# CONTROL STRTEGIES FOR FLEXIBLE OPERATION OF POWER PLANT INTEGRATED WITH CO2 CAPTURE PLANT

Yu-Jeng Lin[a], Chun-Cheng Chang[a], David Shan-Hill Wong[a] Shi-Shang Jang[a] * and Jenq-Jang Ou[b]
a National Tsing-Hua University, Hsin-Chu 30013, Taiwan
b China Steel Corporation, Kaohsiung, 80012, Taiwan

*Abstract*

About 20% power output penalties will be incurred for implementing CO2 capture from power plant. This loss can be partially compensated by flexible operation of capture plant. However, daily large variations of liquid and gas flows may cause operation problems to packed columns. Control schemes were proposed to improve the flexibility of power output without causing substantial hydraulic disturbances in capture plant is presented. Simulations were implemented using ASPEN Plus. In varying lean solvent flow strategy, the flow rate of recycling solvent was manipulated to control the CO2 capture rate. The liquid flow of the absorber and gas flow of the stripper will vary substantially. In an alternative strategy, the lean solvent loading will be varied. Variation of gas throughput in the stripper is avoided by recycling part of CO2 vapor to stripper. This strategy provided more stable hydraulics condition in both columns and is recommended for flexible operation.

*Keywords*

Plantwide control, CO2 scrubbing, ASPEN PLUS, heat integration, flexible operation

## Introduction

In recent years, global warming and climate change caused by greenhouse gases have received widespread concern. The majority of $CO_2$ emission comes from flue gas emitted from electricity generation, coal-fired power plant especially. The most mature technology for post combustion $CO_2$ capture is amine scrubbing. Pilot-scale plants of various sizes have been constructed and operated to investigate the design and operability of such processes.

Implementing $CO_2$ capture incurs penalties of electric power output. First, regenerating lean solvent after scrubbing requires a large amount of heat. The thermal energy is usually acquired from low pressure steam extracted from power plant. Second, the stripped $CO_2$ vapor must be compressed to above 100 bar for transport and sequestration.

Coal-fired power plant usually performs as a base load power plant that produces a steady electricity output. However, power demands fluctuate on daily and seasonal basis. Electricity has higher prices in peak load periods. It was suggested that electric power output can be increased to meet higher electricity demand by turning off $CO_2$ capture plant in peak hours (Cohen et al.(Cohen, Rochelle et al. 2010)). Chalmers et al.(Chalmers, Leach et al. 2009) showed that if $CO_2$ trading price is included, bypassing $CO_2$ capture is valuable when \$/MWh electricity selling price are 2~3 times higher than \$/ton $CO_2$. Thus flexibility added to the power plant was proclaimed as one of the advantages of post-combustion CCS by amine scrubbing.

However, a continuous process such as the amine scrubbing and regeneration process commonly used in CCS cannot be shut down and turned on at will. It should be recognized that when flue gas bypasses the $CO_2$ capture plant, hydraulics conditions of the absorber and the stripper will change substantially. Flooding and poor wetting will occur when the throughput rate is too high or too low. Normal operation cannot be maintained if the throughput is turned down much beyond this limit because of poor wetting.

It was also suggested that rich solvent is stored during peak load period and will be regenerated later in off-peak period (Chalmers and Gibbins 2007; Chalmers, Lucquiaud et al. 2009). This strategy could avoid $CO_2$ emission penalty because $CO_2$ is captured all the time. However, this strategy requires huge additional tanks and solvent inventory for buffering between peak and off-peak load period. The additional cost and safety hazards can be staggering (Haines and Davison 2009). Using this strategy, a normal gas and liquid throughput can be maintained in the absorber; but large changes in throughput can still be found in the stripper.

In this work, we suggested that flexible operation can be achieved by implementation of proper control strategies. The feasibility of this approach is verified using dynamic simulation of an integrated system with power generation and heat recovery sections of a power plant and the corresponding $CO_2$ capture plant by Aspen Plus and Aspen Dynamics. Using this approach, no additional large storage tanks and solvent inventory will be needed, nor will large variations in gas and liquid throughputs be introduced in the absorber and stripper.

