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Optimum Design and Control of Amine Scrubbing in Response to Electricity and CO_2 prices

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Abstract

This paper presents steady state and dynamic modelling of post combustion CO_2 capture using 30 wt% MEA integrated with models of CO_2 compression and the steam power cycle. It uses multivariable optimization tools to maximize hourly profit of a 100 MWe coal-fired power plant. Steady state optimization for design provided optimum lean loading and CO_2 removal as a function of price ratio (CO_2 price / electricity price). The results indicated that for price ratio between 2.1 and 7, the plant should be designed at removal between 70% and 98% and lean loading in the range of 0.22–0.25. Dynamic optimization determined the operation of the capture system in response to two partial load scenarios (reboiler steam load reduction and power plant boiler load reduction) and provided optimum set points for steam rate, solvent circulation rate and stripper pressure control loops. Maximum profit is maintained by allowing the stripper pressure to drop and implementing a ratio control between solvent and steam rate (and flue gas rate for partial boiler load operation).

Keywords: Dynamic modeling; Absorption; Stripping; Optimization; Control

1. Introduction

Dynamic modelling of a process is a helpful tool that is commonly used not only for analyzing the dynamic behaviour and designing simple control strategies but also for optimizing the operation of the plant in response to possible disturbances. However, this strategy has not been previously employed for optimizing the operation and control of CO_2 absorption plants with aqueous amines. In the few works found on dynamic modelling (Kvamsdal et al. [1]; Ziaii et al. [2]), the dynamic simulation of CO_2 capture was used to investigate the dynamic behaviour

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of the absorber and stripper separately in response to the partial load operational scenarios. Lawal et al. [3] analyzed the effects of possible upstream disturbances on the dynamic responses of a combined model of the absorber and regenerator. Several works have focused on reducing overall energy consumption of the capture and/or improvement of absorption performance [4-6]. Since those studies are based on steady state analysis of the plant running continuously at full capacity, they cannot provide insight into dynamic and control performance of the system during transitional operation.

This study presents a fully integrated model of an absorber/stripper using monoethanolamine(MEA) for CO_2 capture. The model was, developed in Aspen Custom Modeller (ACM) and also included an approximation of steady state models of CO_2 compression and power cycle steam turbines to account for the interaction of these components with capture during dynamic operation. This paper, presents the implementation of steady state multivariable optimization tool of ACM® to optimize the most important design parameters, lean loading and CO_2 removal. In an economical study presented by Abu Zahra et al. [7], the lean loading and amine concentration were optimized based on minimization of cost of electricity for a plant designed at 90% removal, which included the terms of total capital cost, operating cost and energy cost. The analysis neglected the effects of capital cost and operating cost of the power plant, capture, and only considered energy cost by using power plant hourly profit as the cost function.

The second part of this study presents the implementation of a multivariable dynamic optimization tool, which is tied with dynamic simulation of the MEA plant, to find final optimum set points for the control loops when two main possible dynamic scenarios are applied. This optimization maximized the power plant profit at the time when the new steady state is reached. The scenarios considered in this study were introduced as possible operational cases in previous work [1, 3, 8]. The first operational scenario is a partial load reboiler steam operation in response to the variation of electricity or CO_2 market conditions. This scenario indicates when the operation of flexible capture is economical, and is discussed in detail in the paper authored by Ziaii et al. [8]. The second one represents the variation of the load of power plant boilers, which can directly affect the operation of the capture.

2. Model development

A model of CO_2 absorption/stripping with 30 wt% monoethanolamine (MEA) was created in a flow sheet of ACM®. The model includes dynamic rate-based models of packed columns (absorber and stripper), simplified steady state models for the heat exchangers, general performance curves for multi-stage CO_2 compressor and pumps and an approximate steady state model for the steam turbine. The stages for steam turbines (HP, IP, and LP) with the extracted steam was extracted for solvent regeneration from the IP/LP crossover of the three-stage steam turbine (HP, IP, and LP). Each stage the turbines was represented with the ellipse law with design conditions reported by Lucquiaud [9]. The flue gas from 100 MWe coal- fired power plant enters the absorber with 13% CO_2. Figure 1 gives the flow sheet of the absorption/stripping process with specified design conditions.

