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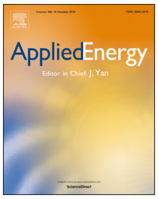

Study of intercooling for rotating packed bed absorbers in intensified solvent-based CO_2 capture process

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HIGHLIGHTS

- Absorbers using packed beds in solvent-based CO_2 capture contribute significantly to plant footprint and capital costs.
- Absorbers using rotating packed bed (RPB) with high concentration MEA reduces volume footprint.
- Fundamental question answered whether intercooling necessary in large scale RPB absorbers with high concentration MEA.
- Intercooling is necessary in large scale RPB absorbers with high concentration MEA.
- Different design options (stationary vs rotary) for the RPB absorber intercooler proposed and evaluated.

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ABSTRACT

Rotating packed beds (RPBs) are a compact and potentially more cost-effective alternative to packed beds for application in solvent-based carbon capture process. However, with concentrated monoethanolamine (MEA) (up to 70–80 wt%) as the solvent, there is a question as to whether intercooler is needed for the RPB absorbers and how to design and operate them. This study indicates that the liquid phase temperature could rise significantly and this makes it essential for RPB absorber to have intercoolers. This is further assessed using a validated RPB absorber model implemented in gPROMS ModelBuilder® by evaluating the impact of temperature on absorption performance. Different design options for RPB absorber intercoolers (stationary vs rotary) were introduced and their potential sizes and associated pressure drop were evaluated based on a large scale flue gas benchmark of a 250 MWe Natural Gas Combined Cycle Power Plant. This paper addresses a fundamental question about intercooling in RPB absorber and introduces strategies for the intercooler design.

1. Introduction

1.1. Background

CCS/CCU technology is a significant climate change mitigation technology [1]. It is considered to be vital for economically and sustainably reaching long-term mitigation targets [2,3]. The PCC process is the most matured and commercially ready approach for deploying CCS/CCU [4,5]. However, a major drawback of the PCC process is that PBs used as absorbers and strippers in the process are large [6], and this contributes significantly to plant footprint, capital, and operating costs [7]. PI technologies such as RPBs are considered to have an excellent potential to reduce the column sizes and consequently the cost and footprint of the entire PCC plant [8]. RPBs have been investigated in this regard in the literature [9–12]. These studies confirmed the potential for significant reduction in size with RPB as predicted in an earlier study by Ramshaw and Mallinson [9]. A report by HiGee Environment & Energy Technologies Inc., a PI company based in Pittsburgh USA, showed that between 1999 and 2011 about thirty-six commercial scale RPB units were installed mainly in China and other places around the world for different applications [13]. One of the installed RPBs, owned by Fujian Refining & Petrochemical Company Ltd, used for co-absorption of H_2S and CO_2 using MDEA solvent is about ten times smaller in size compared to the PB it replaced [13].

1.2. Operating principle of RPB

The RPB absorber comprises annular packed bed (rotor) mounted on a rotating shaft with the gas and liquid phases flowing counter-currently (or co-currently) in the radial direction across the bed (Fig. 1) [14]. The liquid and gas phases are subjected to intense centrifugal acceleration which is many times the gravitational acceleration in PBs.

