25.6	3075.0
NO.21-1	1.36	97.7	8.6	0.2	2.37	3.96	0.23	0.0002	102.4	683.3
NO.21-2	1.36	96.3	10.8	0.4	3.17	4.4	0.23	0.0003	102.4	683.3
NO.21-3	1.36	97.6	8.6	0.2	3.00	4.4	0.23	0.0003	102.4	683.3
NO.22-1	0.173	47.9	9.6	5.0	4.74	2.88	24.14	0.0135	34.2	3075.0
NO.22-2	0.173	33.0	10.6	7.1	3.44	1.87	24.14	0.0094	34.2	3075.0

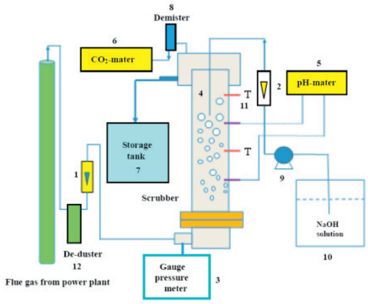
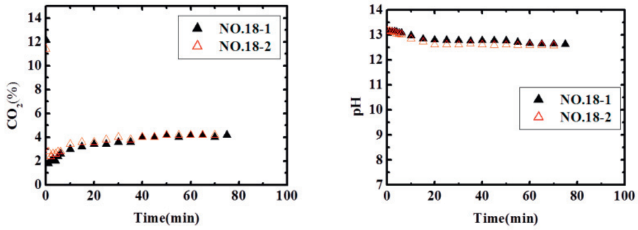


Fig.1: Experimental device conducted at Lin-Kou power plant



(a)y_2 vs. time (b)pH vs. time

Fig. 2: Variations of y_2 and pH, showing the steady-state operating and reproducible for No. 18

Biography

Dr. Pao Chi Chen, Engineering Doctor (Ph.D.-Engineering), now is a professor, Department of Chemical and Materials Engineering, Lunghwa University of Science and Technology. He got Bachelor Degree in Chemical Engineering, Chung-Yuan University, M Sc and Engineering Doctor's degree (Ph.D.) in Chemical Engineering, Department of Chemical Engineering, National Taiwan University. Dr. Chen got a research award from Ministry of Education, Taiwan, 2010. Currently, Dr. Chen focus on the biotechnology, such as peptides and Nano-structured lipid carriers, capture of carbon dioxide, nanotechnology, and technology education.

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