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Hydrodynamics of a Pilot-scale Dual Fluidized Bed Reactor: Cold Model Studies#

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ABSTRACT

The calcium looping (CAL) process is a cost-effective method for post-combustion CO_2 capture, using CaO as a sorbent in the carbonator and $CaCO_3$ for CO_2 regeneration in the calciner. A pilot-scale cold model dual fluidized bed (DFB) reactor system was constructed at the Waste-to-Energy Research Facility (WTERF) at Nanyang Technological University (NTU). This system includes a bubbling fluidized bed (BFB) as a carbonator to capture CO_2 from WTERF's flue gas, and a circulating fluidized bed (CFB) as a calciner to regenerate CO_2 for storage. The hydrodynamics of the pilot-scale system were investigated through a series of cold model experiments. The effects of various operating conditions—such as gas velocities in loop seals, the carbonator and calciner, and solid inventories—on pressure distribution and solid circulation rates were studied. The preliminary objective of these cold model studies was to assess the feasibility of the design for developing a hot model capable of continuously capturing CO_2 from real flue gas. The results indicated that changes in gas velocities caused variations in the pressure profile and axial solid holdup within the system. Gas velocities in the calciner significantly influenced the total solid circulation rate. Stable operation was maintained throughout the system, as determined by the pressure drop between the reactors. These studies contribute to the development of an efficient hot model for carbon capture and lay the groundwork for scaling up the calcium looping process for industrial applications.

Keywords: dual fluidized bed, hydrodynamics, calcium looping, carbon capture, cold model

1. INTRODUCTION

Increased carbon dioxide (CO_2) emissions from the industrial and energy sectors are major contributors to global warming and climate change. Efforts to reduce CO_2 emissions are crucial for mitigating the impacts of climate change. CO_2 capture, utilization, and storage (CCUS) techniques are considered effective for reducing CO_2 emissions. Among these, the CAL process is the most promising, utilizing CaO as a regenerable sorbent in a loop of carbonation and calcination cycles [1].

CAL is typically implemented using a DFB reactor system that serves as both a carbonator and a calciner [2]. These reactors enhance solid-gas reactions and improve heat transfer efficiency [3]. In the carbonator, which operates at high temperatures (650–750 °C) and atmospheric pressure, flue gas from coal-fired power plants reacts with CaO in the sorbents to form $CaCO_3$ [2]. This temperature ensures a low equilibrium CO_2 concentration (around 1% vol), allowing for fast reaction kinetics and a short residence time in the carbonator [4]. Once CaO has fully converted to $CaCO_3$, it is thermally regenerated in the calciner by heating beyond its calcination temperature (850–900 °C), where it decomposes into CO_2 and CaO. The CO_2 gas exiting the calciner is then ready for sequestration or utilization [4]. The regenerated CaO is then cycled back to the carbonator to capture more CO_2, creating a continuous loop for CO_2 capture and reuse [5].

$$CaO(s) + CO_2(g) \rightarrow CaCO_3(s), \Delta H^0_{298} = -178 kJ/mol \quad (1)$$

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g), \Delta H^0_{298} = 178 kJ/mol \quad (2)$$

Measuring hydrodynamic parameters in industrial-scale plants under hot operating conditions is often challenging, making these parameters more theoretical than practical. Among the typical techniques for studying hydrodynamics and fluid dynamics in new systems, the cold flow model (CFM) is primarily chosen as a straightforward approach to address these matters [6]. CFMs offer a versatile platform for testing operational

