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Plantwide Control of CO_2 Capture by Absorption and Stripping Using Monoethanolamine Solution

Yu-Jeng Lin[a], *Tian-Hong Pan*[b], *David Shan-Hill Wong*[a*] *and Shi-Shang Jang* [a*]

[a]Department of Chemical Engineering, National Tsing-Hua University, Hsin-Chu, Taiwan 30013

[b]School of Electrical & Information Engineering, Jiangsu University, Zhenjiang, Jiangsu 212013, China

Abstract - **In this study, plantwide control of an absorption/stripping CO_2 capture process using mono-ethanol-amine was investigated using dynamic simulation. In this system, CO_2 removal ratio is influenced by operating variables such as lean solvent rate and lean solvent loading, which is in-turn determined by reboiler duty in the stripper. Moreover, we found that the long term stability of the system cannot be achieved unless the water balance is properly maintained. Hence the following control structure was proposed. In this scheme, CO_2 removal target is guaranteed using the lean solvent feed rate to the top of the absorber column. The overall water inventory was maintained by controlling liquid level in reboiler of the stripping column using makeup water. In order to operate process with an appropriate lean solvent loading, the temperature at the bottom of stripper is controlled by reboiler duty. This control structure was tested by disturbances involving inlet flue gas flow, and CO_2 concentrations . Dynamic simulations showed that system can achieve removal targets, stabilize quickly while keeping optimum lean loading constant. To ensure minimum energy consumption, optimizing control can be carried out by adjusting the setpoint of reboiler temperature.**

1. INTRODUCTION

Over the past few decades, anthropogenic carbon emission has been recognized as an important contributing factor to global warming and climate change. Therefore, carbon dioxide capture, sequestration and utilization has become a new focus of chemical process technology research. Flue gas from coal-fired power plant is the main source of CO_2 emissions. Among several types of technologies for separation, absorption/stripping CO_2 capture system is considered the most feasible method to deal with flue gas from power plants[1]. Compared with other capture processes, absorption/stripping process offers higher capture efficiency and lower energy consumption. The standard absorption/stripping process mainly consists two columns and a heat exchanger as shown in Figure 1. Flue gas carrying CO_2 from power plant is delivered into bottom of packed absorber to contact with lean solvent, 30 wt% MEA is widely used as absorbent in absorption/stripping process. Treated gas is vented to atmosphere from top of absorber. After absorbing, rich solvent is sent to stripper with reboiler to reproduce MEA solvent. Hot lean solvent out from stripper is reused after being cooled by heat exchanger and cooler.

Heat duty of the reboiler in stripping column is the main energy consumption of this capture process. Several

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*Corresponding author.(e-mail: dshwong@che.nthu.edu.tw, ssjang@mx.nthu.edu.tw).

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publications[2-4] provided optimum operating conditions via steady state simulation. Alie et al.[3] developed an integrated model by Aspen Plus. Several system parameters have been varied to find the lowest reboiler duty settings. The optimum lean loading was found to be 0.25 mol CO_2/mol MEA for all CO_2 concentrations.

Several papers offered dynamic analysis of this capture system[4-6]. Ziaii et al.[4] constructed a dynamic model of stripper by Aspen Customer Modeler. Control strategies were applied during the period of electricity peak load. The majority of the above process dynamic studies focused on only analysis of individual units. There was very little study on the plantwide control of the integrated absorption/stripping system and control aspects. In this process, the MEA solution is used to absorb CO_2 from the flue gas and then regenerated in stripper column. The importance of controlling recycle stream has been demonstrated in several previous studies[7, 8]. The primary objective of this work is to investigate plantwide dynamics and control strategy of the absorption stripping process which is necessary for optimal and stable operation.

