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Thermal-fluid characteristics on near wall of gas-solid fluidized bed reactor

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ABSTRACT

Gas-solid circulating fluidized beds (CFBs) are for carbon capture process because of their remarkable heat and mass transfer characteristics in the target reactor. Bed-to-wall heat transfer is an important issue in designing a reactor to satisfy the required conditions. Bed-to-wall heat transfer is characterized by near-wall particle behavior. Thus, in this study, local bed-to-wall heat transfer and near-wall particle dynamic characteristics were measured in a lab-scale CFB riser. The clustered particle behavior near the wall was investigated primarily using a non-intrusive method, particle-imaging velocimetry (PIV), within the CFB riser. To determine the effects of bed instability on the clustered particle behavior at the wall, bed instability was controlled. Bed instability was estimated by the degree of pressure fluctuation in the riser, and the fluctuation effect was compared, depending on the fluidization regime. Ultimately, the clustered particle behavior on the adjacent wall was compared depending on the pressure fluctuations using the PIV system. We estimated the clustered particle behavior on the adjacent wall of the CFB riser considering fluidization instability. Detailed analysis of the relationship between the bed-to-wall heat transfer and the particle behavior was conducted.

1. Introduction

Global warming issues due to human activities have increased since pre-industrial times. Recent anthropogenic emissions of greenhouse gas (GHG) are the highest in history. Among the GHGs, Carbon dioxide (CO_2) is the major contributor for global warming. According to the Intergovernmental Panel on Climate Change (IPCC) report, continued emission of CO_2 will be able to cause further warming and long-lasting changes in the climate system [1,2]. To reduce CO_2 emission to atmosphere, carbon capture and sequestration (CCS) technology has been proposed as a method to mitigate global warming. There are three different carbon capture technological concept: pre-combustion, post-combustion, and oxy-fuel combustion [3–6]. Among three capture process, post combustion using dry-sorbent has widely been researched since it produces less wastewater, simplifies the apparatus, and is energy efficient. Since CO_2 capture process using dry-sorbent is accompanied by a chemical reaction, heat of reaction should be properly handled. For this reason, an isothermal reactor consisted in gas-solid circulating fluidized bed reactor (CFBs) is used [7,8].

Gas-solid circulating fluidized beds (CFBs) are used widely in energy, chemical, and environmental applications because of the remarkable heat and mass transfer characteristic in the reactor. From the point of view of industrial applications, bed-to-wall heat transfer is an important issue in designing a reactor to satisfy the required conditions. CFB risers are used for catalytic-reaction operations under isothermal conditions. Because of the excellent mixing characteristics of the gas-solid fluidized bed, isothermal conditions are readily achievable. However, heat should be removed or added through the heat transfer surface within the fluidized bed to meet the targeted isothermal conditions [9–15]. From the point of view of carbon capture, desorption energy is highly required in regeneration process. To supply this required energy, heat-exchangeable carbon capture concept has been proposed [16]. The efficiency of this concept depends on how well the heat is transferred through the wall where reactors meet. Thus, bed-to-wall heat transfer characteristics are an important design issue in a gas-solid fluidization reactor.

Bed-to-wall heat transfer is a gas-solid two-phase heat transfer phenomenon that is distinguishable from single-phase heat transfer. This phenomenon is affected by many parameters, such as gas properties, particle properties, particle size distribution (PSD), operating conditions, the fluidization regime, the unit size and its

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Nomenclature

A	surface area (m^2)
A_s	surface area of sphere (m^2)
Ar	Archimedes number, $d_p^3 \rho_g(\rho_g - \rho_g)g/\mu^2$
Bi	Biot number, hL_c/k_s
$c_{p,p}$	specific heat capacity of particle (J/kg K)
D	diameter of reactor (m)
d_p	diameter of sorbent (μm)
g	gravitational acceleration (m/s^2)
H_{bed}	bed height (m)
$\bar{h}_{wall,carb}$	average heat transfer coefficient in the carbonation reactor (W/m^2 K)
$\bar{h}_{wall,regn}$	average heat transfer coefficient in the regeneration reactor (W/m^2 K)
k	thermal conductivity (W/m K)
$m_{sorbent}$	mass of sorbent in bed, $\Delta PA/g = (1 - \varepsilon)\rho_s AL$ (kg)
Q	thermal energy (J)
$\dot{Q}$	heat transfer rate (W)

configuration, and the initial particle packing height [9–26]. Specifically, in the near-wall region of the riser, particles move downwards in various clustered shapes [17]. The behavior of these clustered particles affects primarily the bed-to-wall heat transfer. Indeed, from a mechanistic model of bed-to-wall heat transfer [14], the heat transfer is dominated by these clustered particles near the wall. That is, the interaction between the cluster and the wall can be considered a transient heat conduction process in a homogeneous, semi-infinite medium on the assumption that the cluster exceeds the thermal penetration depth, which is the width of the heat flux across the cluster [10–13]. Clusters have been observed with various shapes, depending on the fluidization conditions [27–29]. Cluster formation is affected predominantly by the slip velocity between the gas and solid particles near the wall. This near-wall slip velocity is in turn affected by the operating conditions, representing the fluidization regime. Thus, bed-to-wall heat transfer can differ depending on the fluidization regime, because this influences the gas-solid interaction near the wall.