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strategies and design modifications before full-scale implementation. This approach reduces the risks and costs of scaling up experimental setups and ensures that potential issues are addressed early in the development process. Simulating different scenarios allows researchers to optimize reactor configurations, enhance process efficiencies, and improve the overall performance of fluidized bed systems [7]. Various experiments and parametric studies have been conducted using CFMs with different dual fluidized bed reactor configurations to study hydrodynamic behaviors under diverse conditions [8]. These studies have led to improvements in the design and operation of DFBs. [9] Liu et al. [10] investigated pressure profiles, solids recirculation flux, and gas leakage to evaluate the hydrodynamic feasibility of a DFB CFM. Yang et al. [11] developed a hydrodynamic model for the cold flow system, consisting of mixed solid particles, and predicted the pressure drop in the system. Cotton et al. [12] studied the hydrodynamics of a pilot-scale cold model of a dual fluidized bed reactor for calcium looping. They investigated the influence of solid flux, gas bypassing between reactors, and fluidization velocity on pressure profiles. Kaiser et al. [13] studied operational stability, pressure profiles, and solids circulation rate (SCR) in a lab-scale DFB cold flow system. They also explored the effects of solids inventory and gasifier-riser connection configuration on system hydrodynamics. Shrestha et al. [14] investigated hydrodynamic characteristics in a cold model of a dual fluidized bed gasifier. They examined the effects of different operating conditions, including inventory and gas velocities in reactors, on solid circulation rate and pressure drop. Investigating cold hydrodynamics of quasi-fluidized beds (QFBs) in CFMs is crucial for modeling and designing hot model reactors. Findings from cold flow experiments on QFB systems can validate results related to DFBs, such as the relationship between solid circulation rate and fluidized velocity, the impact of operating parameters on pressure profiles, and the pressure balance equation. [9]

In this study, a pilot-scale dual fluidized bed cold model was developed to explore hydrodynamic characteristics, including solid circulation rate, pressure profiles, transport velocity, and axial solid holdup distribution, within the calciner and carbonator. The aim of this research is to provide theoretical insights to ensure the reliable performance of the pilot-scale DFB cold model system and to contribute to industrial production. These experiments will enhance our understanding of the fluid dynamics and behavior of the pilot-scale DFB cold model system.

2. EXPERIMENTAL SET-UP AND METHODOLOGIES

A pilot-scale cold model DFB reactor system was constructed for this research. The system primarily consists of a BFB as the carbonator, a riser, a CFB as the calciner, cyclones, loop seals, air distributors, a standpipe, and connecting pipes. Except for the metal cyclones and air distributors, most of the system is made of transparent acrylic plastic to allow observation of operating conditions. The dimensions of the system are shown in Table 1. The schematic and experimental setup of the pilot-scale cold model DFBR system are shown in Fig. 1. Silica sand of various particle sizes was used as the bed material. The properties of the silica sand are listed in Table 1. A series of pressure sensors were installed along the BFB, CFB, riser, loop seals, and standpipe to record variations in static pressure.

Table 1. Data of The Experimental Setup

Parameter	Unit	Value
Height of BFB	mm	2500
Diameter of BFB	mm	200
Height of Riser	mm	7500
Diameter of Riser	mm	70
Height of CFB	mm	1000
Diameter of CFB	mm	180
Height of Standpipe	mm	2500
Diameter of Standpipe	mm	80
Distance between Reactors	mm	1500
Minimum Fluidization Velocity	m/s	0.076
Terminal Velocity	m/s	2.456
Average Particle Size	μm	250, 350
Particle Density	kg/m^3	2720
Geldart Group of Classification		B
Voidage at Minimum Fluidization Condition		0.44
Gas Flow Rate in BFB	m^3/hr	50
Gas Flow Rate in CFB	m^3/hr	30, 50, 70
Gas Flow Rate in Supply Chamber in Loop Seals	L/min	10
Gas Flow Rate in Recycle Chamber in Loop Seals	L/min	30

During the cold model experiments, silica sand particles were packed into the CFB, BFB, standpipe, and loop seals to specific bed heights. Fluidizing air, supplied by a forced draught blower and controlled by mass flow controllers, was introduced into the loop seals, calciner, and carbonator via air distributors at specific gas velocities. Solid particles in the BFB were transported to the CFB through the lower loop seal. Solid particles leaving the CFB and riser were collected in the cyclone and then fell into a standpipe leading to the upper loop seal. The upper loop seal controls the solid flow rate without moving parts, reducing operational issues at high temperatures. To measure the solid circulation rate from the lower loop seal to the CFB, the valve connecting these units was closed, and another exit was opened to allow particles to flow out of the system. A specific amount of sand was withdrawn and weighed over a set period, then reloaded into the system via a make-up tank to maintain the required total sand inventory for subsequent measurements. The solid circulation rate from the riser to the upper loop seal was determined by measuring the time required for the solids to fill a given volume. The initial heights of the CFB and BFB were controlled by adjusting the amount of sand fed into the riser and gasifier from their respective make-up tanks. The effects of these variables on the solid circulation rate (SCR) were then investigated. A steady state was achieved when the pressure drop in the CFB and BFB remained stable.