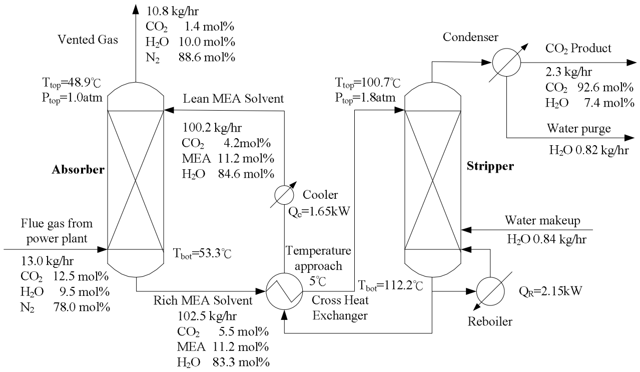

Fig.1. Process flowsheet of the absorption/Stripping CO_2 capture process with stream information of the optimized steady state.

In this work, dynamic behaviors were implemented by Aspen Dynamics. It is a widely used commercial dynamic simulator for studying dynamic process in academia and industry[9]. It has been demonstrated that the rate based model based on mass and heat transfer are more suitable for simulating absorption processes[10], only equilibrium-stage model can be used in Aspen Dynamics. Peng et al.[11] compared dynamic simulation results of equilibrium and rate-based model. Although there were some differences in steady-state value, dynamic responses were similar. It is not our purpose to match plant performance with simulations but to investigate the impact of recycle solvent on control structure design. Dynamic simulation based on equilibrium stage model can be adequately applied.

2. PROCESS DESCRIPTION

A typical absorber/stripper process shown in Figure 1 was simulated. 30% MEA solution was used as the solvent. The stripper pressure is 1.8 atm which is designed slightly above atmospheric pressure to reduce energy requirement and avoid amine degradation.

To describe the absorption equilibrium, the electrolyte non-random-two liquid (ELECNRTL) property method and CO_2-MEA-H_2O system chemistry that includes the following five equilibrium reactions were used.

$$\mathrm{MEA+H_3O^+ \leftrightarrow MEAH^+ + H_2O}$$

$$\mathrm{CO_2 + 2H_2O \leftrightarrow H_3O^+ + HCO_3^-}$$

$$\mathrm{HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{2-}}$$

$$\mathrm{MEA+HCO_3^- \leftrightarrow MEACOO^- + H_2O}$$

$$\mathrm{2H_2O \leftrightarrow H_3O^+ + OH^-}$$

Circulation of regenerated MEA solvent between stripper and absorber constitutes the recycle of the system. A key degree of freedom in designing the steady state operation is the lean loading, i.e. the amount of CO_2 remaining in the lean solution coming out of the bottom of stripper. However, water balance is also a key factor that affects convergence and stability of system. If water vapor in stripped gas is condensed and completely returned into stripper so that water balance depends on flue gas and vented gas only, it is very difficult to obtain a steady state at any chosen recycle lean loading. However, if either water makeup or purge is allowed, different steady states can be reached using different recycle lean loadings.

Table 1. Water balance in different lean loadings.

Lean loading (mol CO_2/mol MEA)	Water input (kg/hr)	Water output (kg/hr)	Water makeup (kg/hr)	Water purge (kg/hr)
0.32	0.77	1.06	0.29	-
0.34	0.77	0.95	0.18	-
0.38	0.77	0.75	-	0.02
0.40	0.77	0.69	-	0.08

Different steady states can achieved at different lean solvent loadings ranging from 0.32 to 0.40 mol CO_2/ mol MEA. As shown in table 1, at low lean loadings, water makeup is required, while at high loadings water purge is necessary. To facilitate easy operation, water condensed from the stripped product gas is no longer directly recycled; instead steady flow of makeup water is used.

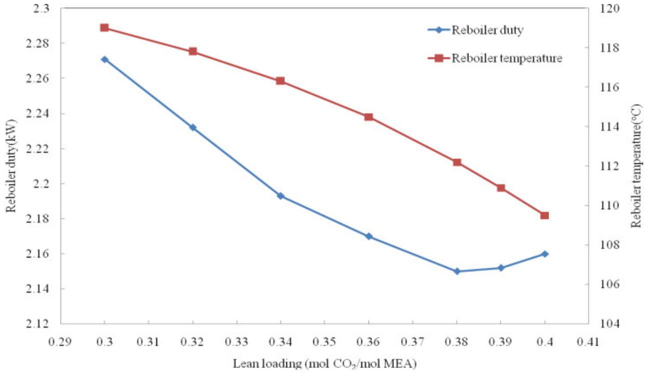

Fig.2. The steady state optimization procedure: relationship between reboiler duty, lean loading and reboiler temperature.