## Process description

### *Power plant*

A power plant model is required so that interaction between multi-stage compressor, turbine output and the CCS capture plant can be simulated. In this work, a reference 580MW power plant burning bituminous coal with 36.3% net efficiency (HHV) (NETL R&D Solutions 2007) was selected. Boiler supplies high pressure steam at 170 bar/560$^oC$ and reheated steam at 38 bar/560$^oC$ for power generation. Flue gas out from boiler then is sent to flue gas desulfurization (FGD) process for removing sulfur dioxide. After that, about 2300 ton/hr flue gas containing 13mol% $CO_2$ will head to $CO_2$ capture plant. Because the plant is regarded as a base load plant, instead of simulating boiler, constant high pressure and intermediate pressure steam condition out from boiler is used as input to the power plant model.

Power extractions from steam are simulated by series of turbines with different outlet pressures. The outlet steam of each turbine is available for preheating condensate or providing heat for the reboiler in the $CO_2$ capture plant. To facilitate heat transfer, saturate temperature of heating steam should be at least 10$^oC$ approach above reboiler temperature (Alie 2004).

### *$CO_2$ capture plant*

The $CO_2$ capture plant includes two columns, absorber and stripper, and one lean/rich solvent cross heat exchanger. Flue gas carrying $CO_2$ generated from power plant is delivered into bottom of packed absorber to contact with lean solvent, an aqueous solution containing 30 wt% MEA. Treated gas is vented to atmosphere from top of absorber. After absorption, the rich solvent is preheated to 100$^oC$ by heat exchanger before being sent to stripper. In the stripper, low pressure steam from power plant is injected into reboiler for $CO_2$ desorption. Then, hot lean solvent out from stripper is reused after being cooled to 40$^oC$ by heat exchanger and cooler. Hot stripped vapor with $CO_2$ and $H_2O$ will be cooled and compressed.

Steam usage in reboiler relies on extracting steam at 2.9 bar from the low pressure turbine. About 50% of the low pressure superheated steam over 200$^oC$ leaves low pressure turbine to the reboiler. To avoid amine degradation caused by intensive heat stress in the reboiler, the superheated steam should be cooled to near saturated temperature before injecting to reboiler. After releasing latent heat in the reboiler, reboiler condensate then is sent back to steam-condensate cycle in power plant.

In this work, absorber and stripper's column diameter are determined by gas and liquid flow rate in each column at 90% capture rate. Fractional capacity is designed as 70%. Fractional capacity is used as a parameter that indicates hydraulic conditions in packed column. It denotes the fractional approach to maximum capacity of column, the flooding point.

### *Multi-stage compressor*

$CO_2$ product accompanying with water vapor is about 100$^oC$ while being stripped out from top of stripper. Before being compressed, $CO_2$ product is cooled to 40$^oC$ by overhead condenser and part of water will be condensed. Further, the $CO_2$ is compressed from 2 to 110 bar through multi-stage compressor, which includes intercoolers to cool the exhaust gas back to 50$^oC$ before entering next stage. Each stage is simulated by compressor, heat exchanger, and condenser, responsible for compressing, cooling, and knocking water out respectively.

### *Heat integration*

Romeo et al.(Romeo, Espatolero et al. 2008) showed that heat integration of intercoolers can save about 2% of electricity output. To implement heat integration, first, heat acquired from cooling $CO_2$ in overhead condenser and intercoolers of the CCS plant is used to preheat condensate coming out of the condenser of the power plant. Part of condensate is delivered to intercoolers in parallel to cool $CO_2$ vapor to 50$^oC$ before entering each compressor. Then, rest of condensate is delivered to overhead condenser of the CCS plant to recover waste heat. Even though large amount of latent heat is recovered by preheating condensate of the steam cycle, additional cooling water is required to cool the $CO_2$ vapor before entering first compressor. Figure 1 shows the process flowsheet with heat integration.