3. Steady state and dynamic optimization

This work uses power plant profit (\$/hour) as the objective function for steady state and dynamic optimization:

$$profit(\$ / hr) = Elec.price(\$ / kWh) \times Elect.gen.(kW) + CO_2 price(\$ / ton) \times removedCO_2(ton / hr) \quad (1)$$

Where the electricity generation is the total work produced by steam in the power cycle, minus lost work due to CO_2 capture and compression. It is also assumed that the total work produced by steam is only a function of total steam rate in the steam cycle and varies proportionally with that variable. The influence of factors such as turbine inlet/outlet conditions is neglected. Equation 2 calculates the lost work of CO_2 capture and compression:

$$W_{lost} = 0.75 Q_{reb} \left(\frac{T^{sat}(P_{ext}) - T_{sink}}{T^{sat}(P_{ext})} \right) + W_{comp} + W_{pumps} \quad (2)$$

The FEASOPT method in ACM® was connected to the steady state model of the MEA plant and operated at steady state to maximize the profit by adjusting the lean loading and CO_2 removal. Other independent process variables were set at their design specification as shown in Figure 1. Optimization was performed with the ratio of CO_2 price to the electricity price varying from 2 to 7(\$/ton CO_2)/(cents/kWh)). This steady state optimization provides optimum design curves for lean loading and removal as a function of price ratio.

Dynamic optimization was used to find optimum operating curves for manipulated variables to maximize the final power plant profit as the disturbance occurs. Four valves (figure 1) were used to control. The valve on the lean solution is manipulated to control the reboiler level. The other three valves regulate the steam rate, solvent rate, and the stripper vapor rate. The operating curves provided by dynamic optimization give the optimum final values of the controlled variables so that they can be used to establish a set point.

The FEASOPT method performed multivariable dynamic optimization and ultimately optimized the set point paths of steam rate, solvent rate, and stripper pressure simultaneously over a range of variations in disturbances for two dynamic scenarios:

1. Partial steam load operation in flexible capture with a price ratio of 2 to 5.
2. Partial boiler load operation in a variable load power plant with the same simultaneous relative decrease in both flue gas rate and power cycle steam rate up to 70% of the full load.