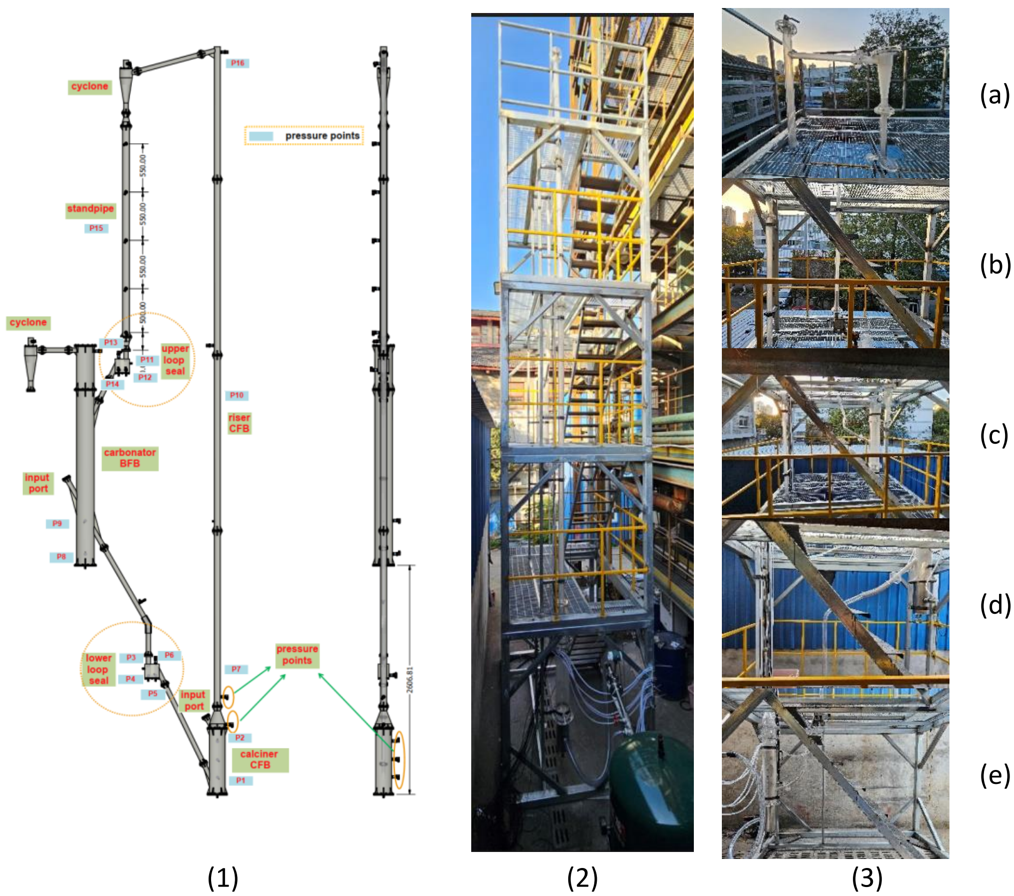

Fig.1 Design (1), Testing Bench (2) and Dfferent Components (3) of The DFBR System

3. RESULTS AND DISCUSSIONS

The voidage profile in the riser offers insights into the distribution of sand particles along its height. The effect of solids with mean sizes of 0.25 mm and 0.35 mm on voidage along the riser is illustrated in Fig. 2. Gas velocities were maintained at 50 m³/h in the bottom zone to keep the bed in a fluidized state. The lower part of the reactor was dense, while the upper part exhibited a dilute phase. The voidage in the dense zone was higher for smaller particles compared to larger ones at low gas velocities. This is because small particles embed into larger particles, reducing the overall voidage. In the riser's transport zone, the voidage increased to 0.998, with larger particles showing higher voidage than smaller particles, as shown in Fig. 2. Beyond this point, the gas flow fully developed into a dilute-phase vertical pneumatic transport system. At the top of the riser, the voidage decreased to 0.912 due to particle accumulation, as shown in Fig. 2. The voidage profile is crucial for designing calcium looping systems.

