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Effect of the Cross-Sectional Geometry on Heat Transfer and Particle Motion of Circulating Fluidized Bed Riser for CO_2 Capture

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Abstract**—**Effect of the cross-sectional geometry on heat transfer and particle motion of circulating fluidized bed riser for CO_2 capture was investigated. Numerical simulation using Eulerian-eulerian method with kinetic theory of granular flow was adopted to analyze gas-solid flow consisting in circulating fluidized bed riser. Circular, square, and rectangular cross-sectional geometry cases of the same area were carried out. Rectangular cross-sectional geometries were analyzed having aspect ratios of 1: 2, 1: 4, 1: 8, and 1:16. The cross-sectional geometry significantly influenced the particle motion and heat transfer. The downward flow pattern of solid particles near the wall was changed. The gas-solid mixing degree of the riser with the rectangular cross section of the high aspect ratio was the lowest. There were differences in bed-to-wall heat transfer coefficient according to rectangular geometry with different aspect ratios.

Keywords**—**Bed geometry, computational fluid dynamics, circulating fluidized bed riser, heat transfer.

I. INTRODUCTION

ANTHROPOGENIC carbon dioxide emissions have been paid attention due to serious global warming issue. Under the current industry based on fossil fuels, carbon dioxide emissions will continue and increase. Changes in the industrial structure are far-future stories, and efforts are needed to reduce current carbon dioxide emissions. One of the efforts is CCS (Carbon capture and sequestration). CCS is a technology that captures, transports and stores carbon dioxide from fossil fuel power plants. According to location of capture process, there are three technologies for carbon dioxide capture technology; post combustion, pre-combustion, oxy-fuel combustion. Post-combustion capture is a technology that can be applied to current power plants and will be commercialized in the nearest period. Three technologies that are used in carbon dioxide capture method are dry-adsorbent, wet-absolvent, and membranes. Dry-adsorbent capture technology has an advantage that there are no secondary contaminants to be released and regenerable solid particles [1], [2].

Fluidized bed reactor is used a fluidization phenomenon. A fluidization phenomenon is an unabsorbed multi-phase upward flow such as gas-solid or gas-liquid etc. In a fluidized bed reactor, the solid particles behave like fluids and are well mixed with the gas. Due to these advantages, fluidized bed reactor is widely applied to chemical industry. Especially, circulating fluidized bed (CFB) reactor is one of representative continuous processes. Under high gas velocities, it represents good gas-solid mixing and excellent heat and mass transfer. Circulating dual fluidized bed reactor is applied to carbon dioxide capture reactor using a dry-adsorbent. In circulating dual fluidized bed reactor, capture reaction occurs in riser and the riser is generally called the reactor [3].

Dual fluidized bed reactor consists of adsorption reactor and desorption reactor. Generally, each reaction rate depends on temperature. For efficient reaction, reaction temperature must be constant. But, carbon dioxide adsorption is exothermic reaction and desorption is endothermic. Adsorption reactor needs cooling and desorption reactor requires energy to achieve the designed reaction performance. Heat transfer is required to maintain the temperature conditions of each reactor.

Heat transfer enhancement is needed from various perspectives. Through high heat transfer coefficient, heat transfer area needed can be reduced for maintaining a designed temperature condition. It can be used to design the reactor compact. Small and simple reactor design saves carbon dioxide capture costs [4].

In fluidized bed reactor, gas-solid behaviors have not been clearly identified. Also, bed-to-wall heat transfer is complex. It varies greatly by various variables [5]-[7]. There are many researches about effect of gas and particle properties [8]. Gas velocity is also proven to be an important factor in bed-to-wall heat transfer [9]. Particle size is a dominant parameter for solid particle behaviors, which affect bed-to-wall heat transfer [10]. There has been some research on the effect of reactor diameter [11]. There have been several studies about the effect of reactor geometry on gas-solid behaviors although the different cross-sectional area [12]. Several studies have been performed about effect of reactor geometry on bed-to-wall heat transfer.

In this study, effect of the cross-sectional geometry on CFB riser for carbon dioxide capture is researched. Numerical simulations were used to model a fluidized bed reactor consisting of a gas-solid two-phase flow. Assuming that the same volumetric flue gas flow rate is processed, cross-sectional area of reactor is constant. Relative to the popular circular reactor, reactors having square or rectangular cross-sectional

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geometry are analyzed. Variation of gas-solid behaviors is checked. And, it was confirmed that the heat transfer was affected by change on gas-solid behaviors.

