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Flexible operation of solvent regeneration systems for CO_2 capture processes using advanced control techniques: Towards operational cost minimisation

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ABSTRACT

We present a novel approach for the control of the solvent regeneration system of amine-based CO_2 capture processes. This relies on the real-time evaluation of the cost-optimal extent of solvent regeneration at given energy and CO_2 prices. To achieve this, a multilevel, model predictive control architecture is proposed and developed for this system. The low-level control regulates the level of solvent inside the reboiler and the power supplied to the system, while the high-level control regulates the extent of the solvent regeneration in order to minimize the operating cost. This approach ensures the safe operation of the system while concurrently enhancing process flexibility. We demonstrate that this new technique can result in a reduction of up to 10% in energy cost required for solvent regeneration. A simulator tool developed in Matlab™ is available on request.

1. Introduction

For the foreseeable future, fossil fuels will continue to play an important role in providing the world's energy mix owing to their energy density, proven resource base and the established infrastructure for their exploitation and distribution (Meeting the energy challenge, 2007). At the same time, concerns surrounding changes in the climate due to anthropogenic emissions of CO_2 have resulted in a number of initiatives to reduce CO_2 emissions (IPPC, 2001). Carbon capture and storage (CCS) technologies offer a promising route to a near-term reduction in the emission of CO_2 to the atmosphere despite the continued use of fossil fuels. Globally, the largest stationary point source of CO_2 emissions is the power generation sector (Metz et al., 2006), and there has been a growing interest in developing technologies suitable for CO_2 capture from the flue gases of power stations. Technology options that are considered viable for near-term deployment can be classified as either pre-combustion CO_2 capture technologies, such as the oxyfuel process (Mac Dowell et al., 2010) or post-combustion CO_2 capture technologies, particularly the absorption of CO_2 with chemical solvents (St Clair and Simister, 1983; Rochelle, 2009).

Solvent scrubbing with amine-based solvents is currently being investigated and developed by power companies and technology providers (Rao and Rubin, 2002). In the current industrial benchmark process, a 30 wt% solution of monoethanolamine (MEA) (Kohl and Riesenfeld, 1974) is used. However, this process requires a significant amount of energy for solvent regeneration (Astarita et al., 1983). It is anticipated that the addition of this technology to a coal-fired power-plant will result in a reduction of the thermal efficiency of a modern power plant from approximately 45% to approximately 35% (Herzog, 1993). Therefore, there exists a strong imperative to reduce the energy penalty associated with CO_2 capture (Wolsky et al., 1994).

In the context of conventional chemisorption-based post-combustion capture processes, it is well accepted that the majority of the efficiency penalty is accounted for by solvent regeneration (Mac Dowell et al., 2010; Lucquiaud and Gibbins, 2011), thus there exists an important opportunity to reduce this penalty through the optimal operation of the solvent regeneration process.

There have been several recent contributions in the literature addressing the issue of control of CO_2 capture processes (Ziaii et al., 2009a,b, 2011; Panahi and Skogestad, 2011). Ziaii et al. (2009a,b, 2011) presented a dynamic, rate-based process model describing a MEA-based CO_2 capture process. They proposed dynamic operation strategies and control configurations for the solvent regeneration process aimed at minimizing energy consumption. Key contributions of their work were the observations that the liquid residence time in the reboiler was found to be the dominant factor in the response time of the system and that, at partial load, the optimal solvent rate, the energy flux to the reboiler and the boiler load are linearly related.

