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Different control strategies for MEA based chemical absorption

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ABSTRACT

When capturing CO_2 from biomass fired combined heat and power plants, the dynamic changes in the feedstock and the heat and electricity demands can clearly affect the operation of the boiler, which can further affect the performance of chemical absorption CO_2 capture. To handle such dynamic changes, control systems are needed. This work aims to compare the performance of two control strategies that can control the reboiler duty in the stripper to achieve a constant capture rate. Control strategy A uses the reboiler temperature as input based on a PID controller; and control strategy B is a modification of control strategy A by introducing a feedforward compensation based on the flowrate of rich solution when regulating the reboiler duty. Based on dynamic simulations, it is found that control strategy B can reduce the settling time and capture more CO_2 with a lower average energy penalty within a certain time length.

Keywords: BECCS, Chemical absorption, Dynamic simulations, Carbon dioxide capture, Control strategy, Energy penalty

NONMENCLATURE

Abbreviations	
BECCS	Bioenergy with CO_2 capture and storage
CHP	Combined heat and power
DV	Disturbance variable
FF	Feed forward
FG	Flue gas
FOPTD	first order plus time delay model
KPI	Key performance indicators
MEA	Monoethanolamine
MEA-CC	MEA based chemical absorption
NETs	Negative CO_2 emission technologies
OP_{fb}	Output value in feedback controller
OP_{ff}	Output value in feedforward controller
PCC	Post-combustion capture
PID	Proportional-integral-derivative
Q_{reb}	Reboiler duty
T	Temperature

1. INTRODUCTION

According to United Nations Environment Programme, in order to achieve the 1.5°C climate goal, CO_2 emissions must be reduced by 7.6% each year between 2020 and 2030 [1]. As one of the major negative emission technologies (NETs) [2], the bioenergy with carbon capture and storage (BECCS) has attracted much attention, which has a potential contribution of CO_2 removal up to 16 Gt CO_2 per year [3].

Among different CO_2 capture technologies, the MEA based chemical absorption (MEA-CC), is the only commercialized one. When using MEA-CC to capture CO_2 from the flue gas (FG) of biomass fired combined heat and power plants (CHPs), the dynamic changes in both FG and available heat for solvent regeneration bring huge challenges to the operation of MEA-CC, such as the capture rate and energy penalty. And the changes in BECCS may be even greater than that in other CO_2 capture systems.

To handle the dynamic changes, the control system is crucial. Even though there have been some works focusing on the dynamic performance of MEA-CC, little attention has been paid to the impact of control systems. The objective of this work is compare the performance of two control strategies for the stripper, in order to

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provide insights and guidelines regarding the system optimization.

2. MODEL DESCRIPTION

The performance of control systems is investigated based on dynamic modelling. The dynamic model used in this work is from our previous work, which was developed in Aspen HYSYS and has been validated . As show in Fig.1. The FG enters the absorber, in which CO_2 is removed. The rich solution is sent into the stripper where heat is supplied to regenerate the solvent and release CO_2. Some controllers have been integrated in the dynamic model, with their manipulated variable listed in Table 1. More information of the dynamic model can be found in ref [4].

