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Packing characterization: Absorber economic analysis

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ABSTRACT

In this paper, an economic analysis of the absorber for a 250 MW coal-fired power plant was conducted. The purpose of the research is to determine the optimal design and operating conditions for the amine scrubbing post-combustion absorber. The Energy Cost (Energy) and the Annualized Capital Cost (CAPEX) for the absorber were calculated to determine the total processing cost as a function of the gas superficial velocity (u_G). To calculate the CAPEX and energy, the mass transfer properties and hydraulic data for these packings were obtained from previous experimental measurements. The minimum total cost for each packing was compared to find the lowest total cost and optimum packing.

The total cost decreases with u_G at first (CAPEX dominant) and then increases (Energy dominant). The minimum total cost represents a trade-off between CAPEX and Energy, and it is achieved at the intersection of the CAPEX region and the energy region.

The optimum operating velocity is between 50 and 80% flood for all packings, which deviates from the experience with distillation column design, usually optimized at 70–90% flood. The lowest total absorber cost from this study is given by packing 200X-H with a value of \$4.04/ton CO_2 removed.

1. Introduction

Greenhouse gas (GHG) generated by human activities is believed to be the major cause of global warming. CO_2 is the most important human-caused GHG. Amine scrubbing for CO_2 capture from coal-fired power plants is the one of the most effective ways to mitigate CO_2 emissions (Rochelle, 2009).

The majority of post-combustion technologies currently utilize a simple absorber/stripper configuration. Optimization work for the stripper side has been done by Lin and Rochelle (2014). The optimized lean loading is around 0.22 CO_2/mol alkali to give a minimum total equivalent work of 30.4 kJ/mol CO_2. The optimization work for the absorber side is needed.

Other researchers have characterized and optimized packing to achieve low pressure drop and high mass transfer efficiency for the absorber (Tsai, 2010; Razi et al., 2013; Zhang and Rochelle, 2014). However, most previous work uses mass transfer models developed in distillation systems, which are not appropriate for CO_2 absorption with amine. The earlier work also lacks thermodynamic and kinetic data for high performance solvents such as 8 m piperazine (PZ).

The objective of this work is to optimize post-combustion absorber performance with consistent packing mass transfer correlations and comprehensive PZ thermodynamic and kinetic data. Absorber total cost changes with $u_G/u_{G,flood}$ and packing geometries are explored to determine the optimum fraction flood and packing.

2. Case study and methodology

The base case system is a 250 MW coal-fired power plant with 90% CO_2 removal from flue gas containing 12 mol % CO_2. The solvent used is 8 m (8 mol/kg water) PZ because it has high reaction rate, high capacity, low volatility, and low degradation rate (Freeman et al., 2011). According to the stripper optimization (Lin and Rochelle, 2014), the total equivalent work of the regeneration process reaches a minimum at lean loading of 0.22 mol CO_2/mol alkali. Considering the solubility of the solvent, the lean and rich loadings are set at 0.3 and 0.4 mol CO_2/mol alkali in this analysis. The absorber operating temperature was controlled around 40 °C to give a low equilibrium CO_2 partial pressure which will yield a large driving force for the absorber (Dugas, 2009). The kinetic properties at the lean and rich loading were from Dugas (2009), and the physical properties were from Freeman et al., 2011. These data were

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Nomenclature

A	column cross section area, m^2
a_e	effective mass transfer area, m^2/m^3
a_P	packing physical area, m^2/m^3
C	experimental constant used in effective area correlation
$C_{CO_2,G}$, $C_{CO_2,L}$	CO_2 concentration in the gas phase, in the liquid phase, respectively
$C_{CO_2,in}$, $C_{CO_2,out}$	CO_2 concentration at the inlet, at the outlet, respectively
C_S	standard gas superficial velocity, m/s
CAPEX	capital costs, $
d	shell thickness, m
Energy	energy costs, $
F_P	packing factor, m^{-1}
G	gas flow rate, m^3/s
G_m	gas flow rate in mass unit, kg/s
$H_{T,L}$	liquid total head, m
HTU	height of transfer units, m
K_{OG}	overall mass transfer coefficient, m/s
k_2	second-order reaction rate constant, $m^3/(kmol\,s)$
k_G	gas film mass transfer coefficient, m/s
k_L	liquid film mass transfer coefficient, m/s
L	Liquid flow rate, m^3/s
L_m	Liquid flow rate in mass unit, kg/s
M	mixing point density, pts/m^3
N	equipment work rate, kW
NTU	number of transfer units
ΔP	Pressure drop, Pa
Q	volumetric flow rate, m^3/s
S	column side length, m
u_G	gas superficial velocity, m/s
u_L	liquid superficial velocity, m/s
Z_{pack}	absorber packed height, m
Z_{WW}	water wash height, m
Z_T	column total height, m
σ	surface tension, N/m
ρ_L	liquid density, kg/m^3
θ	packing corrugation angle, deg
η	equipment efficiency, %
α	installed cost factor
β	annualized cost factor
$E	Electricity price, $/MWh

used in the overall mass transfer coefficient calculation (Eq. (6)). In this work, the VLE data of 8 m PZ from Xu were used to calculate the slope of equilibrium curve ($\Delta C_{CO_2,G}/C_{CO_2,L}$) in Eq. (6) (Xu and Rochelle, 2011).