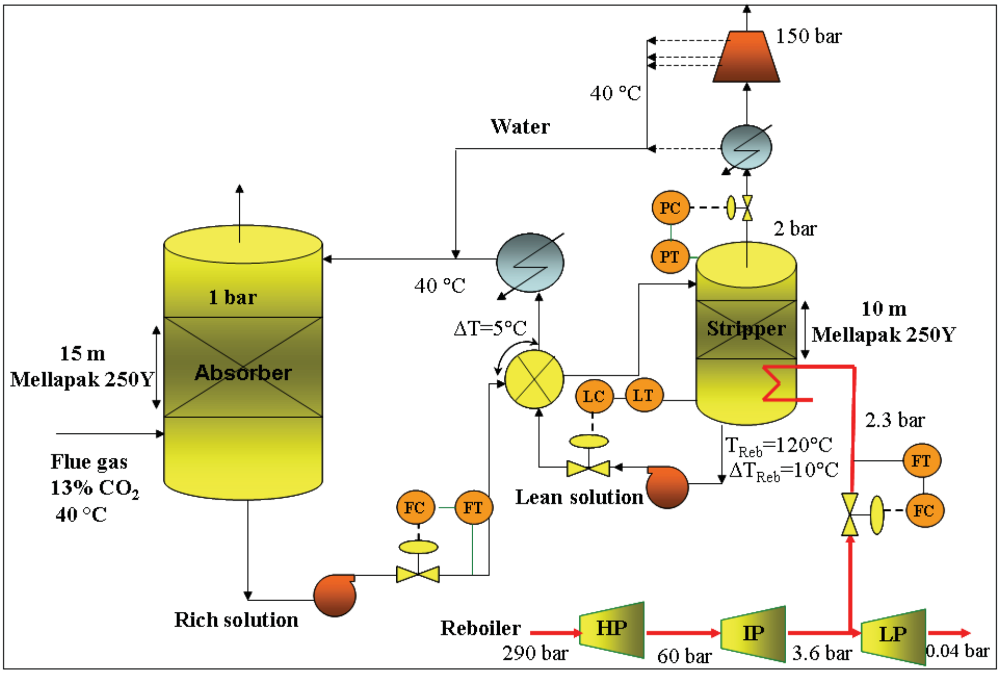

Figure 1: MEA absorption/stripping integrated with power cycle and CO_2 compression system along with control valves

4. Results and Discussion

4.1. Optimization in Response to the Price Ratio

Steady state optimization was performed to optimize design variables (lean loading and CO_2 removal) for different values of price ratios. Then dynamic optimization was carried out for a case study designed at a specific point on the optimum design curve (price ratio = 2.6, removal = 90.1%, lean loading = 0.225) to find the optimum operating curve as the price ratio varies. This means that if the controller set points move on the optimum operating curves as the price ratio varies, we can make the highest profit at the new steady state condition. Figure 2 illustrates the design and operating curves of CO_2 penetration versus price ratio. CO_2 penetration is defined as the fraction of the CO_2 in the flue gas that is released to the atmosphere:

$$CO_2\,penetration = 1 - CO_2\,removal \qquad (3)$$

As shown in Figure 2, for price ratio of 2 to 3 the rate of the reduction is much higher relative to the higher price ratio. The design curve shows a large change around price ratio = 2.1, which means that there are two local optima around this point, at 53% and 70% removal. The optimum operating curve deviates from the design curve specifically when the new price ratio is higher than the initial price ratio because of using different specifications in steady state and dynamic simulation for the liquid level in the absorber sump. Even at the design point (price ratio = 2.6) the optimum operating point does not lie on the design curve. No significant deviation is seen between the design and operating curves for lean loading for the selected case study (Figure 3).

Considering the design curve, at medium and high price ratio where the system is designed at removal higher than 70%, the optimum lean loading is lower than 0.25, while at low level of removal (≤ 53%), the optimum lean loading greater than 0.39. Figure 4 illustrates how the optimum lean loading moves from low to high as removal increases. Comparing the equivalent work curve of 90% removal to 70% and 53%, we can see a flat minimum area at lower removal so that the global minimum can easily change from low to high as the removal varies slightly. That is why the optimum lean loading changes significantly around price ratio = 2.1.

One of the variables that was optimized during dynamic optimization is pressure at the top of the stripper. The results suggest that in order to stay on maximum profit and minimum energy lost, the pressure valve should be kept wide open and the stripper pressure should be allowed to drop as the steam rate reduces.

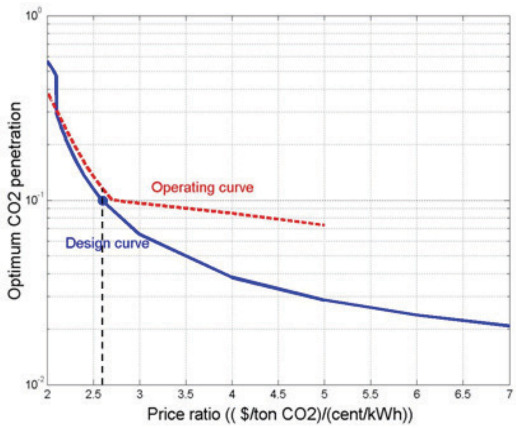

Figure 2: CO_2 penetration at the optimum design and operating conditions, H_{abs}=15m, H_{strip} = 10m, cross heat exchanger ΔT_{design} = 5°C, reboiler ΔT_{design}=10°C, reboiler T_{design} = 120°C, τ_{sumps}=2 min

