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# Carbon capture test unit design and development using amine-based solid sorbent

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## ABSTRACT

This paper presents the design and development of a reactor system and the subsequent modifications to evaluate an integrated process to scrub carbon dioxide (CO<sub>2</sub>) from synthetic flue gas using amine based solid sorbents. The paper presents the initial system design and then discusses the various changes implemented to address the change in sorbent from a 180 μm Geldart group B material to a 115 μm Geldart group A material as well as issues discovered during experimental trials where the major obstacle in system operation was the ability to maintain a constant circulation of a solid sorbent stemming from this change in sorbent material.

The system primarily consisted of four fluid beds, through which an amine impregnated solid sorbent was circulated and adsorption, pre-heat, regeneration, and cooling processes occurred. Instrumentation was assembled to characterize thermal, hydrodynamic, and gas adsorption performance in this integrated unit. A series of shakedown tests were performed and the configuration altered to meet the needs of the sorbent performance and achieve desired target capture efficiencies. Methods were identified, tested, and applied to continuously monitor critical operating parameters including solids circulation rate, adsorbed and desorbed CO<sub>2</sub>, solids inventories, and pressures.

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## 1. Introduction

The United States emits more CO<sub>2</sub> than any other country, except China, with nearly 40% from fossil fuel-fired power plants (U.S. DOE, 2012). Successful carbon management relies on the development of cost effective methods to capture CO<sub>2</sub> from the flue gas of existing power plants (Ciferno, 2008; Pires et al., 2011; Susarla et al., 2015). Baseline studies for adding CO<sub>2</sub> capture and sequestration to existing power plants indicate that, using conventional technology, the cost of electricity would nearly double from coal fired pulverized coal power

plants (Black, 2010). CO<sub>2</sub> capture can be realized in a two-step sequestration process where CO<sub>2</sub> is first separated from product gases and then stored in geological locations within the earth. Chemical solvent based absorption systems have been utilized and studied for nearly a century and have not shown the ability to limit significant cost or loss in efficiency below target values (Burchell et al., 1997; Yong et al., 2002).

Chemical adsorption using solid sorbents has been widely investigated and considered to be a promising alternative to liquid solvents for CO<sub>2</sub> capture. The use of light weight and selective solid sorbents coated with polyamines offer potential

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cost savings over conventional liquid based systems (Fisher and Keller, 2011; Yang and Hoffman, 2009). Solid sorbents have the potential to be used over a wide range of temperatures up to 700 °C and have been shown to be less environmentally impactful, when compared to liquid adsorbents. The use of solid sorbents has the potential to reduce process costs as compared to conventional liquid based systems by reducing evaporative heat losses (Frimpong et al., 2013; Zhenisova et al., 2014). Solid sorbents with high CO<sub>2</sub> capacity and readily adsorb and release CO<sub>2</sub> can improve the cost competitiveness of these processes.

Amine sorbents have a high capacity for CO<sub>2</sub>, can be hydrophobic, and can readily adsorb and release CO<sub>2</sub> (Gray et al., 2003, 2004, 2005, 2008; Heydari-Gorji et al., 2011; Monazam et al., 2012; Samanta et al., 2012; Siriwardane, 2005). These sorbents adsorb CO<sub>2</sub> at low temperatures and release it at elevated temperatures. Scale up to utility applications requires that the solids are transported or conveyed between the adsorber and the regenerator. Fluidized bed technology appeared to be well suited for this type of thermal swing process because gas-solids suspensions can be readily transported between different reactors. Unfortunately, recent attempts to demonstrate integrated adsorption and regeneration were unable to achieve significant CO<sub>2</sub> capture during continuous flow process with an amine based sorbents. Sjostroma et al. (2011) identified multiple potential causes such as deficiencies in sorbent and operating conditions. Long term stable operation and continuous solids circulation between two fluidized beds has been reported to demonstrate a system design that allows for high CO<sub>2</sub> capture efficiency but is still limited to an efficiency lower than 90%. Factors affecting the working capacity of the sorbents, which limits the capture efficiency, are mainly due to high adsorption temperatures and short absorber residence times (Zhao et al., 2013). Recently, a system study done by Proll et al. (2016) with a double loop fluidized bed, showed reduction in sorbent circulation rates resulting in lower energy demand for the capture process. The study showed the potential of high carbon capture rates as well as low overall heat requirements through a temperature or thermal swing process. Temperature swing adsorption technology has previously shown reduction in thermal energy requirement while maintaining continuous CO<sub>2</sub> capture in circulating fluidized bed systems and bubbling fluidized beds (Veneman et al., 2012; Zhang et al., 2014).