The Annualized Capital Cost (CAPEX) and Energy Cost (Energy) for the absorber were calculated to determine the total cost. The equations to calculate the CAPEX and Energy are shown in the following paragraphs. The gas superficial velocity (u_G) was set as the independent variable. All other variables, such as the column side length (S), the liquid superficial velocity (u_L), the column height (Z), the pump work, and blower work, were dependent on u_G. The column side length (S) was the square root of column cross section area (A), since a square column was used for the absorber. Thus, the total cost and minimum cost were determined as a function of u_G. Eight structured packings were analyzed in this work, and the minimum total cost for each packing was estimated. Finally, the optimum operating condition and packing for this case was determined. The base-case specifications are given in Table 1.

Table 1
Base case, 250 MW coal-fired power plant.

Parameters	Value	Units
Gas flow rate	354	m^3/s
Liquid flow rate	1.58	m^3/s
Absorber temperature	313	K
Inlet CO_2	12	Mol %
Lean loading	0.3	mol CO_2/mol alk
Rich loading	0.4	mol CO_2/mol alk

2.1. Packing cost estimation

The structured packings were made of stainless steel. The packing purchase costs as a function of surface area were estimated based on quotes from a single packing vendor. Since most of the metal structured packings have similar geometry, a general cost equation can represent them. Eq. (1) is a representation of the packing cost as a function of specific area, a_P (m^2/m^3):

$$\text{Packing purchased cost (\$)} = \text{Required Packing surface area} * \left(7.31 + \frac{203.05}{a_P}\right) \quad (1)$$

Eqs. (2)–(6) show the calculations for the required packing surface area (Kister, 1992; McCabe et al., 1993; Perry and Green, 2007). All terms in these equations are defined in the nomenclature section. The required packing surface area equals the packed volume (Z^*A) multiplied by the total surface area per volume (a_P). The packed height is given by Eq. (2):

$$Z = \text{HTU} * \text{NTU} = \frac{u_G}{K_{OG} a_e} * \ln\left(\frac{C_{CO_2,in}}{C_{CO_2,out}}\right) \quad (2)$$

The required packing surface area is:

$$Z * A * a_P = \frac{u_G * \text{NTU} * A * a_P}{K_{OG} a_e} \quad (3)$$

where A is the column cross section area, $A = G/u_G$; NTU is the number of transfer units required to obtain 90% removal. NTU can be calculated by:

$$\text{NTU} = 1.2 * \ln\frac{CO_{2,in} - CO^*_{2,in}}{CO_{2,out} - CO^*_{2,out}} \quad (4)$$

Since the equilibrium concentration of CO_2 is negligible compared to the CO_2 concentration in the gas phase, Eq. (4) can be simplified as:

$$\text{NTU} = 1.2 * \ln\frac{CO_{2,in}}{CO_{2,out}} = 2.76 \quad (5)$$

The overall mass transfer coefficient K_{OG} is given by Eq. (6):

$$\frac{1}{K_{OG}} = \frac{1}{k_G} + \frac{H_{CO_2}}{\sqrt{k_2[Am]D_{CO_2}}} + \frac{1}{k_L}\left(\frac{\Delta C_{CO_2,G}}{\Delta C_{CO_2,L}}\right) \quad (6)$$

In previous work, the effective area (a_e), liquid film mass transfer coefficient (k_L), and gas film mass transfer coefficient (k_G) have been measured and the following correlations have been developed based on the experiment data (Tsai et al., 2011; Wang et al., 2012; Wang et al., 2013):

$$k_L = 3.08E-3 * u_L^{0.72} M^{0.42} a_P^{-1.15} \quad (7)$$

$$k_G = 1.08E-2 * u_G^{0.55} M^{0.22} a_P^{-0.36} \quad (8)$$

$$\frac{a_e}{a_P} = C * \left[\left(\frac{\rho_L}{\sigma}\right) g^{1/3} \left(\frac{Q}{A} * \frac{1}{a_P}\right)^{4/3}\right]^{0.116} \quad (9)$$