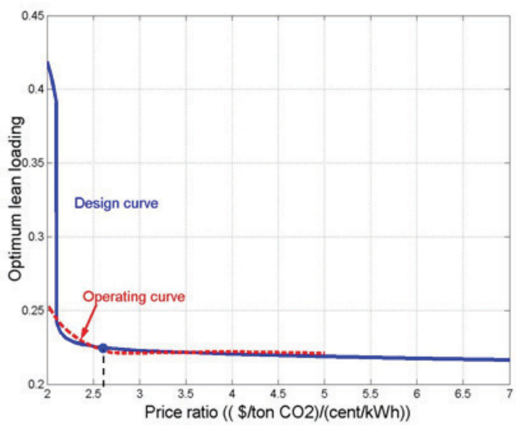

Figure 3: Lean loading at the optimum design and operating conditions, H_{abs}=15m, H_{strip} = 10m, cross heat exchanger ΔT_{design}=5 °C, reboiler ΔT_{design} = 10°C, reboiler T_{design} =120°C, τ_{sumps} =2 min

At the optimum operating conditions the optimum solvent rate is a linear function of the steam rate. Although the slope of the line deviates slightly from one, we can use a ratio control on the steam rate and solvent rate and still stay close to the optimum path. (Figure 5)

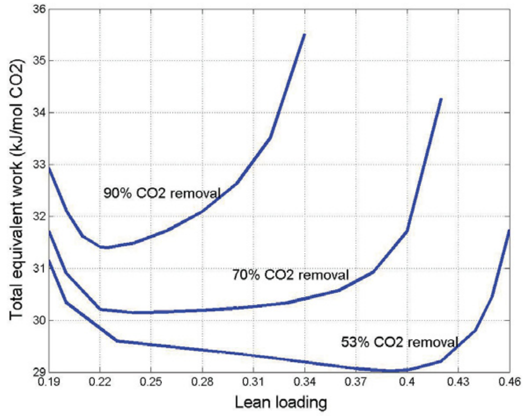

Figure 4: Capture total lost work versus at optimum design conditions, H_{abs}=15m, H_{strip} = 10m, cross heat exchanger ΔT_{design} = 5 °C, reboiler ΔT_{design} = 10 °C, reboiler T_{design} = 120 °C

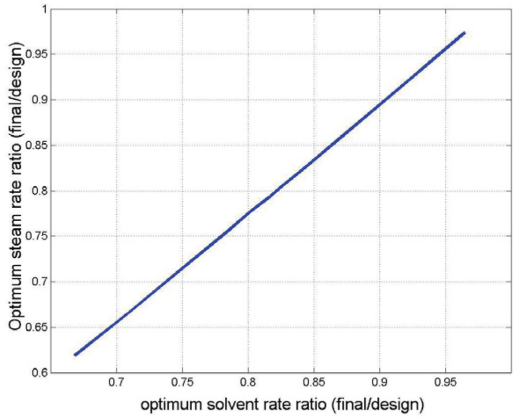

Figure 5: Steam flow at optimum operating conditions, plant designed at price ratio=2.6 (removal=90% and lean loading=0.225), H_{abs}=15m, H_{strip} = 10m, cross heat exchanger ΔT_{design} = 5 °C, reboiler ΔT_{design} = 10 °C, reboiler T_{design} =120 °C, τ_{sumps} = 2 min

4.2. Optimization in Response to the Partial Boiler Load Operation

When the boiler load decreases, the flow of flue gas directed to the absorber and total steam rate entering the first stage of steam turbine decreases. Variation of steam rate in the power cycle leads in changing the rate and the pressure of extracted steam entering the reboiler, which can influence the stripper operation. In the simulation, we assumed that both flue gas rate and total steam rate vary proportionally with the boiler load.

The simulation and optimization of this dynamic scenario is performed for the plant designed initially at 90.1% removal and 0.225 lean loading. As in partial steam load operation, optimizing the pressure shows that keeping the pressure valve always wide open. Therefore allowing the stripper pressure to drop with decreasing steam rate is the most energy efficient and profitable strategy for partial boiler load operation.

Figure 6 indicates that optimum steam rate and solvent rate vary linearly with the boiler load. The deviation of the slope of the solvent rate from 1 is slightly more than steam rate. Since the deviation of slopes of solvent and steam rates are not significant, placing a ratio control among flue gas rate, steam rate, and solvent rate will keep the plant close to the optimum path.

