



# Multiphase flow simulations of a moving fluidized bed regenerator in a carbon capture unit



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## ABSTRACT

To accelerate the commercialization and deployment of carbon capture technologies, computational fluid dynamics (CFD)-based tools may be used to model and analyze the performance of carbon capture devices. This work presents multiphase CFD flow simulations for the regenerator—a device responsible for extracting CO<sub>2</sub> from CO<sub>2</sub>-loaded particles before the sorbent is recycled. The use of solid particle sorbents in this design is a departure from previously reported systems, where aqueous sorbents are employed. Another new feature is the inclusion of a series of perforated plates along the regenerator height. The influence of these plates on sorbent distribution is examined for varying sorbent holdup, fluidizing gas velocity, and particle size. The residence time distribution of sorbents is also measured to classify the flow regime as plug flow or well-mixed flow. The purpose of this work is to better understand the sorbent flow characteristics before reaction kinetics of CO<sub>2</sub> desorption can be implemented.

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## 1. Introduction

Combustion of fossil fuels in thermal power plants is one of the largest sources of greenhouse gas emissions. In addition to promoting energy efficiency and the use of renewable energy sources, carbon capture and sequestration have also been investigated as an alternate approach to limit carbon dioxide (CO<sub>2</sub>) emissions. Post-combustion CO<sub>2</sub> capture using amine-based sorbents is considered as a candidate approach due to the technology maturity of amine-based sorbents [1–3]. However, at present, only a few pilot-scale carbon capture plants are functional, and commercial scale projects are yet to be constructed (see Wang et al. [4] and the database maintained by Carbon Capture and Sequestration Technologies MIT [5]). To accelerate development and commercialization of carbon capture technologies, computational fluid dynamics (CFD)-based modeling tools can be used to simulate and optimize the carbon capture systems. To this end, the Carbon Capture Simulation Initiative (CCSI) was established as a collaborative effort between national laboratories, universities, and industry partners in the United States to develop and deploy computational tools to promote rapid commercialization of carbon capture technologies. This work, performed as part of CCSI's efforts, presents a multiphase CFD model for simulating the flow dynamics in the regenerator unit of a conceptual sorbent-based carbon capture system.

The performance, reliability, and operating cost of the proposed regenerator unit are currently being assessed (for details, refer to Lee et al. [6]). Flow behavior in the regenerator is expected to strongly influence the CO<sub>2</sub> release characteristics of the sorbent particles, thereby affecting the overall efficiency of the carbon capture unit. At this stage, the effects of operating conditions and sorbent properties on flow dynamics in the regenerator are not properly understood. This work investigates the influence of operating conditions, such as sorbent mass holdup, gas velocity, and sorbent particle size on bed flow behavior in a regenerator design with a series of horizontal perforated plates. Because the regenerator is associated with the bulk of the energy penalty of a carbon capture unit [3,7], optimization of the regeneration stage is the critical first step toward developing commercially viable systems. Characterization of the flow dynamics in a regenerator is the precursory step before detailed and computationally more expensive chemical reaction kinetics models can be implemented.

## 2. Background

A number of recent works have presented post-combustion carbon capture systems based on chemical absorption/adsorption of CO<sub>2</sub> from exhaust flue gases [1–4,7–11]. A typical plant layout is presented in Fig. 1, although the design of individual devices and the sorbent type may vary. All carbon capture systems consist of an adsorber and a regenerator. In the adsorber (also called 'absorber'), exhaust flue gases from a power plant react with solid or aqueous chemical sorbents capable of extracting CO<sub>2</sub> from the surrounding gas phase. Details regarding solid particulate sorbents can be found in Lee et al. [12] and Mebane

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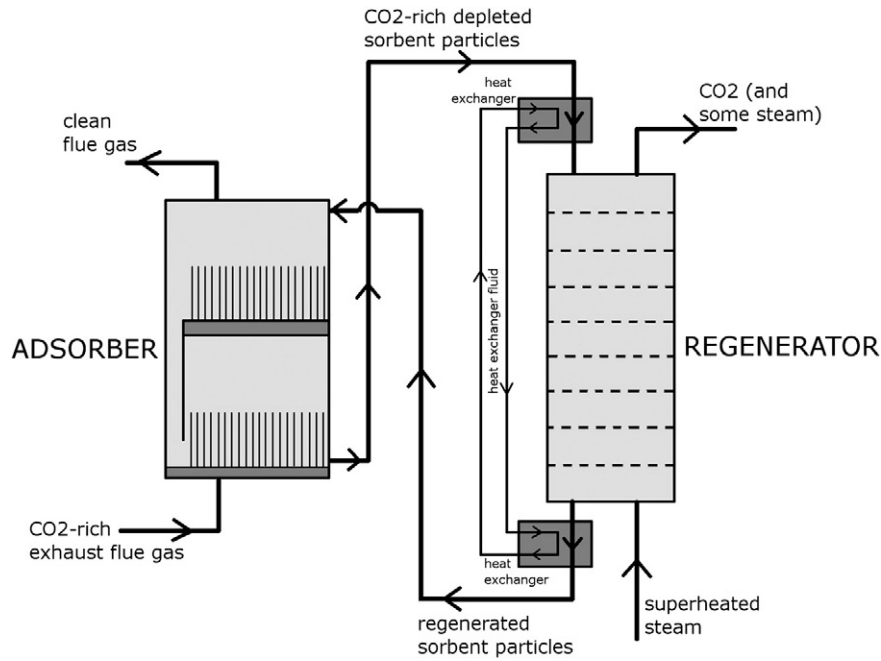