As mentioned, near the reactor wall, a unique particle aggregating phenomenon appears, with a core-annular structure. The particle-gathering phenomenon in the annulus region is known as particle clustering [30,31]. Bed-to-wall heat transfer is influenced predominantly by the near-wall (annulus region) clustered particle behavior; consequently, many researchers have investigated the behavior of such clusters using intrusive and non-intrusive methods [32–36]. These investigations showed that the particles in the annulus region form clusters, and these clusters descend near the wall with a certain shape. The cluster types have been shown to include discrete, round shapes and long, thin-stranded shapes, depending on the operating conditions. Compared with dense (bubbling) fluidization, the annulus region is relatively dilute, so that a thin gas film of the order of a mean particle diameter is observed between the wall and the clusters [30]. In particular, the formation of the clusters is affected primarily by the operating conditions, i.e., the fluidization regime. Although the thin gas film acts as a resistance factor, the clusters predominantly affect the bed-to-wall heat transfer. Generally, bed-to-wall heat transfer is proportional to the suspension density of the riser [30,32,33].

Furthermore, bed instability is another important parameter in fluidization quality, which can be an important issue in a specific reaction process. Although there should be existing fluidization instability, because of natural gas-solid interactions, the difference in the degree of bed instability is influenced by the reaction rate and the particle residence time [37–41]. Fluidization instability emerges because pressure fluctuation is caused by the interaction between the upward gas-solid flow and the descending clusters. Interactions between the upward gas-solid flow and the near-wall descending clusters are related to the operating conditions and characteristics of the facility. Bed instability affects particle behavior and is correlated with bed-to-wall heat transfer. In detail, the degree of bed instability can affect bed-to-wall heat transfer.

In previous researches, they were focusing on the averaged bed-to-wall heat transfer or the visualization of particle behavior in fluidized bed. However, it is necessary to find out the relationship between the local bed-to-wall heat transfer and particle behavior. In this study, local bed-to-wall heat transfer was measured in lab-scale CFB risers, depending on the fluidization regime. Turbulent, fast, and pneumatic fluidization regimes were used as CFB operating conditions. The axial local heat transfer coefficients were estimated at the mid region of the riser ($z/H = 0.5$) because that region can be considered to have a fully developed solid particle flow zone. The clustered particle behavior near the wall was investigated using a non-intrusive method, particle-imaging velocimetry (PIV), within the CFB riser. To determine the effects of bed instability on the clustered particle behavior at the wall, bed instability was controlled. Bed instability was estimated by the degree of pressure fluctuation in the riser, and the fluctuation effects were compared between fluidization regimes. Moreover, the clustered particle behavior on the adjacent wall was evaluated according to the pressure fluctuations, using the PIV system. We estimated the clustered particle behavior on the adjacent wall of the CFB riser, considering fluidization instability. Detailed analysis of the relationship between bed-to-wall heat transfer and particle behavior was conducted.

2. Problem statement of CO_2 capture reactor

Carbon capture process using dry sorbent is considered as a competitive technology [6,7,42]. In this process, two circulating fluidized bed reactor (CFBs) are employed due to high gas-solid mixing and temperature uniformity throughout reactor bed [16,43]. In one reactor, the carbonator, exothermic reaction occurs when CO_2 is adsorbing by dry sorbent with generating heat of reaction. While in the other reactor, referred as regenerator, an amount of energy is required for regeneration of CO_2-rich sorbent. Generally, temperature swing adsorption method is applied to meet the adsorption-desorption reaction continuously. For this, heat exchangers are applied to satisfy the temperature conditions for carbonation and regeneration, respectively. In terms of energy-utilization, when required energy for regeneration can be reduced, energy efficiency of the system and the cost effectiveness are improved to gain a competitive edge for commercialization. As a remedy for this situation, heat-exchangeable fluidized bed reactor system has been applied (Fig. 1(a)) [16]. The main concept of this system is that heat is transferred from carbonator in higher temperature stage to regenerator in lower temperature stage, using the information that temperature conditions are different depend-