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Rotating bed adsorber system for carbon dioxide capture from flue gas

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ABSTRACT

The increasing greenhouse gas emissions from fossil fuel power plants can be reduced by capturing CO_2 from flue gases by means of adsorption, a post combustion capture method. An on-site experiment conducted at a flue gas duct of a 500 MW thermal power plant using activated carbon and zeolite samples revealed a sharp drop in the CO_2 concentration from 10.6% to 2.4%. Based on this study, a rotating bed adsorber (RBA) system following the combined principles of pressure and temperature swing adsorption is proposed as a viable CO_2 capture process. This can be fitted to the existing flue gas duct before the chimney. The RBA consists of disc-shaped adsorbent sheets with parallel passages which are divided into four sectors. At any instant, two of the sectors are exposed to flue gas, while the other two remain in the de-sorption chamber. The de-sorption chamber consists of a heating section which is maintained under vacuum and a cooling section. The effect of the RBA system on the efficiency of a 500 MW thermal power plant was also investigated.

1. Introduction

Over the past few decades, rapid economic growth has led to steady rise in consumption of electricity. In spite of developments in the field of renewable sources of energy, fossil fuels still play a dominant role in the generation of electricity. Due to this increasing dependency on fossil fuels, carbon dioxide emissions have risen significantly. As per Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, global atmospheric concentrations of carbon dioxide have increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 thereby affecting the global climate. The International Energy Agency (IEA) publication "Energy Technology Perspectives 2010" estimates that by 2050 carbon capture and storage (CCS) from power generation will reduce energy-related carbon dioxide emission by about 10%. However, in the power sector carbon capture and storage (CCS) is still an emerging technology and has not yet been successfully demonstrated at a large scale.

Carbon capture processes are being researched by using different approaches. A number of techno-economic studies had been conducted on the three principal CO_2 capture methods: pre-combustion, oxy-fuel combustion and post combustion using amine based solvents. As per the report "Cost and Performance of Carbon Dioxide Capture from Power Generation" by Finkenrath (2011) no single CO_2 capture technology excels in terms of cost and performance for coal-fired power generation. Currently all three capture options result in a significant energy penalty to the base plant. Relative net efficiency penalties of about 23% and 25% are estimated for oxy-fuel combustion method and post combustion (using amines) method respectively for coal-fired power plants.

At present, researchers are trying to develop less energy intensive processes using solid sorbents to remove carbon dioxide from flue gas of fossil-fuel power plants. Some of the sorbent materials that are being investigated include activated carbon (Menard et al., 2005; Dantas et al., 2011), zeolite sorbents (Xiao et al., 2008; Rezaei and Webley, 2009; Won et al., 2011), amine-enriched porous sorbents (Gray et al., 2005), dry carbonate sorbents (Nelson et al., 2009), potassium based sorbents (Yi et al., 2007) and metal organic frameworks (Millward and Yaghi, 2005).

The objective of this paper is to propose a novel rotating bed adsorber (RBA) system to capture carbon dioxide from high flow rate of flue gas. The proposed RBA system is based on post combustion technique. However, the system uses a solid sorbent instead of amine based solvents to capture carbon dioxide. The main purpose of using solid sorbent is to develop a less energy intensive process which has minimum impact on power plant efficiency. The

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Nomenclature

a	specific surface area per unit volume ($m^2\,m^{-3}$)
C	concentration of the adsorbate in the gas phase ($kmol\,m^{-3}$)
$\bar{C}^p$	average concentration of the adsorbate in the pores of the adsorbent ($kmol\,m^{-3}$)
d	gap between successive adsorbent sheets (m)
d_{int}	bed diameter (m)
d_p	particle diameter (m)
D	thickness of half of the section of an adsorbent sheet (m)
D_e	effective diffusivity ($m^2\,s^{-1}$)
D_h	hydraulic diameter (m)
D_K	Knudsen diffusivity ($m^2\,s^{-1}$)
D_L	axial dispersion coefficient ($m^2\,s^{-1}$)
D_m	molecular diffusivity of gas ($m^2\,s^{-1}$)
f_D	Darcy friction factor
h	convective heat transfer coefficient of heating medium ($W\,m^{-2}\,K^{-1}$)
$\bar{k}$	total mass transfer coefficient ($m\,s^{-1}$)
k_f	film mass transfer coefficient ($m\,s^{-1}$)
k_p	pore mass transfer coefficient ($m\,s^{-1}$)
L	bed length (m)
n	heterogeneity parameter
P	pressure (bar)
q_m	maximum adsorbed concentration (mol/kg)
R_p	particle radius (m)
T	gas temperature (K)
T_i	initial temperature of an adsorbent sheet (K)
T_∞	temperature of the surrounding medium (K)
U	superficial velocity ($m\,s^{-1}$)
v	interstitial velocity ($m\,s^{-1}$)
w	thickness of an adsorbent sheet (m)

