Dynamic modelling and simulation of clean coal power generation

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Abstract. Retrofitting coal-fired power plant (PP) with carbon capture technology can be used as an effective transition solution towards clean coal-based energy production. Thus, this study analyses the operational/behavioural performance of retrofitting carbon capture to a coal-fired power plant (PP-PCC plant). A real-time data-driven model representing PP-PCC plant is developed in Matlab/Simulink software facility. The model simulates the dynamic response of integrated plant subjected to operational uncertainty and unprecedented perturbation. A positive variation (increment of flowrate) of air, coal and lean solvent flowrates exhibit significant dynamic responses toward the power plant load, carbon capture efficiency (*CC*) and energy performance (*EP*). Where, variation of these variables contribute to the elevation of capture percentage and improvement of energy performance. This study is beneficial for preliminary understanding of the transient variable behaviours of clean coal power generation as one of the mitigation measure to ensure proposed integration is feasible in term of environmental and economic performances.

1. Introduction

Retrofitting coal-fired power plant (PP) with post-combustion carbon capture (PCC) technology can be used as an effective transition solution towards clean coal-based energy production. Such capture-ready power plants underpin continuous utilization of coal (and other fossil fuels) for power generation over the medium and long term operations. Nevertheless, integration of coal-fired power plant with PCC exhibits operational complexity, enhanced energy penalty and reduction in power plant output. Thus, understanding the transient behaviour of integrated plant is crucial to ensure feasible and viable operations of the PP-PCC plant. Several studies have been done related to the modelling and simulation of combined coal power plant with PCC [1-4]. Coal power plant exhibited highly dynamic response compared to PCC plant when considering retrofitted operation [1]. This performance was influenced by the steam turbine extracted into high pressure turbine and preheater [2]. Moreover, integration of PP and PCC plant required higher energy demand thus affecting the steam extraction at turbine system [3]. Other study has found that the variation of lean solvent flowrate

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and steam flowrate could give significant impact to the plant start-up and shut-down [4]. Based on the existing studies, most of them were discussed related to the dynamic response of the process/operational variables. Whereby, only scarce study discussed on the environmental and energy efficient of PP-PCC plant. Thus, this study fills in the existing research by addressing these two aspects which are CO_2 capture percentage (environmental aspect) and energy performance (energy efficient aspect).

2. Data-driven modelling approach

This study demonstrates dynamic modelling and simulation of coal-fired PP integrated with PCC using Simulink Matlab. The modelling objective is to evaluate the overall plant performance in term of gross power plant load, carbon capture efficiency (*CC*) and energy performance (*EP*) of integrated plant. An innovative approach is employed is this work by using real-time plant data to develop the model. A detail description of the model development is explained in the next section.

2.1. A simplified coal-fired power plant dynamic model

In this section, an overall view of coal-fired power plant with subsystem boundaries for data driven model development are presented in figure 1. The selected subsystems are chosen based on the impacts toward downstream process which is PCC plant and also in term of power plant efficiency. To avoid excess computation in the PP model development, six major subsystem models are developed such as boiler, high pressure-intermediate (HP-IP) turbine, low pressure (LP) turbine, LP feedwater heater, deaerator and HP feedwater. Additionally, minor extraction at HP-IP-LP turbines streams and sprays attemperators streams are neglected in the model development for simplification. An empirical model of coal-fired power plant is developed using System Identification toolbox available in Simulink Matlab by employing multivariable non-linear autoregressive with exogenous input (NLARX) model structure.