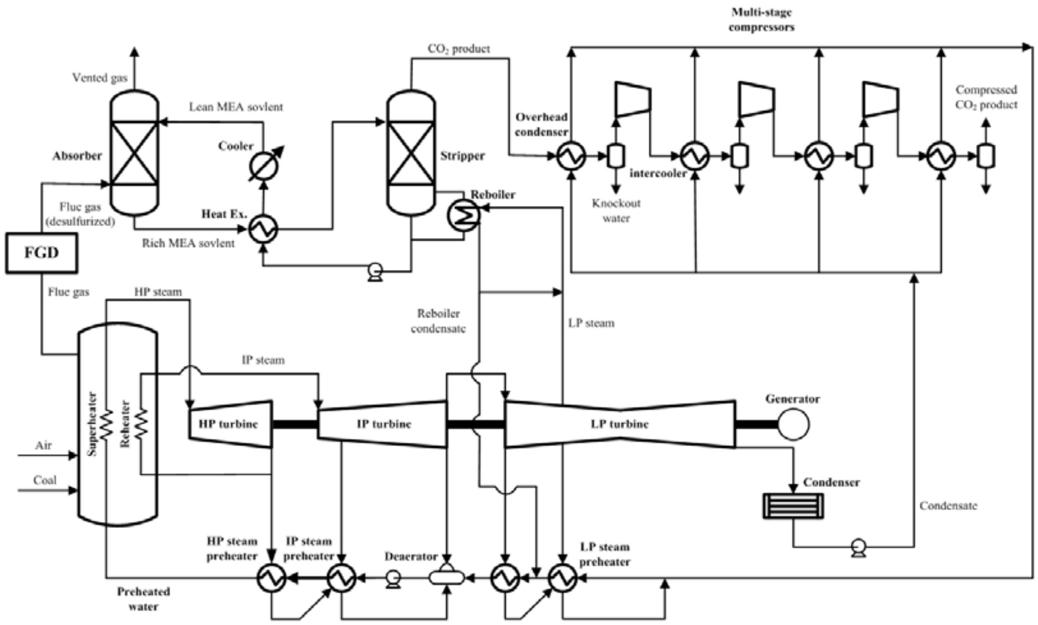


*Figure 1. Integrated system flowsheet with steam-condensate cycle, multi-stage compressor and $CO_2$ capture plant*

## Flexible operation strategies

The actual optimal operating strategy depends on the pricing, duration of the peak load period and the trading price of $CO_2$ emission.  In this study, we assume that an average capture rate 70% should be attained. If the peak load period is 10 hours per day, electricity output can be increased during peak load period by decreasing $CO_2$ capture rate to 50%; then, to balance overall capture rate to 70%, $CO_2$ removal rate has to increase to 90% in the next 14 off-peak load hours. The purpose is to show that we can adjust the $CO_2$ capture rate without causing large disturbances in the capture plant.

### *Variation of Lean Solvent Flow (VLSF)*

A plantwide control strategy of $CO_2$ capture plant was proposed by Lin et al (Lin, Pan et al. 2011). As figure 2 shows, $CO_2$ capture rate is controlled by variation of lean solvent flow (VLSF), and reboiler temperature is controlled by manipulating reboiler steam flow rate. In VLSF control structure, flexible operation can be implemented by adjusting setpoint of $CO_2$ capture rate controller. Lean solvent circulating rate is varied to meet the capture rate target.   In the VLSF strategy, reboiler temperature is controlled at a fixed value. Reboiler temperature is an indicator of lean loading.  Hence the residual loading of $CO_2$ in the recirculating solvent is approximately constant during flexible operation.

The VLSF strategy delivers all the flue gas into absorber. Variation of gas flow rate in absorber is avoided when flexible capture targets are pursued.  However, liquid flow rate will vary substantially in the absorber since the capture rate target is achieved by changing the solvent flow rate. Furthermore, since the net amount of $CO_2$ captured and stripped from the stripper will change, liquid flow in the stripper will also vary substantially.