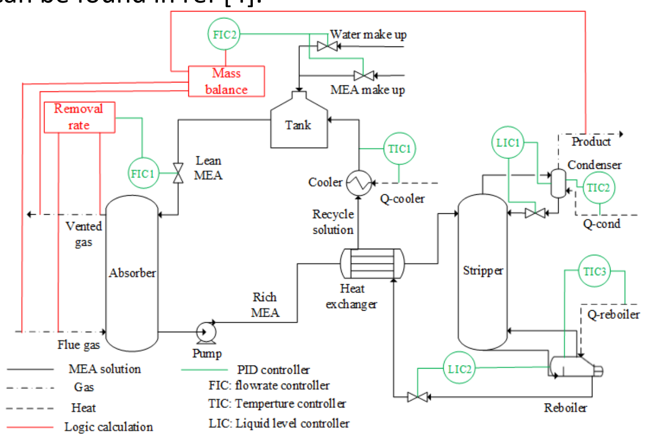

Fig. 1. Dynamic model flowsheet

Table 1. The controlled and manipulated variables of controllers

Controller	Controlled variable	Manipulated variable
FIC1	Removal rate	Lean solution flowrate
FIC2	Mass balance	Make-up of MEA and H2O
TIC1	Lean solution T	The cooling supply to cooler
TIC2	Condenser T	The cooling supply to condenser
TIC3	Reboiler T	The heat supply to reboiler
LIC1	Liquid level of condenser	Reflux flowrate
LIC2	Liquid level of reboiler	Recycle solution flowrate

This work focuses on the controller controlling the reboiler duty. In general, the control objective is to achieve a constant capture rate, which is defined as the ratio of captured CO_2 from stripper to the CO_2 in FG. Two control strategies are considered in this work. Fig. 2 shows a commonly used control strategy, in which the reboiler duty is controlled by reboiler temperature (Control strategy A). A proportional–integral–derivative controller (PID) is used to regulate the reboiler duty. When the flowrate and/or CO_2 (v%) of flue gas (FG) change, the captured CO_2 in the absorber also varies, which can lead to a change in the heat needed by the solvent regeneration. The degree of regeneration can be reflected by the reboiler temperature (T), which implies keeping the reboiler temperature constant can guarantee a constant regeneration rate. When the removal rate is a constant, such a control strategy can achieve a constant capture rate.

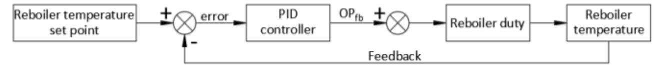

Fig. 2. Control strategy A

The reboiler temperature is clearly affected by the flowrate of the rich solution, which varies with the inlet FG. In order to improve the control performance, another control strategy is proposed, as shown in Fig. 3 (control strategy B). A feedforward (FF) compensation based on the flowrate of rich solution is added to control reboiler duty. In this work, the rich solution, as the only inlet stream of the stripper, is used as the disturbance variable (DV) to determine the heat required by regeneration. The transfer function for the FF compensation is given as follows:

$$\frac{OP_{ff}(t)}{U(t)} = 1.25 * \frac{32.5*t+1}{35*t+1} \tag{1}$$

$$U(t) = \frac{DV(t)-DV_{min}}{DV_{max}-DV_{min}} * 100 \tag{2}$$

where, the OP_{ff} is the output value of feedforward compensation, the t is the time, the DV is the flowrate of rich solution, the DV_{min} and DV_{max} indicate the range of DV.

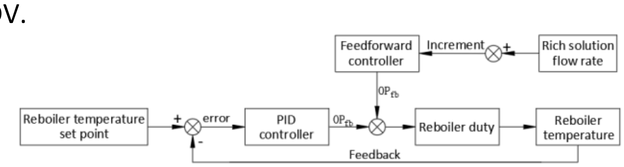

Fig. 3. Control strategy B

A brief comparison about control strategy A and B is presented in Table 2.

Table 2. The controlled and manipulated variables of control strategies

Control strategy	Controlled variable	Manipulated variable
Control strategy A	Reboiler temperature	Reboiler duty
Control strategy B	The change of rich solution flowrate Reboiler temperature	Reboiler duty

3. RESULTS AND DISCUSSION

To test the performance of control strategies, a step increment of 10% in the FG flowrate is introduced to a steady operation flowrate at time t=15min. The real FG data from a biomass CHP plant are used: (CO_2: 14.9v%, O_2: 2.7v%, H_2O: 4.08v%, N_2: 78.32v%). For both control strategies, the set points of CO_2 removal rate and reboiler T are 96% and 385.87K, respectively.