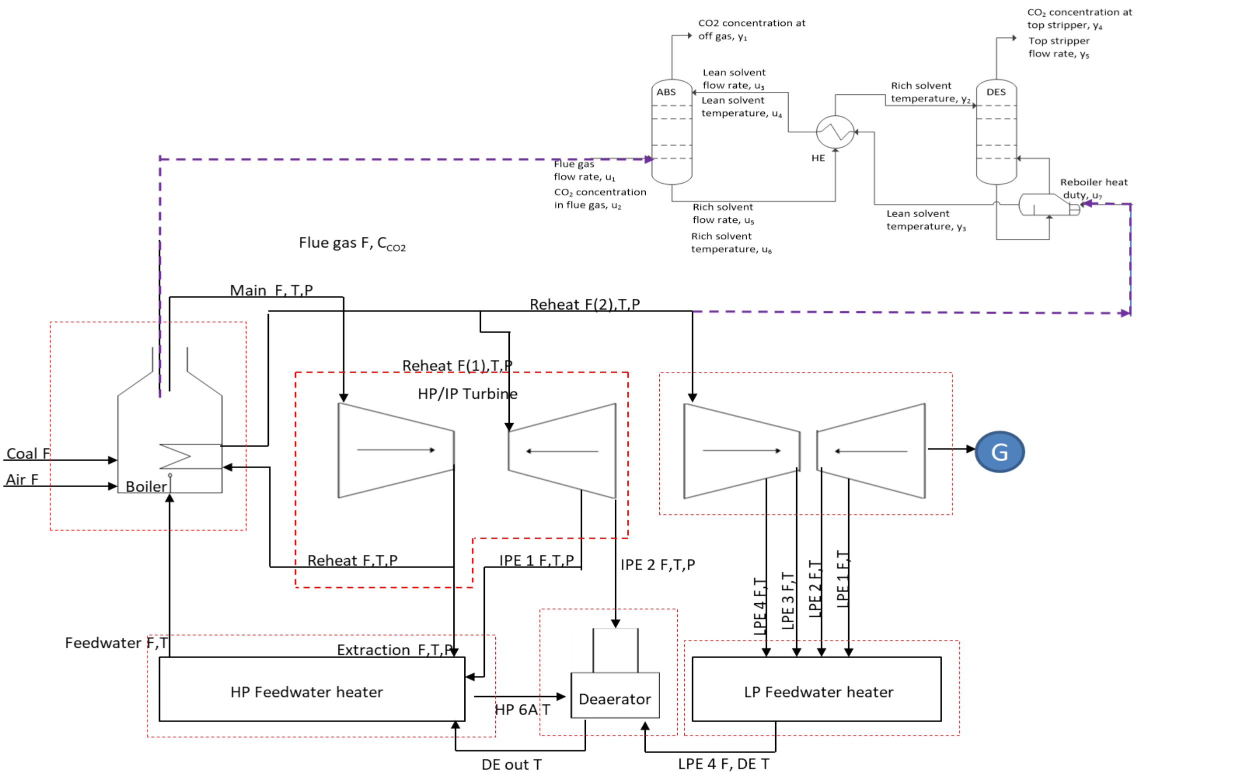

Figure 1. Clean coal power generation through integration of coal-fired PP and PCC plant. Red dash line represents the model subsystem boundaries. Purple dash line represents the connection points.

The actual 660 MW PP data were extracted from the operational data on 8/7/2013 at 6:00:00 - 8:00:00 with 1 min. interval time. Data are then segregated into two subsets, one for model estimation and one for model validation. Models validations represent power plant gross load and flue gas flowrate are depicted in figure 2. Its show that the predicted models are able to replicate actual data which confirm the accuracy and reliability of the developed PP model. After validation process, six models that have best-fit percentage at one-step-ahead prediction output at 95% confidence level are exported to Simulink workspace and linked together to produce a simplify PP nonlinear model.

(a) (b)

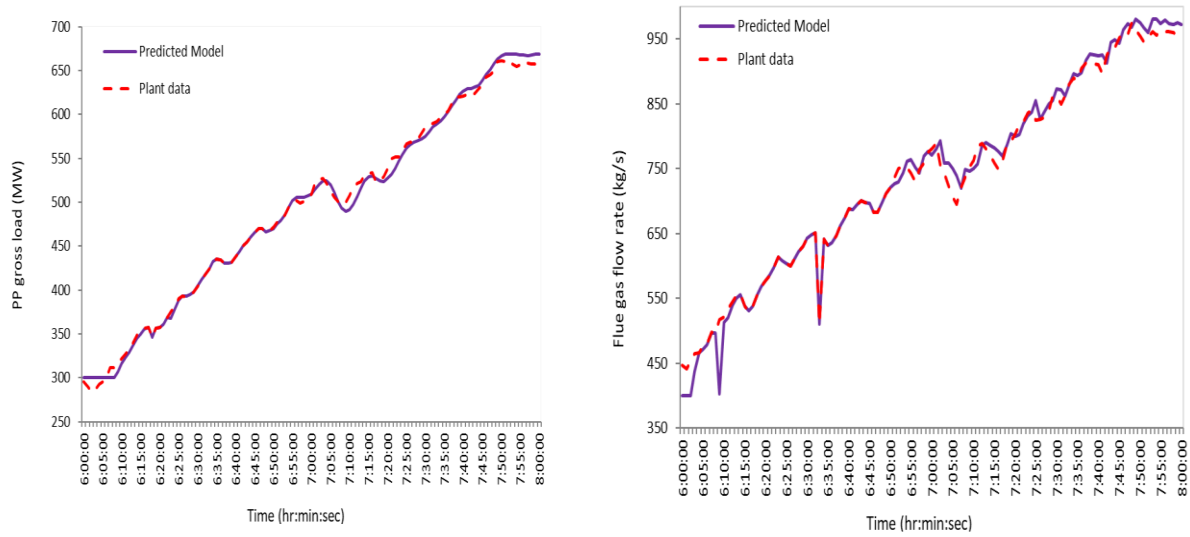

Figure 2. PP model validation for (a) power plant gross load and (b) flue gas flow rate.