Given that water inventory in the process can be manipulated by makeup, an operable case is needed for further control studies. Using steady state analysis, the energy consumptions at varying lean loadings were calculated as shown Figure 2. The optimum case with lean loading 0.38 is selected. The temperature, pressure and component flow rates are listed in Figure 1. This steady state employ a recycle lean solvent rate of 100.2 kg/hr with lean solvent loading 0.38 mol CO_2/mol MEA. A CO_2 removal ratio of 90% was achieved using a reboiler duty of 2.15 kW and water makeup of 0.84 kg/hr. Temperature at the bottom of the reboiler is 112.2 ^{o}C .

3. DYNAMIC SIMULATION AND CONTROL STRATEGY

The steady state optimum case was exported to Aspen Dynamics and pressure-driven type was used to drive system dynamically. In Aspen Dynamics, several controllers were installed automatically including pressure and level controllers of two columns. In addition, temperature controller of cooler was installed to maintain the temperature of the re-circulating lean solvent at 40 ^{o}C.

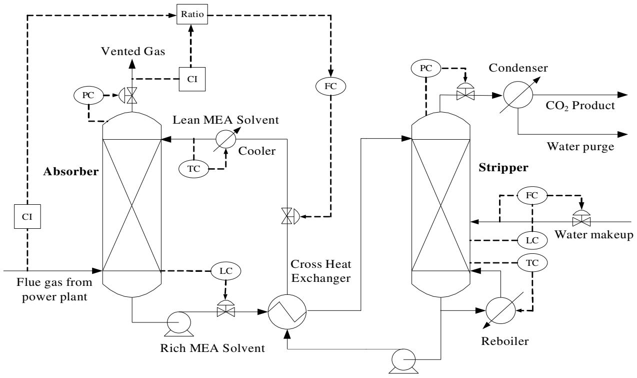

Fig.3. The proposed plantwide control scheme.

The primary objective of this process is to remove a fixed percentage (90%) of CO_2 entering the absorber. Removal ratio can be calculated by measuring the concentrations of the CO_2 in the flue gas inlet and vented gas. To maintain the removal target, the flow rate of the re-circulating lean solvent flow rate is manipulated. However, since re-circulating lean solvent flow rate must be changed, the usual level control of the reboiler using bottom draw rate of the stripper must be relinquished.

Lean solvent loading is the most important parameter in the operation of this process. In the stripper, CO_2 product was stripped from hot rich solvent. However, it is usually difficult to remove all of the CO_2. Less reboiler duty is required if remaining CO_2 loading in the lean solvent is high. However, high lean solvent loading leads to poor absorption performance in absorber. Generally, reboiler temperature is regard as a good indicator of the lean solvent loading. Hence reboiler temperature is controlled by reboiler duty system can be operated at a lean solvent loading desired.

As mentioned in section 2, water make up is a critical factor in determining the actual steady state achieved. If the water condensed from the stripped product gas is not recycled, water will be constantly lost and overall holdup inventory of the absorber/stripper system cannot be maintained. In this process, the holdup in the absorber is maintained by the rich solvent draw rate, loss of inventory will be indicated by loss of holdup in the reboiler. Hence, water make up should be manipulated to stabilize liquid level in the reboiler, replacing the usual level control due to the need of manipulating the re-circulating lean solvent rate.

The completed control scheme suggested is shown in Figure 3. All controller's parameters are tuned via tuning tools applying Tyreus-Luyben rules in Aspen Dynamics.