3.1 Control performance

To evaluate the control performance, the settling time and maximum deviation are used as key control performance (KPI) indicators, which are defined below:

(i) Settling time: the time required for the capture rate to reach and remain within ±5% of the steady state.

(ii) Maximum deviation: the maximum difference between reboiler T and its set point.

As show in Fig. 4, under the control strategy A, the reboiler T doesn't change in the very beginning, which implies there is a time delay. Then the reboiler T drops by 0.5K and fluctuates before it reaches the set point again. The delay is due to the nature of PID controllers, which work based on the error. When the flowrate of FG increases, the flowrate of lean solvent is first regulated to increase, which can further leads to the increase of rich solution flowrate. Due to the thermal inertia, the change of reboiler T is even behind the change of flowrate. When under control strategy B, once the flowrate of rich solution increases, the FF compensation can add an extra signal to increase the reboiler duty. As a result, it can be seen that the reboiler T doesn't drop, while rises instead.

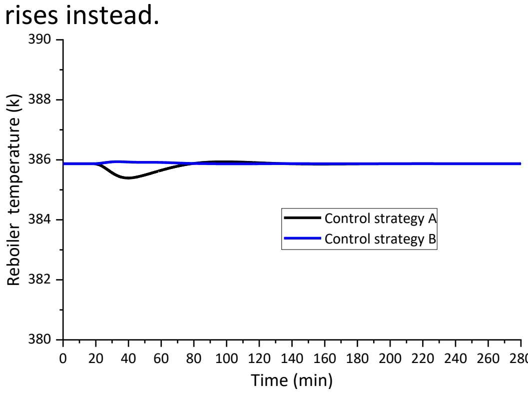

Fig. 4. Responses of reboiler T with different control strategies

Corresponding to the change of reboiler T shown in Fig. 4, the capture rates under both control strategies are plotted in Fig. 5. It has to be pointed out that even though a small change in reboiler T, it can lead to a clear change in the capture rate, which has also been found in [7]. For control strategy A, the decrease of reboiler T causes the decrease of capture rate from 96% to 81.7%; and with the increase of reboiler T, the capture rate also rises. However, for control strategy B, during the delay time, the released CO_2 hasn't changed yet. Nevertheless, as the FG flowrate increases, the inlet CO_2 increases, and consequently, the capture rate drops. Once the reboiler T starts to rise, more CO_2 can be released, resulting in the rise of capture rate.

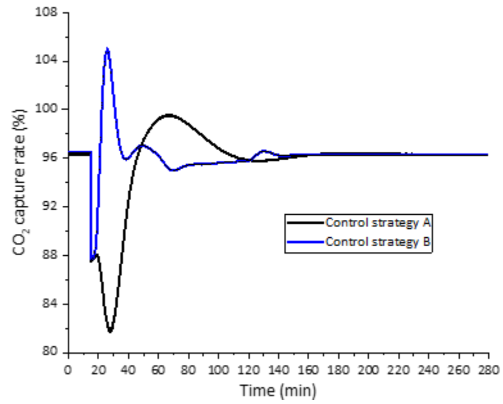

Fig. 5. Responses of capture rate with both control strategies

Table 3 compares the performance of control strategy A and B using the defined KPIs. The settling time is determined based on the capture rate while the overshoot is determined based on the reboiler T, which is more important for the operation. In general, the control strategy B has the better control performance, with the 17.8mins settling time. That is shortened 74.9% than 71mins of control strategy A. And the control strategy A has a 0.48K maximum deviation of reboiler T, which is much larger than the 0.07K of control strategy B.

