SEMI-BATCH CHEMICAL-LOOPING REACTORS INTEGRATED WITH COMBINED CYCLE POWER PLANTS OPERATING AT TRANSIENT ELECTRICITY DEMAND

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Abstract

Chemical-looping combustion (CLC) is a promising process for power generation with low energy penalty and in-situ CO_2 capture. In this work, we focus on the integration of high-pressure, fixed-bed CLC reactors with combined cycle (CC) power plants. We deal with the discontinuous operation of fixed-bed reactors and the dynamic simulation of CLC-CC power plants, which is nontrivial. Modern power plants have to operate in response to daily and seasonal fluctuations in power demand, and balance the electric grid input from renewable sources to maintain grid reliability. Thus, dynamic simulation and optimization of novel power plant configurations with integrated CO_2 capture functions, in response to changing fuel loads are critical in addressing the dynamicity of the electricity market. Given the complexity of the regulatory controllers implemented in a power plant, a supervisory control system is proposed to dynamically optimize the power plant efficiency. The optimal plant efficiency is estimated at 48.9% by optimizing the operation strategy of the CLC reactors. The dynamic analysis shows that the discontinuous operation of batch-type reactors only slightly affects the process efficiency and stability. Dynamic optimization is performed for the fossil-fueled power plant, demonstrating the potential of improvement in the time-averaged real-time efficiency by 1.53% points, with corresponding savings in coal consumption.

Keywords

Combined cycle power plants, Chemical-looping combustion, dynamic simulation, dynamic optimization.

Introduction

Global warming and climate change have motivated research on the mitigation of power plant emissions, specifically CO_2. The options for CO_2 mitigation include carbon capture and sequestration (CCS), energy efficiency improvements, the use of less carbon-intensive fuels, nuclear power and renewables. Renewable energy resources (wind, solar, biomass, hydro, geothermal and tidal power) are already significantly contributing to the electricity market (Keyhani, 2016). The main constraints in their extensive use are their cost, discontinuous supply, geographic dispersion, and environmental impact. Fossil fuel combustion is the primary contributor of human-caused CO_2 emissions, and will be still so in the next decades, due to the anticipated rise in electricity demand. Therefore, CCS has been a focal point of interest in recent years. Among CCS strategies, chemical-looping combustion (CLC) is a promising process that can reduce the energy penalty and cost associated with CO_2 capture. Chemical-looping combustion is a novel process for power generation from fossil fuels, with inherent CO_2 separation and low energy penalty. CLC involves the use of a solid metal oxide as an intermediate oxygen carrier, avoids the direct contact between oxygen and fuel and captures pure CO_2 without dilution. The CLC system often consists of two interconnected reactors, the air reactor (Oxidizer) and fuel

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reactor (Reducer), responsible for the consecutive reactions of oxidation and reduction of the metal oxygen carrier. CLC can be accomplished in different types of reactors and configurations, such as interconnected moving or fluidized beds, alternated fixed beds or fluidized beds, and rotating reactors (Han and Bollas, 2016a). In the configuration with two interconnected fluidized beds, the oxygen carrier transports oxygen between the Oxidizer and Reducer and a continuous production of high-temperature air can be achieved. The main disadvantages of this configuration are the additional energy used to transport the oxygen carrier and the difficulty of separation of oxygen carrier from the air stream. Fixed-bed reactors, with a stationary bed of oxygen carrier, switch between reduction and oxidation steps periodically, to intrinsically avoid the separation of the oxygen carrier from gaseous streams. The challenge in this configuration is to devise an operating strategy that controls the temperature variation inside the reactor bed.

Nowadays, power plants are subject to frequent load changes due to environmental regulations and the dynamicity of the market power demand. Extensive studies on the forecasting of power demand per market sector, have enabled operators to predict the grid load and maintain its reliability (Hsu and Chen, 2003). This enables dynamic simulation and optimization for the efficient, reliable and safe operation of modern power plants. Modern modeling tools, such as gPROMS (Process Systems Enterprise, 2014) and Modelica (Cellier, 2015), enable the simulation of these transient and discontinuous processes. For instance, Casella et al. (2012) used the ThermoPower library of the Modelica language to dynamically simulate Integrated Gasification Combined Cycles (IGCC). In previous work (Chen et al., 2016), we explored the theoretical feasibility of integrating CLC with combined cycle (CC) power plants. A system-level model was used to analyze the steady-state and dynamic performance of integrated fixed-bed CLC reactors with a CC power plant, validated against a commercial plant (Kehlhofer et al., 2009). The CLC-CC plant was estimated to reach an efficiency of 48.9% with 90% CO_2 capture. This efficiency was accomplished by optimizing the operation strategy of high-pressure fixed bed CLC reactors. The optimization problem formulation and solution is discussed in more detail in Han and Bollas (2016b). Dynamic simulation showed that the discontinuous operation of the batch-type CLC island only slightly affects the CC operation, with small oscillations of about 1%.