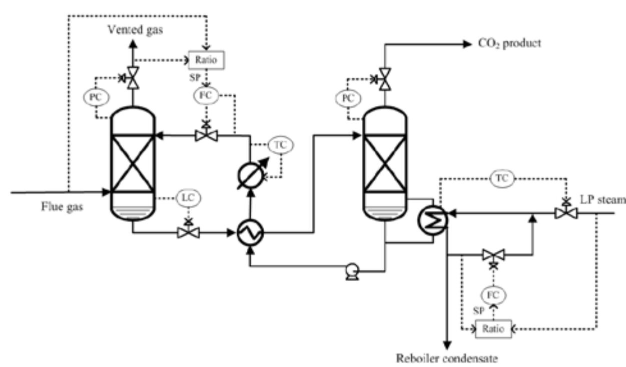


*Figure 2. Control structure of CO2 capture plant in variation of lean solvent flow strategy.*

### *Variation of Lean Solvent Loading (VLSL)*

To avoid the potential fluctuations in liquid flow in the absorber and gas and liquid flow in stripper, we propose an alternative control strategy that stabilizes the hydraulic conditions of both columns during flexible operation.

First, if the circulating lean solvent rate is fixed, lean solvent loading can be used to meet different $CO_2$ capture rate. The lean solvent loading can be reduced so that more $CO_2$ can be captured in the absorber with a steady lean solvent flow. Conversely, if we wish to reduce $CO_2$ capture rate, a higher the lean solvent loading can be allowed, thus reducing the load of the reboiler. Hence the scheme is based on variation of lean solvent loading, VLSL.

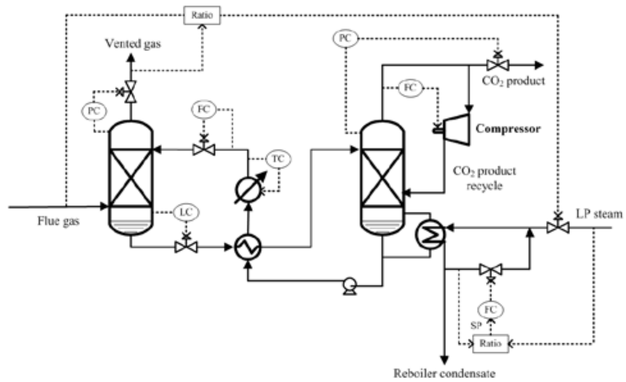


*Figure 3. Control structure of $CO_2$ capture plant in variation of lean solvent loading strategy.*

By changing the loading of the lean solvent, the gas and liquid flow in the absorber and liquid flow will be stabilized. However, the gas flow rate in stripper changed as the quantity of captured $CO_2$ produced at the top of the stripper changes. Hence, we propose to recycle part of $CO_2$ product vapor to bottom of stripper so that gas flow instability in stripper can be avoided by adjusting the recycle rate back to stripper. The recycle of $CO_2$ product has little effect compared with the case without recycling. If 30% of $CO_2$ product is recycled, mole fraction of $CO_2$ in vapor increases from 0.476 to 0.480 at the bottom. The composition of $CO_2$ vapor at top of stripper and the reboiler duty required are almost unchanged.

The control scheme of variation of lean solvent loading is shown in Figure 3. Lean solvent flow rate is controlled at a given value by a flow controller. $CO_2$ capture rate is controlled by manipulating reboiler steam flow rate.

## Dynamic simulation results and discussions

To understand dynamic behaviors while implementing flexible operation, the integrated system modeled in Aspen Plus is exported to Aspen Dynamics and then simulated dynamically. After being exported to Aspen Dynamics, basic controllers that maintain steady operation are installed. There are several pressure controllers and level controllers in columns and vessels. Figure 4 shows control scheme of multi-stage compressor and steam cycle. Varying speed control method is applied in compressors' control to meet correct gas flow rate. To implement heat integration between intercoolers when $CO_2$ vapor flow rate is changing, condensate should be adequately distributed to overhead condenser and intercoolers. So, temperature controllers are installed to manipulate condensate flow rate to each intercooler and rest condensate is sent to overhead condenser.

A base case with 70% capture is used to demonstrate flexible operation decreasing capture rate to 90% and decreasing to 50% in two operating strategies. Fractional capacity is 63% in absorber and 54% stripper in base case.