4. RESULTS AND DISCUSSIONS

4.1. Water makeup. To demonstrate the importance of proper water makeup in maintaining the system overall inventory and performance, the following simulation was carried out. Starting with the steady state of the optimum case, the water makeup was increased and decreased by 20% and the level control is relinquished at 0.5 hour. It was found that the liquid level in the reboiler will deplete or accumulate (Figure 4). If a higher water makeup was used, water will accumulate resulting in a steady decrease in concentration of MEA, and increase in reboiler duty. On the other hand, if there is not enough water makeup, concentration of MEA will keep increasing, and the liquid level in the reboiler will deplete. Therefore, it is important to maintain the correct water makeup by tracking the reboiler level.

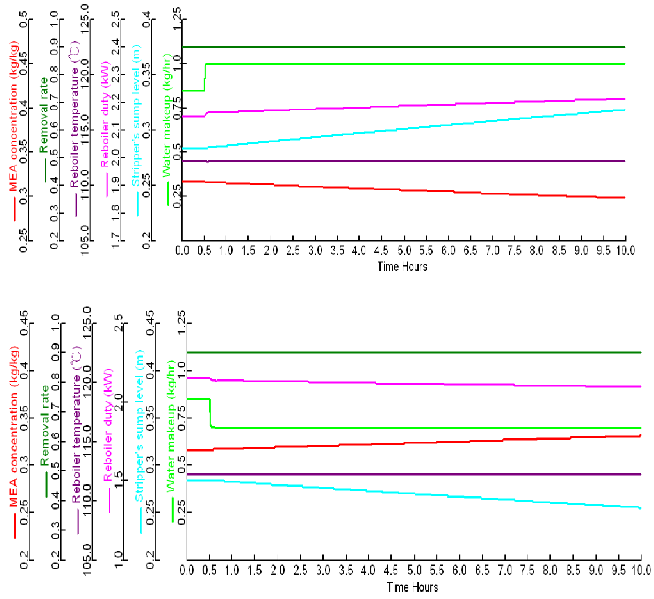

Fig.4. Dynamic responses when level control of the stripper was relinquished and water makeup was (a) increased or (b) decreased.

4.2. Disturbance in inlet flue gas. Now the CO_2 capture process can be operated stably with minimum reboiler duty consumption. The ability of the control to regulate input disturbances is tested. Responses to ±10% step change in inlet flue gas rate were presented in Figure 5. Due to more flue gas input, lean solvent flow rate increased to keep 90% removal. In the meanwhile, stripper performance was controlled by reboiler temperature controller. It can be seen that the 90% removal target can be successfully maintained with corresponding increase in recycle solvent rate. The reboiler temperature remained unchanged.

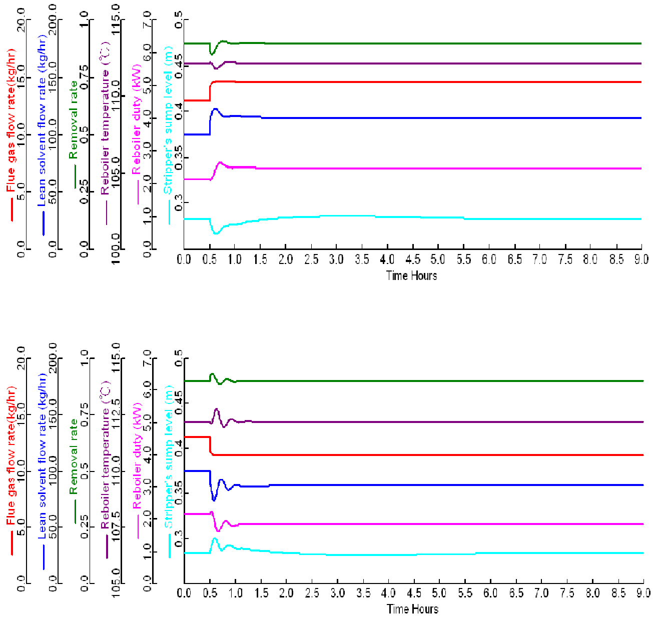

Fig.5. Dynamic responses to +/- 10% disturbance to inlet flue gas flow.