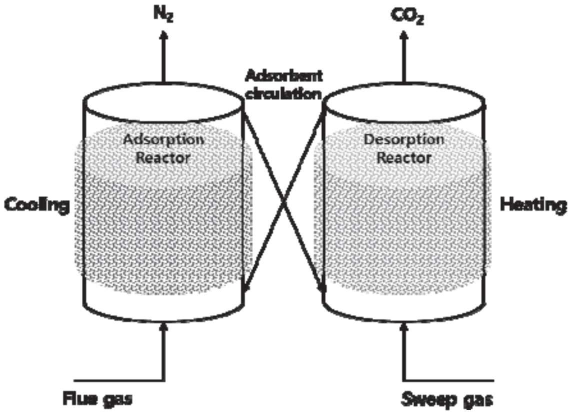

Fig. 1 CFB riser for carbon dioxide capture

II. RESEARCH METHOD

A. Numerical Simulation

TABLE I
A SUMMARY OF THE GOVERNING EQUATIONS AND CONSTITUTIVE EQUATIONS

Conservation of mass
Gas phase: $\frac{\partial}{\partial t}(\varepsilon_g \rho_g) + \nabla\cdot(\varepsilon_g\rho_g\vec{v}_g) = 0$ Solid phase: $\frac{\partial}{\partial t}(\varepsilon_s \rho_s) + \nabla\cdot(\varepsilon_s\rho_s\vec{v}_s) = 0$
Conservation of momentum
Gas phase: $\frac{\partial}{\partial t}(\varepsilon_g\rho_g\vec{v}_g) + \nabla\cdot(\varepsilon_g\rho_g\vec{v}_g\vec{v}_g) = -\varepsilon_g\nabla p + \nabla\cdot\bar{\bar{\tau}}_g + \varepsilon_g\rho_g\vec{g} + K_{gs}(\vec{v}_g - \vec{v}_s)$ Solid phase: $\frac{\partial}{\partial t}(\varepsilon_s\rho_s\vec{v}_s) + \nabla\cdot(\varepsilon_s\rho_s\vec{v}_s\vec{v}_s) = -\varepsilon_s\nabla p - \nabla p_s + \nabla\cdot\bar{\bar{\tau}}_s + \varepsilon_s\rho_s\vec{g} - K_{gs}(\vec{v}_g - \vec{v}$
Conservation of energy
Gas phase: $\frac{\partial}{\partial t}(\varepsilon_g\rho_g h_g) + \nabla\cdot(\varepsilon_g\rho_g\vec{v}_g h_g) = \varepsilon_g\frac{\partial p_g}{\partial t} + \bar{\bar{\tau}}_g : \nabla\vec{u}_g - \nabla\cdot\vec{q}_g + Q_{sg}$ Solid phase: $\frac{\partial}{\partial t}(\varepsilon_s\rho_s h_s) + \nabla\cdot(\varepsilon_s\rho_s\vec{v}_s h_s) = \varepsilon_s\frac{\partial p_s}{\partial t} + \bar{\bar{\tau}}_s : \nabla\vec{u}_s - \nabla\cdot\vec{q}_s + Q_{gs}$
Constitutive equations (Kinetic Theory to Granular Flows(KTGF))
Transport equation derived from kinetic theory $\Theta_s = \frac{1}{3}u_{s,i}u_{s,i}$ (granular temperature) $\frac{3}{2}\left[\frac{\partial}{\partial t}(\varepsilon_s\rho_s\Theta_s)\right] = (-p_s I + \bar{\bar{\tau}}_s):\nabla\vec{v}_s - \gamma_{\Theta_s} + \phi_{gs}$ $k_{\Theta_s} = \frac{150\rho_s d_s\sqrt{\Theta_s\pi}}{384(1+e_{ss})g_{0,ss}}\left[1 + \frac{6}{5}\varepsilon_s g_{0,ss}(1+e_{ss})\right]^2 + 2\rho_s\varepsilon_s^2 d_s(1+e_{ss})g_{0,ss}\sqrt{}$ [16] $\phi_{gs} = -3K_{gs}\Theta_s$ $\gamma_{\Theta_s} = \frac{12(1-e_{ss}^2)g_{0,ss}}{d_s\sqrt{\pi}}\rho_s\varepsilon_s^2\Theta_s^{3/2}$[17]

This study is performed through numerical analysis. To analyze gas-solid two-phase flow, Eulerian-Eulerian approach is applied. Eulerian-Eulerian approach is to model both gas phase and solid phase as an interpenetration continuum. For two-phase flow simulation, this approach, which is also called the two-fluid model, is evaluated as a reasonable method having advantages of less computational costs and good accuracy in comparison with other approaches; VOF, mixture, and DPM. Basically, mass conservation equations, momentum conservation equations and energy conservation equations are calculated considering the volume fraction. To consider interphase exchanges, empirical models are applied. Interphase momentum transfer coefficient of the gibilaro model is applied [13], which is the most common model for CFB. Interphase energy transfer coefficient of the gunn model is applied [14], which is the most common model for granular flows. For simulating of solid particle flow, kinetic theory to granular flows is applied. By introducing granular temperature proportional to the kinetic energy of the particles random motion, random particle behavior is predicted. The detailed equations are in Table I.