A small scale system was designed and constructed to evaluate various solid sorbents operated in a circulating fluid bed system using a thermal swing process. The original design incorporated the hydrodynamic characteristics of a certain class of particles; however, the sorbent that was ultimately available deviated from these. Other factors were also discovered that required modification of the system. The evolution of the experimental system is traced from concept through shakedown to final configuration. The design basis is described and causes for major modifications identified. Critical process measurement and control systems were developed to improve process stability and provide real-time measurement of process performance.

Sjostroma et al. (2011) demonstrated that CO<sub>2</sub> adsorption occurs within a short section (less than 0.7 m) in the entrance of the riser. Ryan et al. (2013) and Breault and Huckaby (2013) present CFD simulations showing the CO<sub>2</sub> removal all taking place within the 0.7 m riser entrance region. As a result, the focus of this research was to further elucidate regeneration of

the sorbent in a closed loop system since adsorption had been experimentally demonstrated.

## 2. Unit design and development

A small scale circulating fluidized bed system (Carbon Capture Unit or C2U) was designed to test the effectiveness of solid amine based sorbents for use in the capture of CO<sub>2</sub> from flue gas. The original C2U design can be seen in Fig. 1 where each component is identified along with fluidization gas inlet locations marked numerically. The C2U consisted of four fluidized bed vessels: the adsorber, the regenerator, plus the upper and lower loop seals. Nitrogen was supplied at all fluidization locations and would act as a synthetic flue gas. Note that in a commercial unit, steam will replace the N<sub>2</sub> used in these test units for fluidization of the regenerator. The regenerator product gas will then consist of steam and CO<sub>2</sub>, the steam will be condensed and the remaining high purity CO<sub>2</sub> would then be compressed to be utilized or sequestered. Nitrogen and CO<sub>2</sub> were introduced to the adsorber plenum (1) and passed through a distributor plate into a fluidized bed of CO<sub>2</sub> free sorbent where CO<sub>2</sub> was captured from the flue gas in an exothermic process. A reduction in pipe diameter at the adsorber top increased exiting gas velocity and acted as a riser transporting the CO<sub>2</sub> laden sorbent. Within the adsorber, the sorbent captured CO<sub>2</sub> as particles migrated upward toward the riser inlet. Sorbent particles, with adsorbed CO<sub>2</sub>, and flue gas with reduced CO<sub>2</sub> concentration, were subsequently transported via the riser to the crossover. Particles and remaining flue gas passed through a crossover and into a cyclone where solids and gas were separated. Solid particles exited the cyclone bottom and the remaining flue gas exited the cyclone top and was vented to atmosphere. CO<sub>2</sub> carrying sorbent filled the cyclone dip-leg. Aeration (N<sub>2</sub>) near the base of the cyclone dip-leg (8) was used to move sorbent into the upper loopseal that was fluidized with N<sub>2</sub> (7). Particles then moved through the loopseal, overflowing into the regenerator.

Within the fluidized regenerator (6), solids at the regenerator top gradually moved downward as particles at the bottom were removed through the underflow. During this process, the sorbent was heated by contact with internal coils through which heated oil was circulated, releasing captured CO<sub>2</sub> in an endothermic reaction. The CO<sub>2</sub>, now in concentrated form, exited the regenerator. Particles were drained from the bottom of the regenerator at the same rate they entered the top. As the moving bed of CO<sub>2</sub> stripped sorbent reached the bottom of the regenerator it passed into the standpipe. The standpipe was aerated with stripping gas (5) and move air (4). At the L-valve, particles were transported through a horizontal pipe section fluidized with sparger gas (3) and eventually arrived at a second loopseal. As with the upper loopseal, sorbent was fed into the bottom and migrated upward to the top. Sorbent fell from the top of the lower loopseal (2) to the bottom of the adsorber, completing the sorbent circulation loop. Streams 2–4 enter the adsorber as well.

Alterations were made to the system to improve operability and solids transport as experiments progress (Fig. 2). Glass beads were successfully circulated in the original geometric design (Mod 0), however, lighter sorbent would not successfully circulate. The lower loopseal was dropped to the adsorber level and the 90° L-valve was replaced with a sweeping arc (Mod 1). Additionally, the cyclone dip-leg was shortened, effectively increasing the overall height between the bottom of the

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