Both optimum removal and lean loading increase as boiler load decreases (Figure 7). From a process control perspective, the current results indicate that keeping L/G constant in both absorber and stripper is a control strategy that enables the plant to run close to the optimum path during variable load operation of power plant.

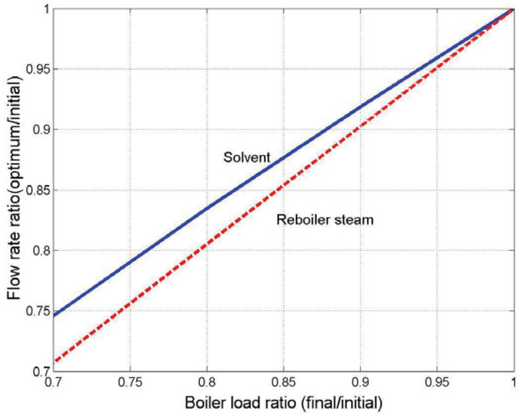

Figure 6: Optimum steam rate and solvent rate (normalized by initial rates) with variable boiler load, H_{abs}=15m, H_{strip} = 10m, cross heat exchanger ΔT_{design} = 5 °C, reboiler ΔT_{design} = 10 °C, reboiler T_{design} = 120 °C, τ_{sumps} = 2 min

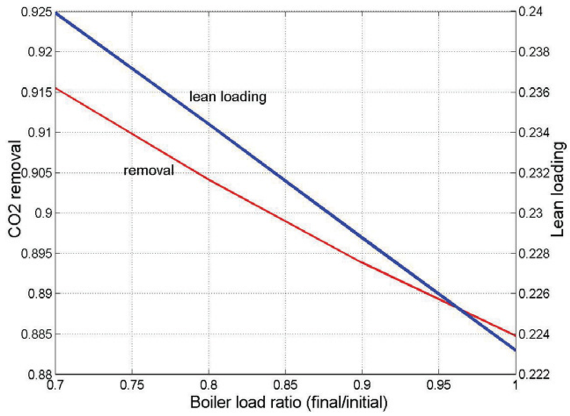

Figure 7: Optimum CO_2 removal and lean loading with variable boiler load, H_{abs}=15m, H_{strip} = 10m, cross heat exchanger ΔT_{design} = 5 °C, reboiler ΔT_{design} = 10 °C, reboiler T_{design} = 120 °C, τ_{sumps} = 2 min

5. Conclusions

The dynamic model of the absorption/stripping process was integrated with the first order approximation model of the power plant steam turbines. By doing so, the variation of steam pressure at the IP/LP crossover point is taken into account in dynamic simulation. After implementing the multivariable steady state optimization tools of ACM®, power plant profit was maximized to optimize lean loading and CO_2 removal at different values of price ratio (CO_2 price/electricity price) for design purposes. As a result, for price ratio between 2.1 and 7, the plant should be designed at removal between 70% and 98% and lean loading in the range of 0.22–0.25. For a price ratio lower than 2 , the plant should be designed at high lean loading (≥ 0.39).

Two important operational scenarios were dynamically simulated: partial reboiler steam load and partial boiler load operations. After implementing the multivariable dynamic optimization tools of ACM® to maximize profit, solvent rate, steam rate, and stripper pressure were optimized. The results show that for both scenarios, keeping the pressure valve wide open and allowing the stripper pressure to swing is found to be the most profitable strategy. For reboiler steam partial load operation, a linear relationship exists between the optimum solvent rate and reboiler steam rate with the slope very close to 1. For boiler partial load operation, a linear relationship exists between the optimum solvent rate and reboiler steam rate with the boiler load (or flue gas rate). The slope of the line is relatively close to 1. This significant observation leads to a practical application in which the ratio control between the solvent rate and steam rate in scenario 1 and ratio control among the solvent rate, steam rate, and flue gas rate in scenario 2 can be proposed as optimum strategies in response to the discussed disturbances.

6. Acknowledgments

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7. References

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