In this work, we present a platform for dynamic optimization of CLC-CC plants in response to time-varying fuel loads. This analysis can be used to address the dynamicity of the electricity market. An open-source, sharable and scalable virtual plant model is used to analyze the optimal plant efficiency and the stability of a CLC-CC plant with transient operations. This virtual CLC-CC plant is constrained for CO_2 capture, fuel conversion, and gas turbine temperature requirements.

Impact of renewables on the power sector

The integration of renewables into the electric grid promises to significantly reduce CO_2 emissions of the transportation and power generation sectors. Extensive programs associated with the use of renewables in the power sector, such as solar panels, wind turbines, wave power plants and biofuels, have been initiated in many countries to partially replace the load of fossil fueled power plants (Eser et al., 2016; Keyhani, 2016). The penetration of renewables will become even more substantial in the next decades. The U.S. Energy Information Administration (2015) reported that the renewable share in the U.S will grow to 18% by 2040. Eser et al. (2016) studied the effect of increased renewable generation on the operation of thermal power plants. Their work showed that the increased penetration of renewables in 2020 will result in a 4–23% increase in the number of start-ups of conventional plants. Wang et al. (2016) highlighted the importance of load self-regulation for grid stability, when the power generation system operates with a high penetration of variable renewables (solar and wind).

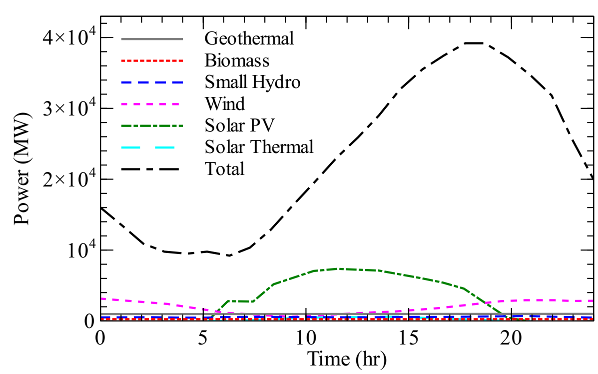

Figure 1. Power generation by renewables and total daily power demand (ISO California, 2016)

The power generation and demand in the state of California are shown in Figure 1 (here the data of the

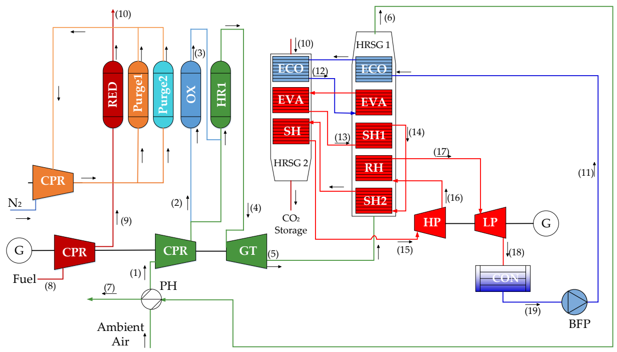

Figure 2. Diagram of the combined cycle integrated with CLC. (CPR: Compressor; G: Power Generator; GT: Gas Turbine; SH: Superheater; RH: Reheater; EVA: Evaporator; ECO: Economizer; HP: High-pressure Turbine; LP: Low-pressure Turbine; CON: Condenser; BFP: Boiler Feed Pump; PH: Preheater; OX: Oxidation; RED: Reduction; HR: Heat Removal)

day of July 24, 2016 is used as an example) (ISO California, 2016). Figure 1 shows that the power generation by renewables corresponds to 20.5% of the daily power demand (769718 MWh). Specifically, the sum of power generation by solar and wind corresponds to 14.3% of the total power demand. However, the peak production time of solar is noon, while the peak production time of wind is midnight. This phenomenon results in variations of the power generation by renewables and necessitates the transient operation of conventional power plants to balance the grid load.