2.2. A simplified PCC plant dynamic model
A simplified PCC plant model is developed by using multivariable non-linear autoregressive with exogenous input (NLARX) model structure. Details of the PCC model development can be found in [5].

2.3. Integration of coal-fired power plant with PCC plant model (PP-PCC)
Integration of coal-fired PP and PCC plant involves two connections which include flue gas flowrate and steam extraction. Flue gas emitted from the PP is fed to the PCC plant while steam used in the reboiler is extracted from the HP-IP turbine of the power plant as illustrated in figure 1. Figure 3 shows a simplified 3 x 3 PP-PCC model developed in Simulink/Matlab environment. As of preliminary study, only three significant inputs are being evaluated. While, the outputs are power plant gross load, *CC* and *EP*. Detail calculation of *CC* and *EP* are available in [1].

3. Result and discussion

3.1. Dynamic simulation analysis (open loop analysis)
As an initial study, three scenarios are analyzed to understand the operational performance of integrated PP-PCC plant which includes positive step change of coal mass flowrate, air mass flowrate and lean solvent flow rate. These positive step changes replicate the hypothetical daily operation of a PP-PCC plant. To run the open loop dynamic simulation, the process model was initialized using nominal values at this condition; coal mass flowrate rate at 75 kg/s, air mass flowrate at 400 kg/s and

lean solvent flow rate at 30 L/min. The disturbances were introduced one at a time during ten hours of simulation time and was changed independently, where one input is varied and the others remain constant. The coal mass flowrate is increased from 50 kg/s to 70 kg/s to represent the increased of energy demand (figure 4). Based on figure 4, the *E*P and *CC* responses change gradually (*EP*: reduce, *CC*: increase) at the onset of disturbance. Contrariwise, PP load increase rapidly when subjected to the positive step change. This finding supports a study conducted by Lawal et.al [1], whereby PP plant exhibits speed response compared to PCC plant in the retrofitted mode. Figure 5 shows the positive step change of air flow rate from 250 kg/s to 300 kg/s. It can be seen that the step change did not affect the PP load generation and *EP*. Contrariwise, *CC* response reduced intermittently at the onset of disturbance. The third experiment analyses the effect of lean solvent flowrate towards integrated plant. Here, we want to analyse the performance of PP load, *CC* and *EP* at constant input rate of power plant (coal and air mass flowrates). This scenario is created to imitate the actual operation of power plant during off-peak season, whereby at this period PCC plant can be operated at maximum capacity (higher CO_2 capture percentage). Based on the simulation result (figure 7), only small overshoot occurred at the onset of the step change especially for PP load and *EP* responses. At this condition, PCC plant is able to achieve maximum capture percentage throughout the simulation period.

4. Conclusion

The objective of this dynamic analysis is to assess the behaviour of retrofitting PCC plant with coal-fired power plant when dealing with operational uncertainty and unprecedented perturbation. Based on the simulation analysis, perturbation of coal mass flowrate gives significant effect to the integrated plant compared to the other inputs variables (air mass flowrate and lean solvent flowrate). Whilst, variation of lean solvent flow rate exhibits minimal impact to the integrated plant which reflects the sluggish response of PCC plant. It can be concluded that the integration of PP-PCC plant could contribute to mitigation of CO_2 emissions and enhance energy performance through the variation/manipulation of process variables. Nevertheless, installation of control strategy is required in order to achieve feasible operation. Furthermore, this present study also provides significant contribution towards achieving the Sustainable Development Goals (SDGs); SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) respectively.