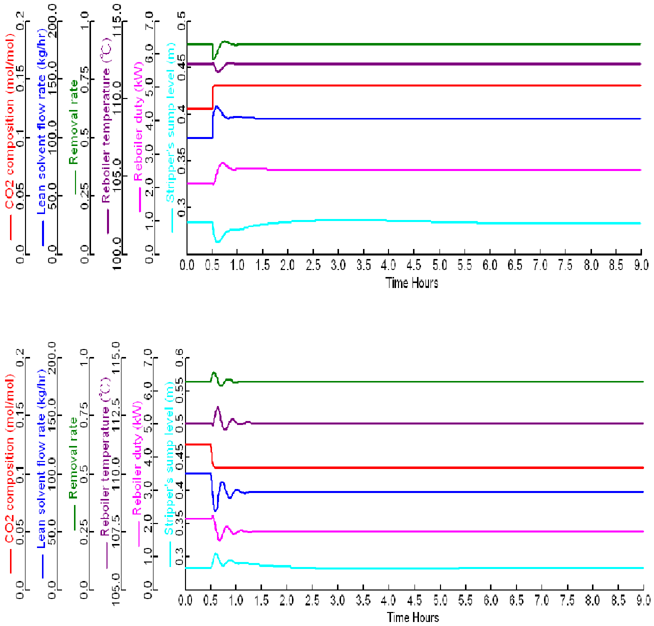

Fig.6. Dynamic responses of disturbances in CO_2 composition in flue gas (a) 12.5 mol% to 14.5 mol% (b) 12.5 mol% to 10.5 mol%.

Responses to positive and negative step change in CO_2 composition in flue gas inlet at 0.5 hour are shown in Figure 6. CO_2 composition step change in positive and negative case was made from 12.5 mol% to 14.5 mol% and 12.5 mol% to 10.5 mol%, respectively. The dynamic responses are similar to flue gas flow case.

4.3. Optimizing Control. Given the new steady state which is acquired after regulations mentioned above, the primary question would be whether the given steady state is an energy efficient one. According to the control strategy suggested, the only operating degree of freedom is the temperature of the stripper. Hence a gradient-based step-by-step optimization can be implemented. Steps of 0.5 °C was used to determine the gradient. The maximum step was limited to 2 °C. Steady states can be obtained in each of the subsequent optimization move after reboiler temperature setpoint being changed.

Results of optimization are shown in table 2. The results show that the optimal target of the reboiler temperature is robust to all disturbances studied. The robust of this target value is most desirable to optimal control.

5. CONCLUSIONS

In the above study, three important factors, namely: lean solvent flow, lean solvent loading and water makeup, that affect CO_2 removal performance, energy efficiency and long term stability of the absorption/stripping CO_2 capture process using monoethanolamine solution were identified.

A control structure is proposed in which CO_2 removal, which can be measured by CO_2 concentrations in the inlet flue gas and vented gas at the top of the absorber, is guaranteed by manipulating the lean solvent feed rate to the top of the absorber column. Liquid level in reboiler of the stripping column is controlled by makeup water flow rate in order to maintain water inventory balance. The temperature at the bottom of stripper is controlled by reboiler duty so that a fixed lean solvent loading can be achieved.

Table 2. Re-optimized results: reboiler duty and stripper bottom temperature in different system disturbances.

System disturbance	Steady state		Re-optimized	
	Reboiler T (^oC)	Reboiler duty (kW)	Reboiler T (^oC)	Reboiler duty (kW)
Optimum case	112.2	2.150	-	-
Flue gas flow rate +10%	112.2	2.474	113.2	2.471
Flue gas flow rate -10%	112.2	1.863	111.7	1.860
CO_2 composition 12.5% to 14.5%	112.2	2.532	113.2	2.530
CO_2 composition 12.5% to 10.5%	112.2	1.788	111.7	1.785

System disturbances including flue gas total flow and CO_2 concentration were considered to test operability of the closed loop system. Dynamic results showed that the entire system can be controlled successfully at 90% removal ratio and optimal lean loading of 0.38 mol CO_2/mol MEA. The minimum energy consumption can be found by simply adjusting the setpoint of reboiler temperature using an optimizing control procedure.

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