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Nomenclature

a	effective interfacial area of packing per unit volume (m^2/m^3)
a_t	total area of packing per unit volume (m^2/m^3)
a_p^i	surface area of the 2 mm diameter bead per unit volume of the bead (1/m)
A	tangential section area (m^2) $= 2\pi rZ$; Heat exchanger area (m^2)
$C_{p,soln}$	specific heat capacity of MEA solution (kJ/kg K)
C_p	specific heat capacity (J/kg K)
d_i	tube inside diameter (m)
d_o	tube outside diameter (m)
d_e	hydraulic diameter (m)
d_h	hydraulic diameter (m) $= 4\epsilon/a_t$
d_p	effective diameter of packing (m) $= 6(1-\epsilon)/a_t$
$D_{G,i}$	gas diffusivity of component i (m^2/s)
$D_{L,i}$	liquid diffusivity of component i (m^2/s)
E	enhancement factor
F_t	log-mean temperature correction factor
G	volumetric gas flowrate (m^3/s)
G^m	gas molar flowrate (kmol/s)
h_G	gas phase specific molar enthalpy (J/kmol)
h_L	liquid phase specific molar enthalpy (J/kmol)
$h_{g/l}$	interfacial heat transfer coefficient (W/m^2 K)
h_{sol}	heat transfer coefficient for solvent side (W/m^2 K)
h_w	heat transfer coefficient for cooling water side (W/m^2 K)
H	Henry constant (Pa m^3/mol)
ΔH_r	heat of absorption (kJ/mol CO_2)
ΔH_{vap}	heat of vaporisation of H_2O (J/kmol)
k_f	thermal conductivity of MEA solution/cooling water (W/m K)
k_{app}	apparent reaction rate constant (1/s)
$k_{g,i}$	mass transfer coefficient of gas for component i (m/s)
$K_{tot,i}$	overall mass transfer coefficient of gas for component i (mol/(m^2 Pa s))
$k_{l,i}$	mass transfer coefficient of liquid for component i (m/s)
L^m	liquid molar flowrate (kmol/s)
L_m^*	liquid mass flowrate per unit tangential section area (kg/m^2 s)
L_P	path length (m)
m_{CO_2}	molar flow of CO_2 entering absorber (kmol/s)
$\dot{m}_{CW}$	cooling water flowrate (kg/s)
$\dot{m}_{fg}$	molar flowrate of flue gas (kmol/h)
$\dot{m}_{sol}$	solvent flowrate (kg/s)
M_{MEA}	molar mass of MEA (kg/kmol)
$[MEA]$	MEA solution concentration (mol/L)
N_i	component molar fluxes (mol/m^2 s)
p_{CO_2}	equilibrium partial pressure of CO_2 (kPa)
$P_{g,i}$	gas phase partial pressure of component i (Pa)
P_i^*	equilibrium partial pressure of component i (Pa)
Pr	Prandtl Number
p_t	tube pitch ($=1.25\ d_o$)
Q	intercooler duty (W)
r	radius (m)
r_i	inner radius of the packed bed (m)
r_o	outer radius of the packed bed (m)
r_s	radius of the stationary housing (m)
R	ideal gas constant (J/K mol)
Re	Reynolds number
R_t	parameter for calculating F_t for shell and tube heat exchanger
S_t	parameter for calculating F_t for shell and tube heat exchanger
T	temperature (K)
T_g, T_l	gas and liquid side temperature (K)
$T_{soln,IN}$	solvent temperature at inlet intercooler (K)
$T_{soln,OUT}$	solvent temperature at outlet of intercooler (K)
W_{MEA}	MEA concentration (wt%)
u_L	liquid velocity (m/s)
u_P	channel velocity for plate exchanger (m/s)
U	overall heat transfer coefficient (W/m^2 K)
V_G	parameter for Chen et al. gas film model $= 1-0.9\frac{V_o}{V_t}$
V_m^*	gas mass flowrate per unit tangential section area (kg/m^2 s)
V_O	volume between the outer radius of the bed and the stationary housing (m^3) $= \pi(r_s^2-r_o^2)Z$
V_t	total volume of the RPB (m^3) $= \pi r_s^2 Z$
x_i	component molar fraction in liquid phase
y_i	component molar fraction in gas phase
Z	height of the rotor (m)

Greek letters

α_{lean}	lean loading (mol CO_2/mol MEA)
α_{rich}	rich loading (mol CO_2/mol MEA
$\Delta\alpha$	$\alpha_{rich}-\alpha_{lean}$
ρ_{soln}	density of MEA solution (kg/L)
ΔP	pressure drop (N/m^2)
ΔT_{lm}	log mean temperature difference (K)
μ	viscosity (Pa s)
σ_c	critical surface tension for packing material (N/m)
σ_L	liquid surface tension (N/m)
ε	packing porosity (m^3/m^3)
ρ_G	gas density (kg/m^3)
ρ_L	liquid density (kg/m^3)
λ_L	liquid thermal conductivity (W/m K)
μ_G	gas dynamic viscosity (Pa s)
μ_L	liquid dynamic viscosity (Pa s)
ω	rotating speed (rad/s)

Abbreviations

CCS/CCU	carbon capture and storage/utilization
FG	flue gas
ICAE	international conference on applied energy
ITC	international test centre
MDEA	methyl diethanolamine
NGCC	natural gas combined cycle
PB	packed bed
PCC	post-combustion CO_2 capture
PI	process intensification
RPB	rotating packed bed
RPM	revolutions per minute

The presence of centrifugal acceleration enhances mass transfer, which occurs both in the bed and the area between the packing and the casing [15,16], and extends the flooding limits. This is the reason for the drastic reduction in packing volume in RPBs. The bed is made of packing materials which could be wire mesh [17], expamet [18] or beads [19] among others.

1.3. Problem statement

In PBs with 30 wt% MEA solution as solvent, liquid phase temperature rise in the absorber has been identified and the effects on overall performance studied extensively [21–23]. The earlier study by Freguia and Rochelle [21] showed that the liquid phase temperature