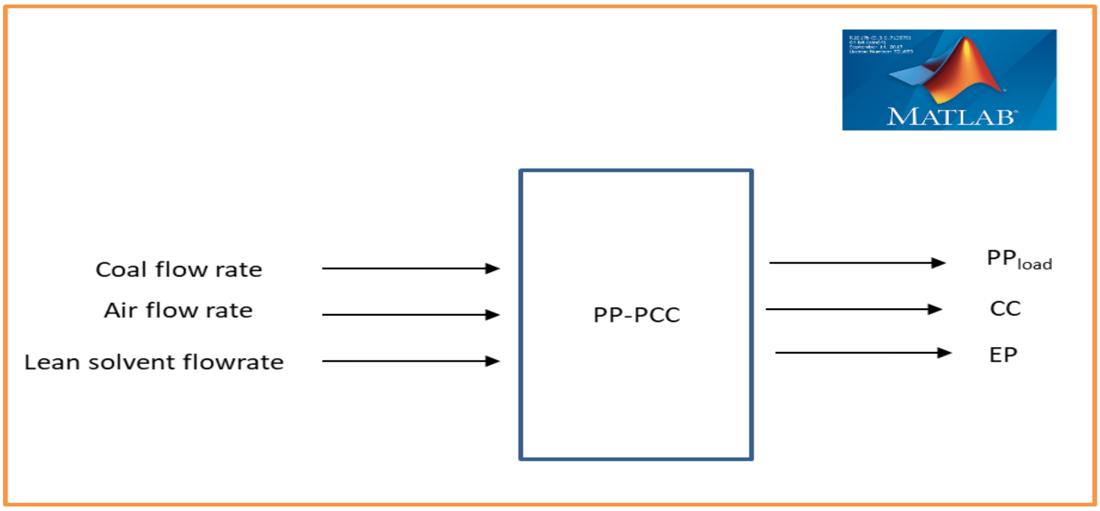

Figure 3. A simplified PP-PCC plant model in Simulink/Matlab environment.

