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Investment decision of monoethanolamine based post combustion CO₂ capture plant via application of control strategies

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Abstract. The abatement of anthropogenic CO₂ gas and extensive demand for electricity has motivated cleaner power production from fossil fuels. Monoethanolamine (MEA) based post combustion CO₂ capture plant (PCC) is a promising and mature technology to realize large scale cuts in carbon emissions at national and global levels. A carbon capture plant features non-linearity and multifaceted process interactions, therefore presents operational challenges requiring robust control strategies to ensure optimal but flexible operation of the plant as it responds to variable power plant output. This paper investigates two control strategies (viz, conventional feedback (PID) control and model predictive control (MPC)) with the control objective being formulated as economic functions around CO₂ emissions (US\$/t-CO₂) and operational cost (US\$/d). This presents a management capability to the power plant operator unlike the commonly used operational (technical only) objective of maximising CO₂ capture (CO₂%) at a given setpoint in conjunction with plant net energy performance (EP_n). This economics-based formulation in the control strategy together with a demonstrated stability analysis fits well into plant-wide control implementation of MEA based PCC plants and supports cleaner production of electricity while helping such operation economically viable. It can be seen that embedment of MPC into PCC plant features attractive economic value (positive investment decision) based on the two above criteria. Whereas, CO₂ emission cost and operational cost exhibit 30% and 60% of cost saving compared with the deployment of PID controller.

1. Introduction

Carbon capture and storage (CCS) is one of the essential systems to mitigate the CO₂ emission in a short to medium term. It is predicted that around 17% of the total CO₂ mitigation will be contributed by CCS technology by the year 2035 [1]. Post combustion CO₂ capture (PCC) is one of the matured CCS technology being deployed globally. Nevertheless, PCC plant features dynamically responsive process and multifaceted interactions thus require implementation of advance and robust control strategy to ensure stable and feasible operation under the unprecedented plant perturbation [2, 3].

Several studies have been done related to the PCC-plant wide control targeted two significant variables which include CO₂ capture rate [2-9] and specific energy penalty [2, 4, 6]. [4] and [5] employed



proportional, integral and derivative (PID) feedback controller and feed-forward controller to overcome servo problem in PCC plant, respectively. On the other hand, [7] used model predictive control (MPC) algorithm to flexibly control the performance of PCC plant subjected to servo (CO₂ capture rate) and regulator (variation in flue gas flowrate) problems. Similarly, [6] designed and embedded nonlinear MPC into actual PCC pilot plant to obtain maximum capture rate concurrently to maintain minimum consumption in reboiler duty. Whereas, [9] developed nonlinear MPC for the PCC absorber column to evaluate performance indices of MPC subjected to the plant upstream perturbation. Additionally, recent studies have explored application of intelligent control such as artificial neural network algorithm to adapt with the operational flexibility of PCC plant and dynamic control of the process [3, 8].

This work extends existing control studies of PCC plant from managerial perspective by evaluating economic feasibility (e.g. investment decision) of the plant embedded with an advance control strategies. Two control scheme (*viz.*, conventional feedback (PID) control and model predictive control (MPC)) are designed based on the economic functions such as CO₂ emissions (US\$/t-CO₂) and operational cost (US\$/d). This presents a management capability to the power plant operator unlike the commonly used operational (technical only) objective of maximizing CO₂ capture (CO₂%) at a given setpoint in conjunction with plant net energy performance (EP_n). Thus, fill in the research gap in this PCC plant-wide control area.

2. A reduced PCC model

A reduced model of PCC plant is attained by using a non-linear autoregressive with exogenous input (NARX) technique. The model is adopted from the study conducted by [4] and presented as a 4 x 2 system implemented in Simulink Matlab workspace. The input variables encompass of flue gas flow rate (u_1), CO₂ concentration in flue gas (u_2), lean solvent flow rate (u_3) and reboiler heat duty (u_7) as illustrated in Figure 1(a). Meanwhile, the output variables consist of CO₂ capture (CO₂%) and net energy penalty (EP_n) which derived from Equations 1 and 2 respectively. Comprehensive explanation on the development and viability of PCC model can be referred to [4].

$$\text{CO}_2 \text{ capture, (CO}_2\%) = \frac{(y_4/100) * y_5}{(u_1 * u_2)/100} \times 100\% \quad (1)$$

$$\text{Energy penalty, EP}_n \text{ (MJ/kg)} = \frac{(u_7) \div 1000}{(y_4/100) * y_5} \quad (2)$$

Where, y_4 and y_5 are CO₂ concentration in the stripper top and top stripper flow rate respectively. Detail of inputs-outputs model can be obtained in [4].