The pressure profile is a crucial design parameter, providing valuable information about sorbent particle distribution. Pressure profiles are essential for hydrodynamic testing, aiding in understanding solids and gas movement throughout the reactor. The pressure drop in the riser is typically caused by pressure heads due to gas friction, solids suspension, particle acceleration, and solids friction. Pressure profiles of the cold model at different locations and gas flows are shown in Fig. 3. Results indicate that increasing the primary fluidization rate raises overall system pressure, particularly in the loop seal, where a pressure drop increase is observed. This occurs due to the higher solids circulation rate through the loop seal, causing a pressure difference and increasing the solids inventory in the standpipe. The pressure drop in the carbonator was lower than in the calciner, with stable pressure maintained across different operations. The highest pressure was in the loop seals (P11-14), while the lowest was in the standpipe (P15). Pressure drops in the riser (P7, P10, P16) and carbonator (P8-P9) followed a typical pressure distribution for a pneumatic conveying system, showing a distinct decrease with height. At lower fluidizing gas velocities, where most particles remained at the bottom of the reactors, a higher pressure drop was observed, while the rest of the reactors exhibited slight pressure changes. The pressure decreases linearly with height in the riser. This pressure difference drives the entire system.

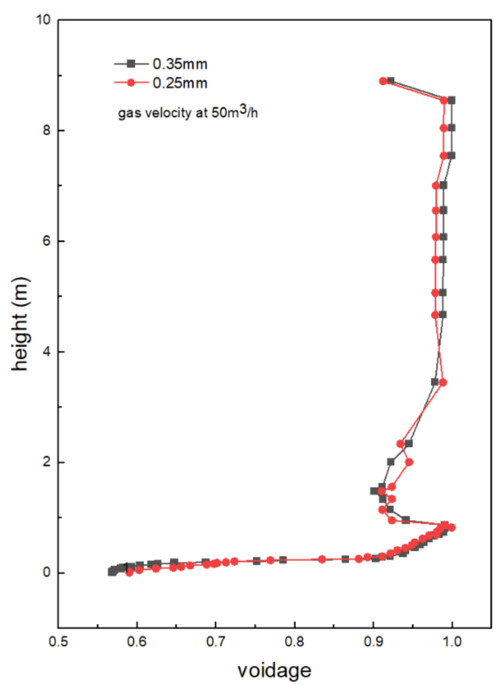

Fig.2 Voidage Profile in The Riser for Different Particle Sizes

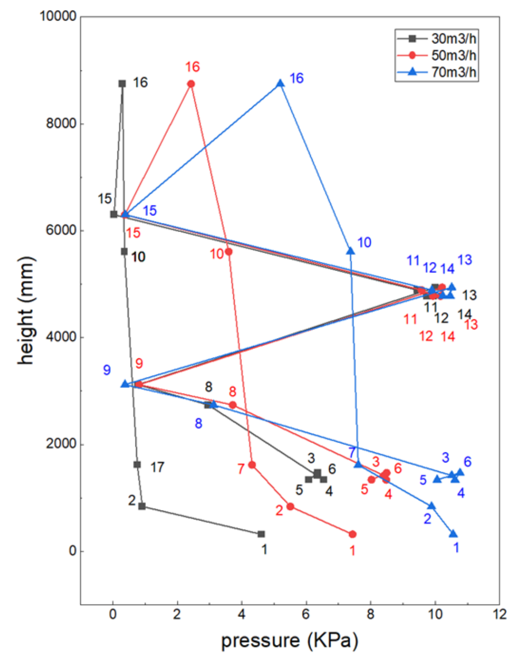

Fig.3 Pressure Profile in Different Locations and Different Gas Flow, Particle Size=350µm

4. CONCLUSIONS

A pilot-scale cold model calcium looping system, including BFB, CFB, loop seals, standpipe, air distributors, and cyclones, was constructed to investigate the influence of gas flow velocities on pressure profiles, voidage profiles, and solid circulation rates. At low gas velocities, voidage in the dense zone was higher for smaller particles compared to larger ones. As gas velocities in the riser increase, the pressure drop along the carbonator rises while it decreases across the riser. The system's pressure profile aligned well with those reported in the literature. Increasing the gas flow rate in the reactors raises the solid circulation rate, which subsequently increases the amount of solids in the downcomer and standpipe. At lower gas flows, solids accumulate in the lower part of the reactors, leading to pressure drops mainly in this area. Under fast fluidization conditions, a uniform pressure drop is observed along the riser, indicating more even solids distribution throughout the height. This study provides valuable insights into the hydrodynamic behavior of sands in the system and aims to validate the feasibility of the cold model system's design for calcium looping while determining if it meets the required operational boundary conditions.

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