Greek letters

ϵ_b	bed void fraction
ε_p	particle porosity
τ	tortuosity factor
α_T	equilibrium adsorption constant (bar^{-1})
ρ_g	gas density ($kg\,m^{-3}$)
μ_g	gas viscosity ($kg\,m^{-1}\,s^{-1}$)

Dimensionless numbers

Bi	Biot number
Fo	Fourier number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number

RBA can be retrofitted to the existing flue gas outlet duct of the power plant. The paper also showcases the several advantages of the proposed RBA system over the conventional carbon capture processes. Unlike the PSA (pressure swing adsorption) process, the RBA system operates on combined principles of pressure swing and temperature swing adsorption. Compared to the conventional carbon capture processes, the salient feature of the RBA system is the minimal effect of the process on the auxiliary power consumption and Net Heat Rate of the existing power plant. Hence, a direct substantial reduction in the cost of CO_2 capture is possible.

2. Rotating bed adsorber (RBA) system for CO_2 capture

The basic configuration of the RBA system is presented in Fig. 1(a). Implementation of the system in the power plant is shown in Fig. 1(b). The arrangement consists of an adsorbent bed mounted on a rotating structure. The rotating bed comprises of an adsorbent in the form of disc-shaped sheets with parallel passages in between for flue gas flow. The entire adsorbent bed is divided into four equal sectors. The sectors are separated from each other by a narrow gap. At any instant, half of the adsorbent bed is exposed to the flue gas in the flue gas duct for adsorption, while the other half remains in the desorption chamber.

The desorption chamber consists of two separate sections – heating zone and cooling zone. The heating section is maintained under vacuum. To reduce the load of the vacuum pump, two separate sections for regeneration are employed. The cyclic movement of the sectors of the adsorbent bed is shown in Fig. 2(a), (b), (c) & (d) respectively.

In the heating section, steam is used to provide thermal energy to the sector of the adsorbent bed maintained under vacuum for regeneration. The temperature of the sector is then reduced in the cooling section before it enters the flue gas duct again for further adsorption. Design and numerical analysis details of the heating and cooling sections are discussed later in this study.

3. Materials and methods

3.1. Experimental

The solid sorbents for the experiment were chosen after a study on the physical and chemical properties of different commercially available sorbents. The adsorbents were chosen based on the affinity for CO_2. The experiment was carried out with activated carbon and zeolite due to their following characteristics.

Activated carbon: Activated carbons present acceptable CO_2 adsorption capacities due to their large micropore volume and extremely high surface area (300 to ~4000 m^2/g). A polymodal pore size distribution provides good access of sorbate molecules to the interior. Moreover, the heat of adsorption, or bond strength, is generally lower for activated carbon than for other sorbents (Yang, 2003). As a result, relatively lower energy is required for regeneration of the sorbent. Besides, activated carbon is easily available and is relatively economical.

Zeolite: Zeolites have been widely used for separation of bulk gas mixtures and purification of gas because of their unique porous properties. The composition of zeolite can be altered to form uniform pores of a specific diameter so that it can selectively adsorb molecules with dimensions smaller than the pore size. Moreover, the cationic form of zeolite can be changed for preferential adsorption of a particular gas. In a mixture of gases containing CO_2, N_2 and O_2, the strength of adsorption on zeolites is typically in the order $CO_2 > N_2 > O_2$ (Breck, 1984) at ambient pressure and temperature. The affinity of CO_2 is due to the interaction of its large quadrupole moment with the electric field of the zeolite (Cui et al., 2003). The larger permanent quadrupole moment of CO_2 (-13.71×10^{-40} C m^2) compared to that of N_2 (-4.91×10^{-40} C m^2) and O_2 (-1.33×10^{-40} C m^2) is responsible for the higher selectivity of CO_2 on zeolites.

A cylindrical vessel was used as the adsorption chamber.

3.1.1. CO_2 breakthrough curves

A stack monitoring kit along with the vessel containing activated carbon pellets was connected through a tapping to the flue gas duct between Induced Draught (ID) fan outlet and chimney inlet as shown in Fig. 3. The properties of the adsorption bed and activated