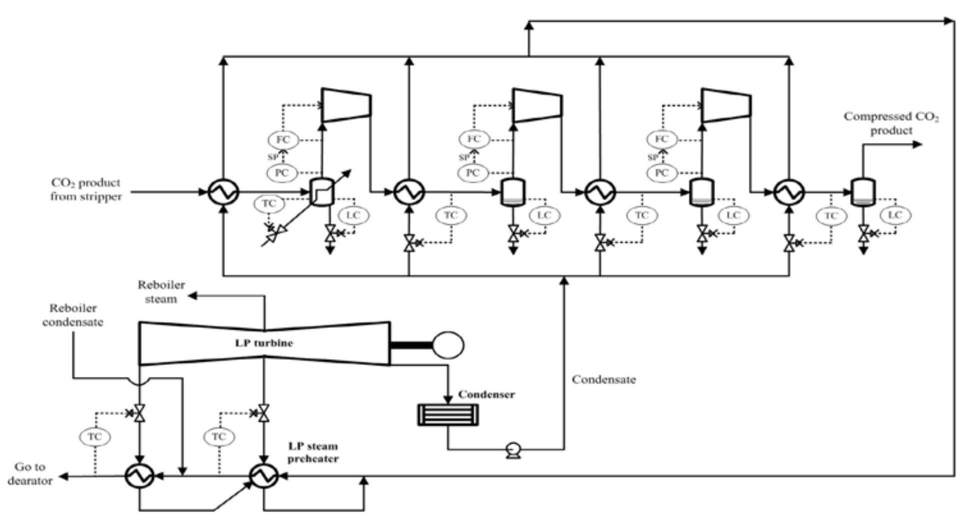


*Figure 4. Control scheme of multi-stage compressor and steam cycle*

*Results of variation of lean solvent flow*

To demonstrate operability, setpoint of capture controller is changed in ramp rate of 1% capture rate/min. Setpoint given is from 70% to 50% or 90% in 20 minutes to increase or decrease power output.

Figure 5 shows dynamic responses of flexible operation implemented by VLSF strategy. $CO_2$ capture rate starts to change at 5th minute. When $CO_2$ capture rate is changing, lean solvent rate is manipulated to track correct capture rate. To cope with the changing circulating solvent rate, reboiler steam is manipulated to maintain reboiler temperature. We can see that lean solvent loading is keeping nearly at 0.37 mol $CO_2$/mol MEA.

Using this operation strategy, fractional capacity in absorber varied in a relatively smaller range compared to simple bypass, between 55% in peak hours and 70% in off-peak hours. However, the fluctuation in stripper still exists. Fractional capacity decreases to below 40% when $CO_2$ capture rate is reduced to 50%.

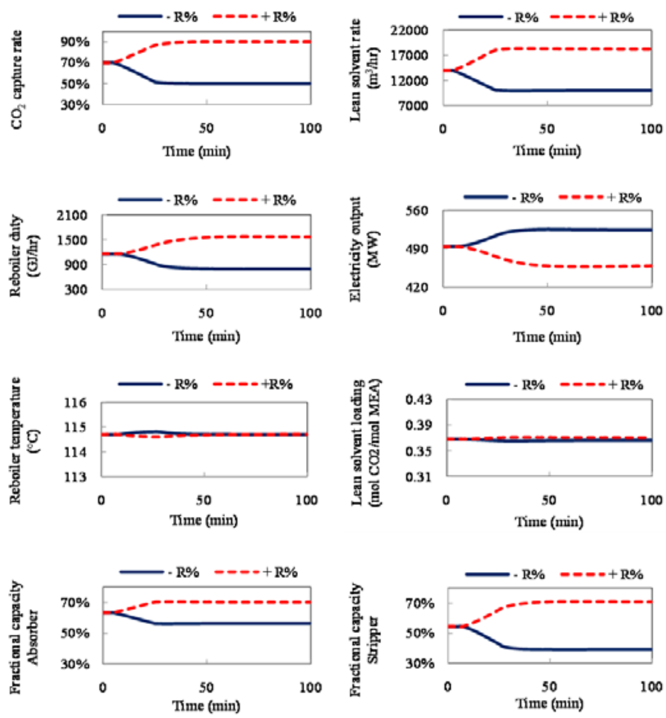


*Figure 5. Dynamic responses of flexible operation adjusting capture rate from 70% to 50% and 70% to 90% implemented by variation of lean solvent flow strategy*