Fig. 1. Simplified schematic of the carbon capture system design proposed by the Carbon Capture Simulation Initiative (CCSI) team.

et al. [13]. After additional processing steps, the clean exhaust gases subsequently are released into the atmosphere. Meanwhile, the loaded CO<sub>2</sub>-rich sorbent is transferred to the regenerator. The regenerator (also called the ‘stripper’ or ‘desorber’) is responsible for extracting the adsorbed CO<sub>2</sub> from the sorbent through the reverse chemical reaction. The regenerated sorbent is then recycled back to the adsorber for reuse. Typically, the regenerator operates at a higher temperature than the adsorber as the CO<sub>2</sub>-release rate is larger at higher temperatures, whereas lower temperatures are more favorable for CO<sub>2</sub> capture. A heat exchange between outlet streams from the regenerator and the adsorber improves the efficiency of the capture unit.

Efforts to model the dynamic behavior of a carbon capture unit have focused on modeling the absorber and regenerator individually [1,2,8,11,14], as well as with both devices together as a complete cycle [7,9,10]. In these works, 1D dynamics models of the devices are developed based on macroscopic conservation equations supplemented with constitutive relationships available in the literature. The sorbents used are typically aqueous solutions of monoethanolamine-based compounds. The microscopic flow behavior of the aqueous sorbent in these devices is not studied and transverse variations are ignored. Often, a plug flow behavior is considered along the device height, an assumption whose validity in systems with solid sorbents, as will be shown, is questionable. The flow dynamics of sorbent particles in such fluidized bed carbon capture systems needs to be studied in greater detail.

There have been a number of experimental studies that investigate the use of solid sorbents for CO<sub>2</sub>-capture. A number of works characterize the performance of inorganic sorbents as well as newer amine-based (see, for example, Abanades et al. [15], Sjoström and Krutka [16], Gray et al. [17]). Very few studies model the flow behavior of sorbents inside the carbon capture devices. Chalermisinsuwan et al. [18] investigate the flow dynamics and reaction kinetics of an inorganic sorbent inside a closed loop capture system using CFD. They show that the capture efficiency may be improved by reducing the flow rate of CO<sub>2</sub> into the device, or by using a better sorbent. Measurements of the granular diffusion coefficients demonstrate significant axial and radial mixing of sorbents inside the devices, which limits the use of the axial plug flow model for such solid sorbent-based systems. Thus, it is important to characterize the axial mixing of sorbents in the capture devices

(as discussed in Section 4.2 of this work). A smaller-scale capture unit studied in Khongprom and Gidaspow [19], similar in design as the system in Chalermisinsuwan et al. [18], was reported to have a better capture efficiency. The improvement was attributed to better sorbent distribution and flow in the more compact adsorber.

As CFD-based studies specific to capture systems with solid sorbents are scarce, the existing literature on fluidized bed reactors may provide better understanding of the flow in these carbon capture devices. The operating flow regime strongly governs the performance of fluidized bed reactors. The fluidization regime is governed by the upward velocity of gases in the bed, often expressed as a multiple of the superficial minimum fluidization velocity  $v_{g,mf}$ . At minimum fluidization, the gas pressure drop is balanced by the weight of the bed. The minimum fluidization velocity  $v_{g,mf}$  is given by:

$$v_{g,mf} = \frac{(\rho_s - \rho_g) g d_p^2 (1 - \phi_{s,mf})^3}{150 \mu_g \phi_{s,mf}}, \quad (1)$$

where  $\rho_s$  and  $\rho_g$  are densities of the solid particles and fluidizing gas, respectively;  $d_p$  is the particle diameter;  $\mu_g$  is gas viscosity; and  $g$  is acceleration due to gravity. The bed solid volume fraction at minimum fluidization  $\phi_{s,mf}$  is assumed to have a constant value of 0.55 in this work. For beds operating in the bubbling fluidization regime, superficial gas velocities on the order of 1 to 10 times  $v_{g,mf}$  are typical. For the current regenerator, a downward axial flow corresponding to the flow rate of sorbents is superimposed on the bubbling bed, and the design is called the “moving bed regenerator” [20,21].

The mean solid volume fraction and distribution of solid particles are likely to influence the performance of the moving bed regenerator. For relating the mean solid fraction with the gas velocity and particle properties, Jamialahmadi et al. [22] suggested using the Kozeny–Carman equation or the Ergun equation. The Ergun equation [23] is expressed as:

$$\frac{\Delta P}{\Delta y} = \frac{150 \mu_g v_{g,sup} \phi_s^2}{d_p^2 (1 - \phi_s)^2} + \frac{1.75 \rho_g v_{g,sup}^2 \phi_s}{d_p (1 - \phi_s)^3}, \quad (2)$$

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