In this work, data of transient power demand (along with its forecast) in the New England area was used to simulate the dynamicity of the grid (ISO New England, 2016). Previous work shows that, as the penetration of renewables becomes higher, the distributed generation will impact the dynamic performance and requirements of the power plant system. We present the basic formulation of the optimization problem that serves a supervisory control structure implemented into power plants. The supervisor optimizes the plant efficiency within constraints imposed by the local controllers, by manipulating regulatory control set points and the remaining degrees of freedom.

Integrated CLC-CC

In previous work (Chen et al., 2016), we explored the feasibility and operability of fixed-bed CLC reactors integrated with natural gas-fueled CC power plants, operating at steady state and dynamicity. The CLC-CC plant, as shown in Figure 2, was fueled with a total heat input of 431.3 MW of natural gas. The CC power plant model was firstly tuned and validated against the steady-state data of an existing 250 MW commercial power plant located in Monterrey (Nuevo Leon) (Kehlhofer et al., 2009). Then the conventional combustion chamber was replaced by a series of semi-batch CLC reactors, comprising a continuous CLC island. The CLC island consists of multiple fixed bed reactors operating in parallel. This configuration, shown in Figure 2, makes it feasible to convert the batch feeding of natural gas (for one reactor) to a continuous system. Once the reduction is complete in one reactor, fuel is fed to the next reactor. Thus, the overall exhaust of the CLC island is the mixture of the streams out of all the reactors operating at the same stage. Due to this mixing, the variations in temperature of the streams feeding the CC is minimized. The reactors operating in parallel have identical transient profiles as those presented in previous work (Chen et al., 2016), with a time delay $\theta=(\eta_{\mathrm{rct}}-1)\tau_{\mathrm{red}}$, where η_{rct} is the reactor number and τ_{red} is the reduction cycle time interval. To minimize the variation of temperature in each CLC reactor, optimization was performed to find the optimal values of the time duration for reduction, oxidation and heat removal, the air mass flow rate and preheat temperature, and the metal oxide loading. A tool chain was devised for the integration of the CLC model developed in gPROMs (Process Systems Enterprise, 2014) and the CC power plant model, developed in Dymola (Cellier, 2015). The virtual CLC-CC plant generated a relatively flat power output of 211 MW and the plant efficiency was estimated at 48.9% for a Ni-based oxygen carrier operating at a maximum temperature of 1100 °C. The dynamic simulation showed that the discontinuous operation of batch-type CLC reactors slightly affects the performance of the CC with small fluctuations of about 1% around the desired steady-state conditions.

Optimization problem formulation

The objective of the plant-level optimization problem is to maximize the net efficiency of the power plant while matching the market demand transient. This was accomplished by calculating optimal time-varying input trajectories, subject to constraints for the system operability and safety during the transition between states. The net plant efficiency was calculated as (Kehlhofer et al., 2009):

$$\eta_{net} = \frac{P - P'}{\dot{m}_{NG} LHV_{NG}}, \quad (1)$$

where η_{net} is the net efficiency of the plant, $\dot{m}_{NG}$ is the mass flow rate of natural gas, LHV_{NG} is the lower heating value of natural gas, is P the power generated, and P' is the power consumed gas compressors and water pumps.

Given that the system of regulatory controllers in power plants is complex, the design of a supervisory controller is more practical for power plant optimization. The supervisory controller manipulates the regulatory control set points and the remaining degrees of freedom, within the constraints imposed by the local controllers. Previous work (Kumar et al., 2016; Suresh et al., 2011; Wang et al., 2014; Xiong et al., 2012) showed that it is feasible to improve the plant efficiency by increasing the temperature of the superheated steam that feeds the steam turbine of the bottoming cycle. Sanpasertparnich and Aroonwilas (2009), estimated a subcritical fossil fueled power plant efficiency as high as 41.3%, by manipulating the temperature of the preheated air, the moisture content in coal, the temperature of the main steam, temperature of the reheat steam, and the pressure of the steam exiting HP and LP turbines. Tzolakis et al. (2012) performed plant-level optimization by manipulating mass flows extracted from the series of steam turbines. The results showed that a net efficiency increase of 0.55% was feasible by changing the extraction flow ratios.