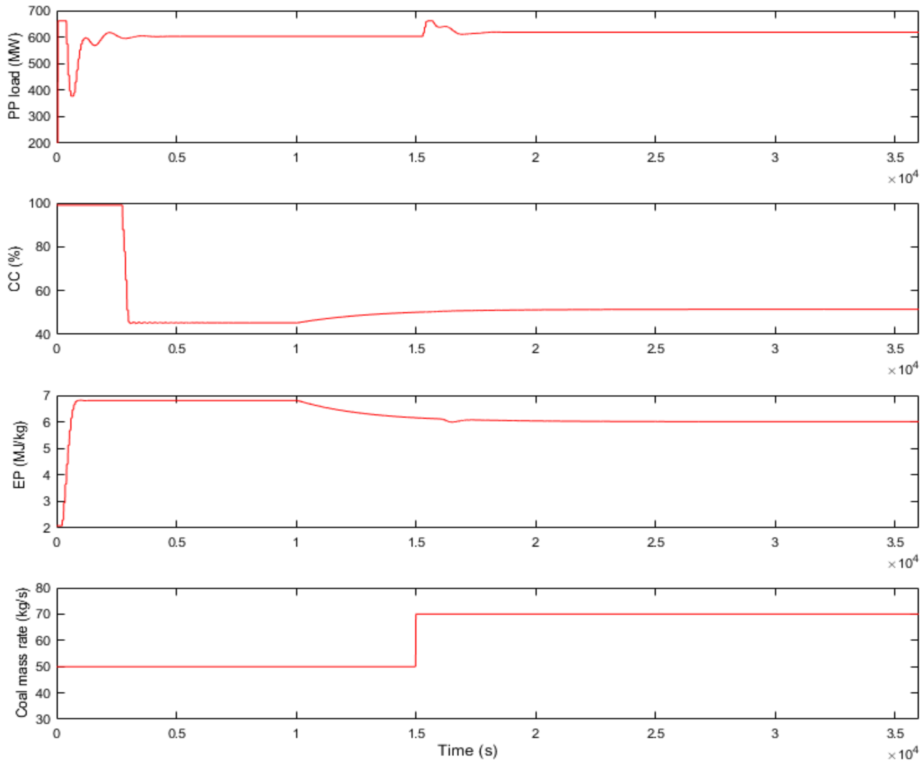

Figure 4. Positive step change of coal flow rate

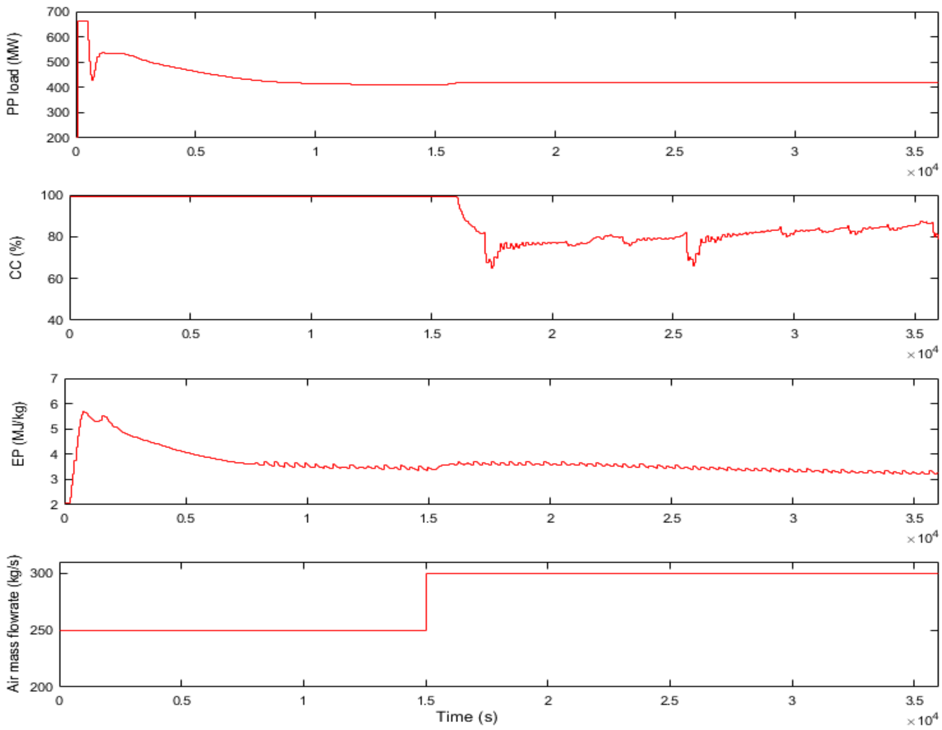

Figure 5. Positive step change of air flow rate.

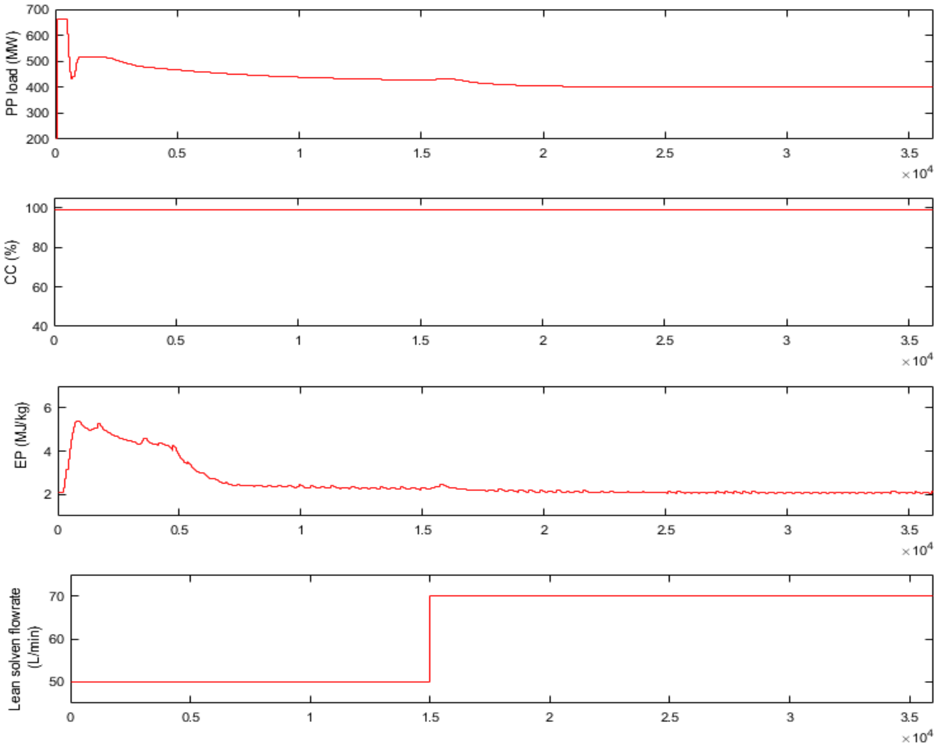

Figure 6. Positive step change of lean solvent flow rate.

References

[1] Lawal A, Wang M, Stephenson P and Obi O. 2012. *Fuel.* **101** 115-128
[2] Mircea D and Dorin B. 2014 *Procedia Technology*. **12** 723-729
[3] Elizabeth H and Gerd O. 2019 *Energy Procedia*. **1** 1019-25
[4] Marx S T and Schmitz G. 2016. *Ind. Eng. Chem. Res.* **46** 12038-045
[5] Norhuda A M, Ashleigh C, Paul F and Ali A. 2016. *J. Cleaner Production*. **113** 635-653