3. Design of control strategies

3.1. Stability analysis

The adopted PCC model is a nonlinear model (discrete-time dynamic model) exhibits intricate differential equations. Therefore, it is difficult to evaluate the nonlinear stability analysis which demands a high degree of mathematical insight and competence. Thus, the model is linearized to determine stability criterion based on the poles coordination. As can be seen in Figure 1(b), all discrete poles lie inside the unity circle which features that the system is stable and thus provides a stable response to a bounded input.

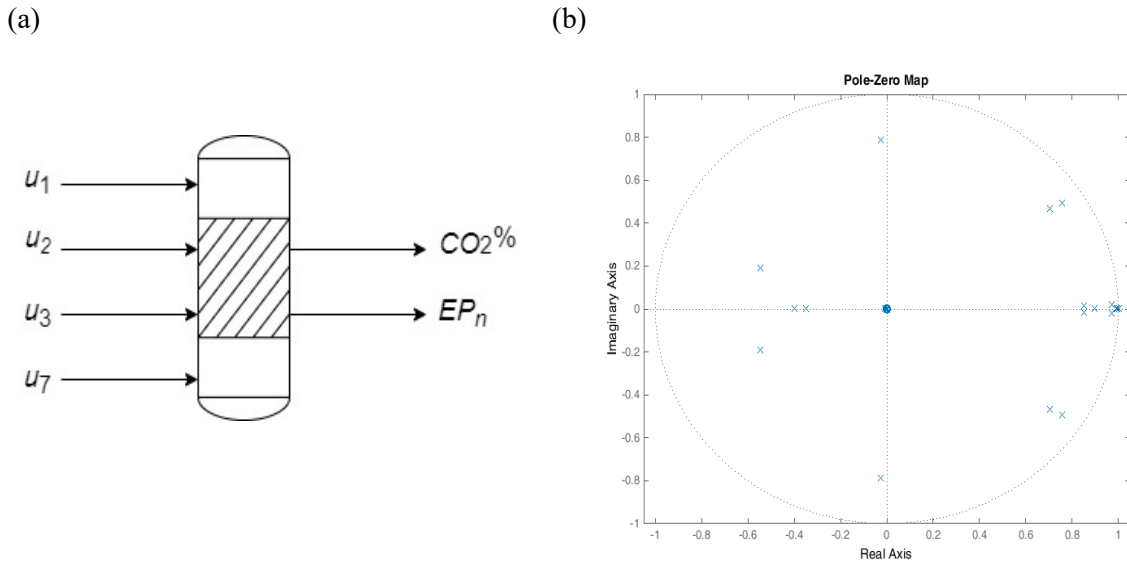


Figure 1. (a) A simplified 4 x 2 PCC model, (b) Stability analysis of PCC model

3.2. Control design analysis

Two types of control algorithms, which include PID controller and MPC are designed to ensure PCC plant is capable to capture high CO_2 emission at optimal energy performance. To achieve that, two control objectives ($CO_2\%$ and EP_n) are set at various capture percentages and at constant energy performance (4 MJ/kg) as illustrated in Figure 2. Figure 2 shows a common scenario in PPC-power plant operation where, CO_2 capture rate ($CO_2\%$) is set at various set points to reflect the amount of flue gas emissions (and also CO_2 emissions) from the power plant. At high energy demand (peak hour), more CO_2 emission will be emitted thus it is necessary for PCC plant to launch a transitory decrement of capture rate ($CO_2\%$) so that steam can be fully utilized in turbine system instead of extracting to reboiler system at PCC plant. Additionally, EP_n is controlled at optimal energy penalty at 4 MJ/kg CO_2 [10] to reflect optimum energy consumption (minimum energy penalty) used for regeneration process.

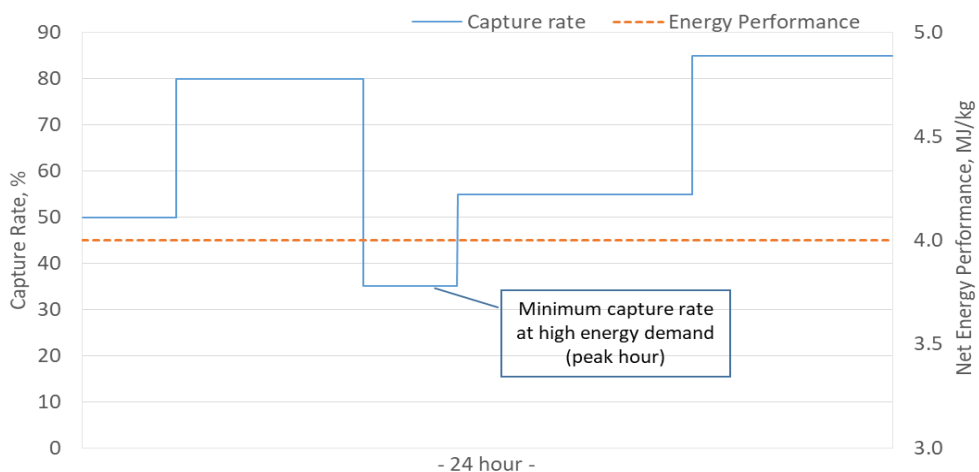


Figure 2. A hypothetical scenario of PPC-power plant operation for 24-hour operation.