In summary, the temperature of the preheated air and superheated steam, T_{SH} and T_{Air}, are common manipulated variables that can be used to improve the plant efficiency. This efficiency optimization also translates to coal consumption reduction and decrease of the plant CO_2 footprint. These admissible inputs were chosen as time-varying manipulated variables for efficiency optimization. The objective of optimization was to maximize the integral of the plant efficiency, as shown in Eq. (2):

$$\max_{\mathbf{c}(t_n)} \int_0^\tau \eta_{net}(t)dt$$

subject to:

$$\mathbf{f}(\mathbf{x}_c(t), \mathbf{c}^(t_n), w(t)) = 0 \quad (2)$$

$$\mathbf{y}(t) = \mathbf{g}(\mathbf{x}_c(t), \mathbf{c}(t_n), t)$$

$$\mathbf{c}^d(t_n) \in \mathbf{C}, \mathbf{y} \in \mathbf{Y}$$

where $\mathbf{f}$ is the system of algebraic and differential equations describing the conservation of mass and energy, $\mathbf{x}_c(t)$ is the vector of temporal state variables related to the controllers used, $\mathbf{c}(t_n)$ is the set points manipulated by the supervisory layer, $\mathbf{y}$ are the system outputs, t_n the duration for every step change, $\mathbf{C}$ and $\mathbf{Y}$ are constraint sets, τ the duration of optimization horizon, and t is the time. The regulatory controllers are PID with limited output, anti-windup compensation and set point weighting. The air is preheated by the heat of flue gas exiting the Economizer. To simplify the problem, the preheating process for feed air is not shown here, but it is feasible to control the temperature of the preheated air, by manipulating the mass flow of the Economizer exhaust gas sent to the air preheater. T_{SH} was regulated by a temperature controller, which measures the superheated steam temperature and manipulates the spray valve opening, which controls the mass flow of feedwater mixed with the hot steam. The optimization layer offers the optimal set points of controllers. The supervisory control architecture changes the set points of the local regulatory controllers, T_{SH} and T_{Air}, every hour, seeking to match an optimal input trajectory. The data used for the problem formulation is shown in Table 1. The variability range of the admissible inputs was based on common practice and previous work (Kehlhofer et al., 2009; Singer, 1991), the duration, τ, was 24 hours, and the step change time, t_n, was 1 hour.

Table 1. Inputs for the optimization problem

Admissible inputs	T_{SH}(°C)	T_{Air}(°C)
Min	500	150
Max	600	300
Temporal inputs	$t_n(hr)$	$\tau(hr)$
Value	1	24

Results and ongoing work

First, the efficiency optimization was performed for a 600 MW fossil-fueled, regenerative subcritical power plant. This plant model was tuned and validated against the data reported by Singer (Singer, 1991). The boiler operated under nominal conditions of 170 bar and 538°C. The problem formulation described in the previous section was applied, with the supervisory controller manipulating the local controller set points, i.e. T_{Air} and T_{SH}. Firstly, the efficiency optimization was performed for the full load fossil fueled power plant operating at steady state. As shown in Figure 3(a), the power plant was estimated at an optimal efficiency of 40.23% and the coal load reduction was 156 tons/day. This efficiency was accomplished by increasing T_{Air} from 200°C to 248°C, and increasing T_{SH} from 538°C to 568°C – Figure 3(b). This suggests that the plant efficiency can be improved by increasing T_{Air} and T_{SH}, which is consistent with prior work (Kumar et al., 2016; Sanpasertparnich and Aroonwilas, 2009).

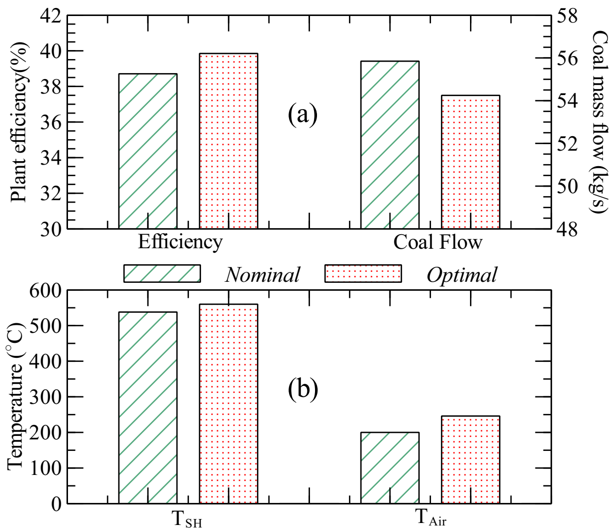

Figure 3. Steady-state optimization for a 600 MW fossil-fueled subcritical power plant