Table 3. The control performance of control strategies

	Settling time	Maximum deviation
Control strategy A	71mins	0.48K
Control strategy B	17.8mins	0.07K

3.2 System performance

The influence of the control strategy on the performance of CO_2 capture is also assessed by using total amount of captured CO_2 and the average energy penalty (kJ/kg CO_2) as KPI. To fairly compare the two control strategies, the total amount of CO_2 capture within 240mins is obtained:

$$Total\ captured\ CO_2 = \sum_{t=0min}^{t=240min}(CO_2\ captured(t) * step\ time) \quad (3)$$

Based on the result of captured CO_2, the average energy penalty is further defined as:

$$Average\ energy\ penalty = \frac{Total\ Q_{reb}}{Total\ CO_2\ captured} \quad (4)$$

Where, the total Qreb is follows:

$$Total\ Q_{reb} = \sum_{t=0min}^{t=240min}(Reboiler\ duty(t) * step\ time) \quad (5)$$

The dynamic variation of captured CO_2 is showed in Fig.6, the variation is similar to the capture rate. The drop of captured CO_2 under Control strategy A is mainly due to the big drop of reboiler T, which causes less CO_2 released. Under control strategy B, even though the capture rate drops, the released CO_2 doesn't decrease; therefore, the captured CO_2 doesn't drop.

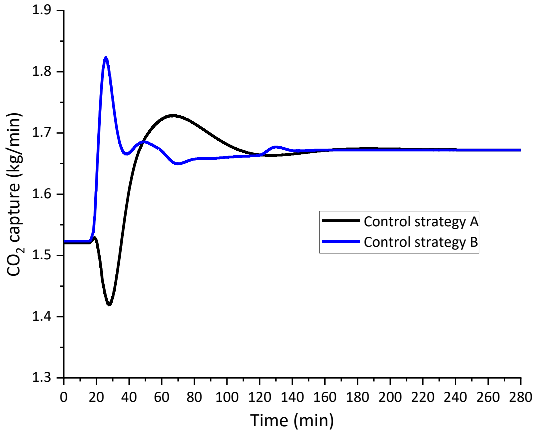

Fig. 6. The captured CO_2 with different control strategies

Fig. 7 represents the dynamic variation of energy penalty. Under Control strategy A, when reboiler T drops, the reboiler duty is regulated to increase; while the captured CO_2 decreases, resulting in a sharp increase of energy penalty. Under Control strategy B, the increased amount of captured CO_2 first causes the energy penalty to decrease; whereas, the further increase of reboiler duty leads to the increase of reboiler penalty.

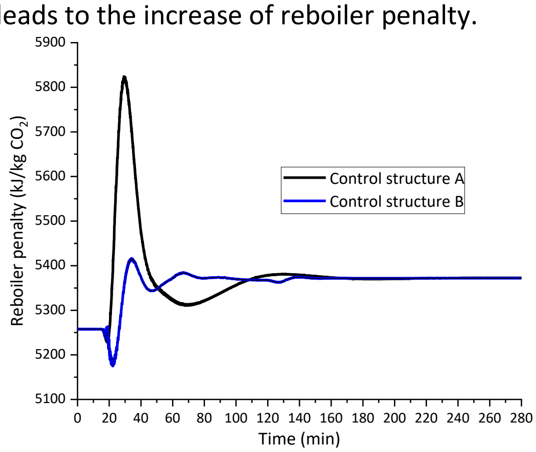

Fig. 7. The reboiler penalty with different control strategies

The total captured CO_2 and the average energy penalty are compared in Table 4. For the studied time length, control strategy B can achieve a larger amount of captured CO_2 and a lower average energy penalty.

Table 4. The system performance of control strategies

	Total captured CO_2 (kg)	Average energy penalty (kJ/kg CO_2)
Control strategy A	463	5376
Control strategy B	466	5342

4. CONCLUSIONS

This work studies the influence of control strategies on the performance of chemical absorption CO_2 capture. Two strategies for controlling the reboiler duty are compared based on dynamic simulations. Based on the results, the following conclusions are drawn:

- The control strategy only based on the reboiler temperature has a longer settling time and larger maximum deviation.
- Adding a feedforward compensation based on the flowrate of rich solution can improve the performance, which can achieve a large amount of captured CO_2 and a lower average energy penalty.

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