3.2.1 PID controller

Two control loops based on PID algorithm are developed in PCC plant. The CO₂% and EP_n are controlled by manipulating lean solvent flow rate (CO₂%-u₃) and reboiler heat duty (EP_n-u₇) respectively as illustrated in Figure 3(a). These control pairing are adopted based on the previous studies conducted by [4]. Anti-windup scheme is employed in both PID controllers to enhance controller performance when the controller hits specified saturation limits. The controllers' parameters were auto-tuned using PID toolbox in Simulink (Mathworks, USA).

3.2.2 MPC controller

The advantage of MPC over PID is its ability to handle multiple input multiple output system without involving multiple control loops. Furthermore, MPC algorithm capable to adapt with the servo and regulator problems concurrently avoiding excessive movement of the input variables. The CO₂% and EP_n are simultaneously controlled by regulating lean solvent flow rate and reboiler heat duty as illustrated in Figure 3(b). The MPC scheme is designed and tuned using the MPC toolbox in Simulink (Mathworks, USA).

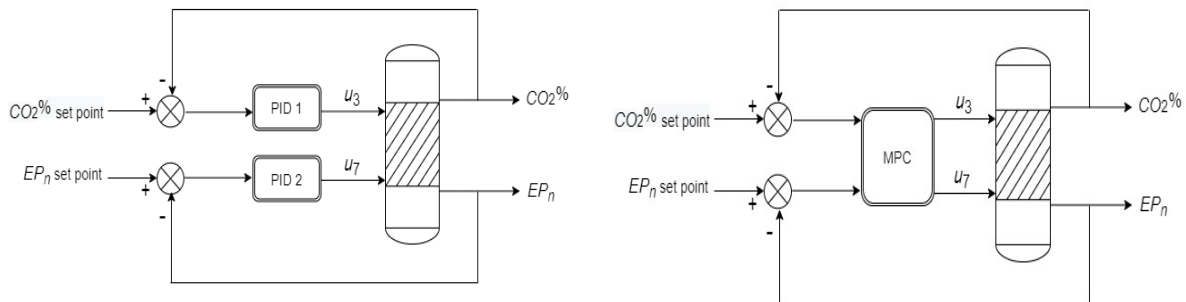


Figure 3. (a) PID control strategy (b) MPC control strategy

3.3. Investment decision analysis

Investment decision (commercial value) of the PCC plant is appraised via cost of CO₂ emissions (US\$/t-CO₂) and operational cost (US\$/d) as delineated in Equations (3) and (4) respectively.

$$CO_2 \text{ emission cost} = (100 - CO_2 \%) * C_t \tag{3}$$

$$Operational \text{ cost} = EP_n * C_e * 0.18 * 0.00028 * ((y_4/100) * y_5) \tag{4}$$

Where carbon price, C_t and electricity prices, C_e are evaluated at US\$ 14/t-CO₂ and US\$ 11.00/MWh based on the Malaysia's hypothetical market scenario (Scenario 3) adopted in [11]. Additionally, Equation (4) shows the conversion of thermal energy to electrical energy to obtain cost in US\$/d.

4. Result and discussion

Figure 4 shows PID and MPC performances in achieving PCC plant setpoints. It can be observed that MPC controller outperformed the PID controller for both CO₂% and EP_n. Where, MPC manages to stably and optimally tracking the plant setpoints without incurred significant burden to the plant operation. Contrariwise, PID only able to meet a capture rate's set point at 50% while unable to reach the allocated set points at other captures level. Similar performance exhibited in EP_n. Whereas, embedment of PID controller into PCC plant has caused sluggish and unstable operation due to highly dynamic of PCC plant and incapability of PID algorithm to overcome sudden changes of the set point. Interestingly, a fuzzy and unstable response occurs at the initial simulation time (as shown in the figure) because in the Simulink model, initial time reflects to the plant start-up. Thus, in practical, it takes a while for PID/MPC controller to adapt with the plant operation.