Dynamic optimization was performed for the same power plant model, but operating with changing fuel loads. The load profile was created by scaling the data for the total power demand of the New England area (maximum value ∼18000 MW) (New England, 2016), to 600 MW maximum, assuming that the power demand from one power plant is proportional to the total power consumed by the market, as shown in Figure 4(a). In particular, we chose the data of a specific day as a sample of power demand fluctuations. The forecasting of this data predicts the real-time electricity demand with an error less than 8%. A controller was implemented to enable the power plant model to satisfy the real-time power demand, by manipulating the flow rate of coal. The mass flow rates of water circulating in the plant and air mixed with the fuel were assumed to be proportional to the power load, which led to respective temporal profiles. The dynamic optimization showed that the improvement of time-averaged efficiency was 1.53% points, as shown in Figure 4(b), with corresponding savings in coal consumption of 158 tons/day, as shown in Figure 4(c). As a whole, the optimized power plant operates with higher $T_{Air}(t)$ and $T_{SH}(t)$, as shown in Figures 4(d) and 4(e). Figure 4(d) shows that the optimal temperature profile of preheated air fluctuates around an averaged optimal value of 246°C, due to slight fluctuations in the temperature of flue gas exiting the boiler. In Figure 4(e), the power plant operating at lower load has higher optimal $T_{SH}(t)$ than that when the plant is operating at higher load.

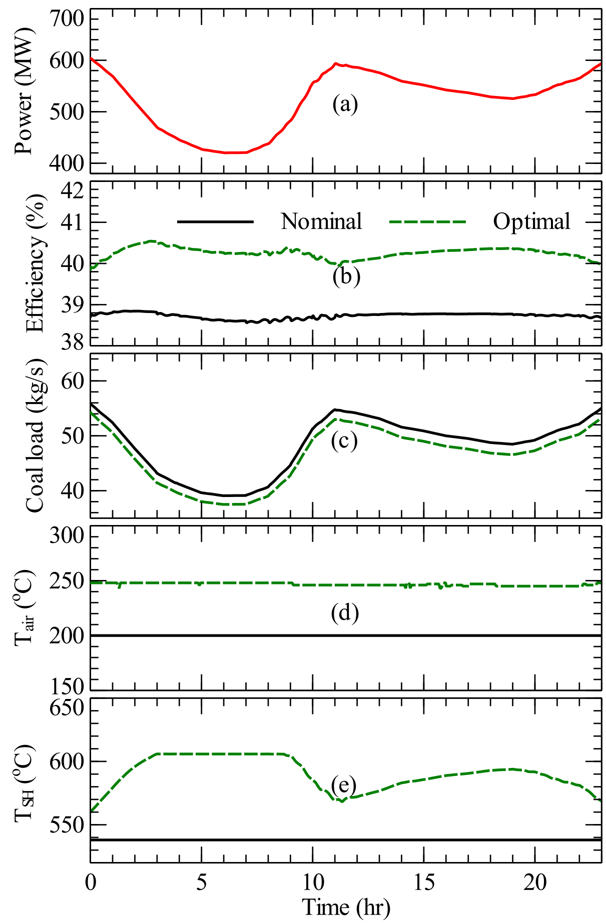

Figure 4. Dynamic optimization for a 600 MW fossil fueled subcritical power plant

Extension of this supervisory control architecture to the CLC-CC power plants discussed earlier, has the objectives of maximum plant efficiency, plant stability and safety, and profitability at minimum emissions footprint. The formulation of this optimization problem in an uncertain power market environment has not been considered before for chemical-looping plants. Plant-level CLC-CC optimization is critical because of the competitiveness of the modern power market, the various options for CCS, and the corresponding complexity in decision making with regard to pant operation. The issues of feasibility and optimality of fossil-fueled power generation with CO_2 capture is addressed in this work with targets for 90% CO_2 capture efficiency, while maximizing the thermal efficiency of the power plant ($> 48\%$ thermal).

Conclusions

Equation-oriented models were used to analyze the performance of subcritical power plants and CLC reactors integrated with CC power plants. Plant-level efficiency optimization was performed for a fossil fueled power plant at steady-state and transient operation. Steady-state optimization identified values for the preheat air temperature and superheated steam temperature that improve plant efficiency. Dynamic optimization is consistent with steady-state optimization; specifically, the optimal $T_{SH}(t)$ when the plant is operating at lower load is higher than that when the plant is operating at higher load. The improvement of time-averaged real-time efficiency is 1.53% points with corresponding savings in coal consumption of 158 tons/day. This modeling and optimization framework is extended to a semi-batch CLC-CC power plant operating dynamically in response to changing fuel loads.

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