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Nomenclature

$\mathbf{f}_c$	the free response vector for the MIMO controller
$\mathbf{f}_p$	the free response vector for the pressure control
$\mathbf{f}_T$	the free response vector for the temperature control
$\mathbf{T}$	lower triangular matrix whose nonnull entries are 1
$\mathbf{u}$	input vector for the MIMO control
$\mathbf{w}$	setpoint vector for the MIMO control
$\mathbf{y}$	output vector for the MIMO control
$\Delta\theta_{CO_2}$	solvent regeneration ($molCO_2/molMEA$)
δ, λ	weighting constants
$\frac{\varepsilon^{HB}_{e*\alpha,MEA-CO_2}}{k_B}$	the amine–CO_2 inreaction in the SAFT-VR thermodynamic model (K)
$\mathbb{V}_{Lqd}$	the volume of liquid accumulated in the reboiler (m^3)
μ_i	the chemical potential of component i (J/mol)
ρ_L^{Out}	the molar density of the liquid in the reboiler ($mol\,m^{-3}$)
σ	the time constant of the pump model (s)
$\theta^{Lean}_{CO_2}$	the lean solvent loading in the stream leaving the reboiler ($molCO_2/molMEA$)
$\theta^{Rich}_{CO_2}$	the rich solvent stream entering the reboiler ($molCO_2/molMEA$)
a, b, c, d, e	empirically derived constants
A_c, B_c, D_c, C_c	discrete polynomials matrices of the CO_2 capture and reboiler level model
A_p, B_p, C	discrete polynomials
C_{CO_2}	the CO_2 price (€/Ton)
C_{energy}	the energy price (€/MWh)
e	zero mean white noise
$F_{CO_2,sp}$	the CO_2 capture molar flow setpoint ($mol\,s^{-1}$)
F_{CO_2}	the molar CO_2 capture flow ($mol\,s^{-1}$)
G_c	prediction matrix for the MIMO controller
G_p	prediction matrix for the pressure control
G_T	prediction matrix for the temperature control
$G_{j,k}$	transfer function corresponding to the output j and the input k
H^L_{in}	the enthalpy of the rich solvent stream to the reboiler ($kJ\,kmol^{-1}$)
H^L_{out}	the enthalpy of the lean solvent stream to the reboiler ($kJ\,kmol^{-1}$)
H^{Tot}	the total enthalpy accumulated in the reboiler ($kJ\,kmol^{-1}$)
H^V_{out}	the enthalpy of the reflux vapour stream leaving the reboiler ($kJ\,kmol^{-1}$)
J_c	the MIMO control cost function
J_p	the pressure control cost function
l^*	the level of liquid in the reboiler (m)
l^*_{sp}	the level of liquid in the reboiler setpoint (m)
L_f	the solvent inlet flow command ($mol\,s^{-1}$)
L_{in}	the molar flow of liquid into the reboiler ($mol\,s^{-1}$)
L_{out}	the molar flow of liquid out the reboiler ($mol\,s^{-1}$)
M^{Tot}_L	the total material holdup in the liquid phase (mol)
M^{Tot}_V	the total material holdup in the vapour phase (mol)
$m_{cp,24}$	amount of CO_2 captured during a day (kg)
m^{Tot}_i	the component holdup in the reboiler at time t for the component i (mol)
N	the control horizon for the pressure controller (samples)
N_c	the control horizon for the MIMO control (samples)
P^L_{out}	the pressure of the liquid stream out the reboiler (bar)
P^V_{out}	the pressure of the vapour stream out the reboiler (bar)
P^L_{in}	the pressure of the liquid stream into the reboiler (bar)
$P_{reb,sp}$	the reboiler pressure setpoint (bar)
P_{reb}	the reboiler pressure (bar)
Q, R	weighting matrices for the MIMO controller
Q_{in}	the energy added to the reboiler (kJ/s)
T^L_{out}	the liquid temperature leaving the reboiler (K)
T^V_{out}	the vapour temperature leaving the reboiler (K)
T_{reb}	the reboiler temperature (K)
v^L_{out}	the specific molar volume of the liquid phase leaving the reboiler ($m^3\,mol^{-1}$)
v^V_{out}	the specific molar volume of the vapour phase leaving the reboiler ($m^3\,mol^{-1}$)
V_{out}	the molar flow of vapour out the reboiler ($mol\,s^{-1}$)
x^{in}_i	the mole fraction of the liquid stream into of the reboiler for the component i
x^{out}_i	the mole fraction of the liquid stream out of the reboiler for the component i
y^{out}_i	the mole fraction of the vapour stream out of the reboiler for the component i

Recently, Panahi and Skogestad (2011) presented a detailed study of the control of a CO_2 capture process. Again, the aim of their work was to minimize the energy consumption in the solvent regeneration stage of the process. Their main focus was the identification of the best control variables to use. They identified three different operating regions for the process based on the inlet flue gas flow rate. They observed that the number of unconstrained degrees of freedom changes with the operating region or inlet flue gas flowrate.

Regarding control technology, since the 1990s model predictive control (MPC) has been successfully applied to a wide variety of industrial processes (Camacho and Bordons, 2004). For example, some early papers (Bezzo et al., 2005; Volka et al., 2005; Karacan, 2003) present the design and implementation of MPC strategies aimed at the regulation of distillation columns. In this work, we propose the use of model predictive control as this technique is well suited for tackling constrained multivariable input and output (MIMO) systems. We present a control strategy based on MPC technology, focusing on the reboiler system with the explicit aim of enhancing the flexibility the CO_2 capture process, whilst concurrently minimizing the operational costs.

The remainder of this paper is outlined as follows: In Section 2, we identify the methodology and the novel contribution aspect of this work. Then, in Section 3, we describe the reboiler system installed in the pilot plant unit on which the model presented in this paper is based. Subsequently, in Section 4 we describe the thermodynamic and process models used in this work. Here we also detail the steady state validation of the model performed. In Section 5 we outline the control problem we are facing and the steps we have taken to tackle it. In Section 6 we present the results of the simulations we have performed and, finally, in Section 7 we present our conclusions and identify some future directions for this work.

2. Methodology and novel contributions of this work

The key contribution of this paper is a novel approach to control the solvent regeneration system installed in the CO_2 capture pilot plant located at Imperial College London facilities. This is achieved by the implementation of a two-level control architecture which