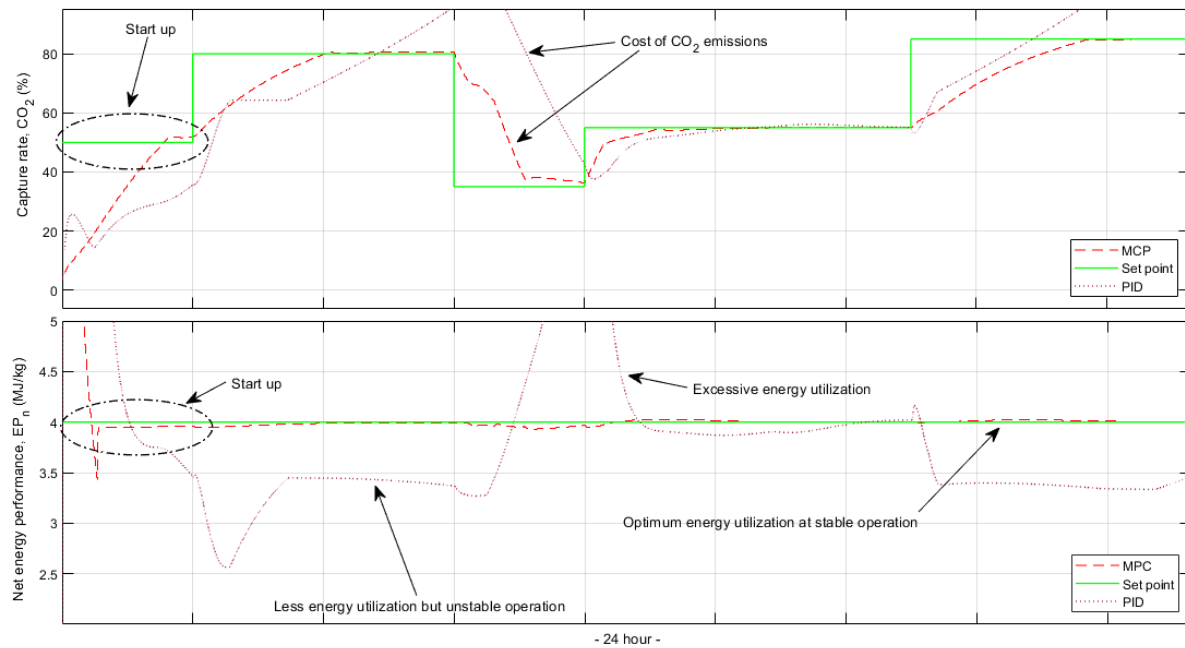


Figure 4. PID and MPC performance subjected to CO₂% and EP_n for 24-hour simulation time

Table 1 illustrates investment decision criteria of PCC plant via CO₂ emission cost and PCC operational cost. These costs are calculated based on the top/bottom outlier (exceeded the set point) which deviate from the setpoints (not meeting the set point). By means, the calculated cost shows how much PCC-power plant’s runner/owner has to pay (loss of revenue) due to the excessive emission of CO₂ and substantial utilization of energy for regeneration process. Subsequently, to identify the economic value of PCC plant to be integrated with the existing power plant. Result indicated that deployment of PCC plant embedded with MPC imposes significant cost saving compared to the installation of PCC plant embedded with PID algorithm. Whereas, CO₂ emission cost and operational cost via MPC exhibits 30% and 60% of cost saving compared to the deployment of PID controller as tabulated in Table 1. This outcome underpins the control performance of MPC scheme in term of its robustness and flexibility to optimally accommodate plant uncertainties. One should take note that the investment decision performs in this work consider cost profile during plant start up to imitate actual operation of PCC-power plant. Since, in practical, plant start up can cause significant operational burden in regard with the implementation of plant-wide control scheme. Thus, it is vital to consider plausible financial penalty at start up point to inflict real investment and economic analysis of PCC plant as one of the relevant CCS technology towards cleaner production

Table 1. Economic values (cost of CO₂ emission and operational cost) of PCC plant embedded with PID/MPC controller.

Type of controller	CO ₂ emission cost (US\$/t-CO ₂)	Operational cost (US\$/d)
PID	331,005	90,500
MPC	230,160	35,260

5. Conclusion

PCC plant emerges as one of the promising technology to mitigate excessive emissions of CO₂ especially from the fossil fuel power plant. This work analyses the significant contribution of advance plant-wide control strategy to determine investment decision of PCC plant from the investor/ managerial perspective. The result indicates that the embedment of MPC into PCC plant features attractive

economic value (positive investment decision) based on the two costs criteria (CO₂ emission cost and operation cost). MPC algorithm is able to flexibly optimize the performance of PCC plant subjected to the set point changes. Significant cost reduction is obtained from the application of MPC at 30% and 60% for CO₂ emission cost and operation cost, compared with the application of PID controller. The outcome of this work including the simulation analysis approach is useful in studying investment decisions of PCC plant from the perspective of power generator, investor and government.

6. Acknowledgement

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