*Results of variation of lean solvent loading*

Figure 6 shows dynamic responses of flexible operation implemented by VLSL strategy. In this operating strategy, system successfully attains $CO_2$ capture targets of 50% and 90%. Lean solvent flow rate is fixed at 14000 $m^3$/hr. The reboiler temperature was increased to 118 $^oC$ to meet a higher $CO_2$ capture rate target of 90% and reduced to 110$^oC$ to meet a lower $CO_2$ capture rate target of 50%. Lean solvent loadings also change from 0.37 to 0.41 and 0.33 mol $CO_2$/mol MEA at 50% and 90% capture rate respectively. Comparing new steady state value of reboiler duty obtained by two operating strategies, VLSL has slightly lower energy requirement at 90% capture and slightly higher at 50% capture rate.

In VLSL strategy, 30% of $CO_2$ product is recycled to stripper initially and then fractional capacity increases to 63%. Recycle rate is manipulated to maintain the gas flow rate out from top of stripper constant. By stabilize throughput of absorber and stripper in constant value, we can see that the fractional capacities in both columns are almost unchanged. Fluctuations in both columns due to large variations of liquid and vapor rate during flexible operation are avoided in this control strategy.

**Conclusions**

Certain degree of flexibility is built in by manipulating the target of $CO_2$ capture in peak-load and off peak-load periods. However, large changes in hydraulic conditions absorber and stripper will occur if the amount of flue gas entering the capture plant and the amount of circulating solvents change substantially. Such changes are not desirable from the operation point of view. To implement flexible operation but avoid potential fluctuations in packed columns due to large variation of liquid and gas flow rate, two operating strategy are proposed. In variation of lean solvent flow strategy, instability in absorber is partly reduced by delivering all flue gas to absorber. Capture rate is controlled by manipulating lean solvent rate and reboiler temperature is controlled at constant to maintain a nominal lean loading. In variation of lean solvent loading strategy, lean circulating solvent rate is unchanged to reduce fluctuations in both packed columns. Further, part of $CO_2$ product is recycled to stabilize stripper's operation. This strategy is able to maintain stable hydraulic conditions in both the absorber and stripper during both peak and off-peak load hours. The net power output is similar to the other strategy.

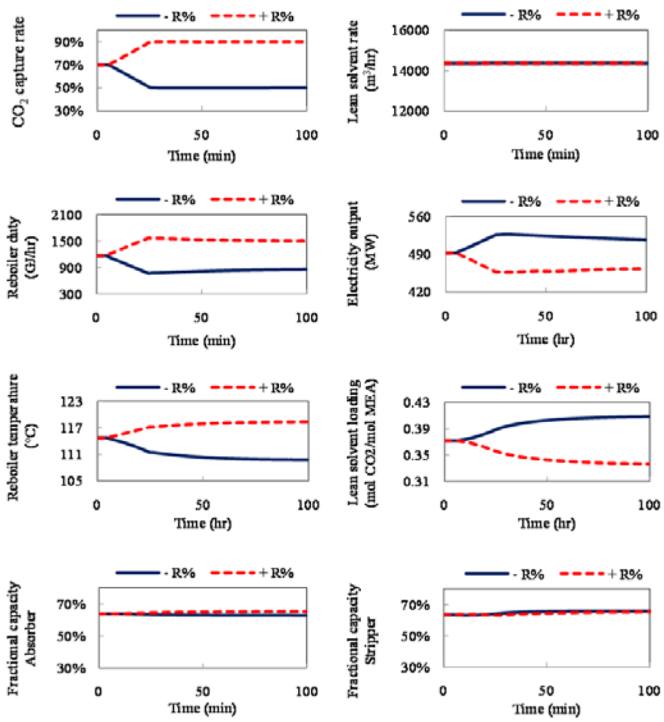


*Figure 6. Dynamic responses of flexible operation adjusting capture rate from 70% to 50% and 70% to 90% implemented by variation of lean solvent loading strategy.*

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