Using commercial software ANSYS Fluent 17.2, numerical simulation is conducted. For simulating a vivid gas-solid flow, transient simulation is performed. Time step is 10^{-3} second.

Under quasi steady state, when the amount of solid input at the inlet is equal to the amount of solid output at the outlet, results is analyzed. Also, in order to comfirm the instantaneous and the tendency of gas-solid behaviors, value at each time interval and time-averaged value are checked.

B. Validation

To ensure reliability, model validation is conducted. Gas-solid behavior is an important factor in this study. Solid mass flux distribution is a good parameter to reveal gas-solid behavior. Fig. 2 shows that the numerical simulation results for solid mass flux distributions are similar to experimental data. It is confirmed that the numerical analysis well simulates the actual behavior

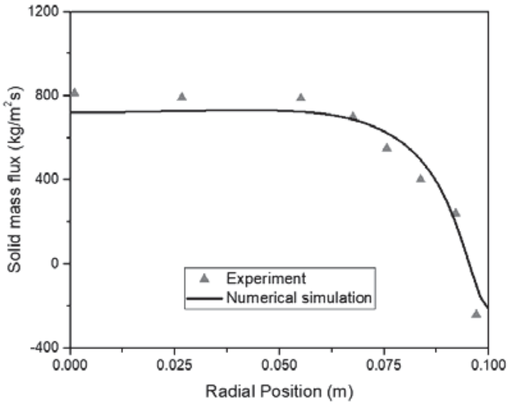

Fig. 2 Comparison with experimental data and numerical simulation

C. Operating Condition and Gas-Solid Properties

Operating conditions for carbon capture vary depending on gas and adsorbent solid particle. It is assumed that adsorption temperature is 60 °C and flue gas volumetric flow rate is 340 Nm^3/hr. In all cases, the cross-sectional area is the same, so superficial gas velocity is equally 1.2 m/s. Adsorbent solid particle density is 1700 kg/m^3, and diameter is 100 μm, which is considered as a complete sphere. It is classified into Geldart A, and fluidization regime of reactor is turbulent bed [15]. Solid circulation rate is 5 kg/m^{2}s. The detailed properties of gas and solid particles are in Table II.

TABLE II
PHYSICAL AND THERMAL PROPERTIES OF GAS AND SOLID

Property (Unit)	Value	Property (Unit)	Value
Gas density (kg/m^3)	1.061	*Solid particle density* (kg/m^3)	1700
Gas dynamic viscosity (kg/m•s)	2.0 X 10^{-5}	*Solid particle diameter (μm)*	100
*Gas thermal conductivity (*W/m•K*)*	0.0288	*Solid particle thermal conductivity (*W/m•K*)*	1
*Gas specific heat (*kJ/kg•K*)*	1.007	*Solid particle specific heat (*kJ/kg•K*)*	1.4

D. Comparative Study Using Numerical Analysis

To analyze the effect of the cross-sectional geometry of CFB reactor, the cross-sectional area is treated as control variable. Compared with the conventional circular cross-sectional shape, square and rectangular cross-sectional shapes are analyzed. In consideration of the influence of the aspect ratio of the rectangular shape, the rectangular reactors having four different aspect ratios are simulated. Numerical simulations are performed for a total of six cases, but the four cases with unique characteristics are analyzed.

III. RESULTS

A. Pressure Difference

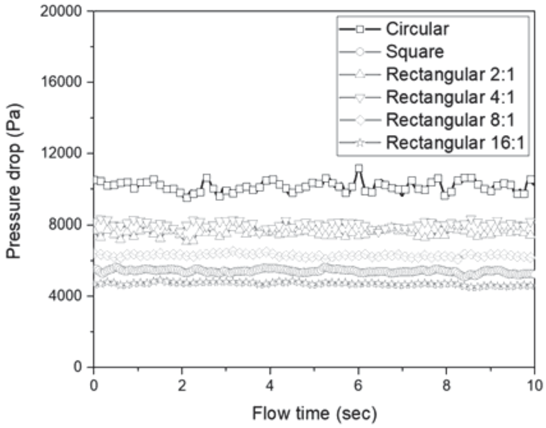

Fig. 3 Pressure difference with flow time according to the different cross-sectional shape

Pressure difference across the fluidized bed reactor means a sum of the weight of gas and solid particles and the wall friction due to gas and solid particles. In the turbulent fluidized bed regime, the weight of solid particles is a major value for the pressure difference value. Fig. 3 shows that the pressure difference oscillates with respect to each specific value. This means that the fluidized bed reactor is in a quasi-steady state, which is a continuous operation state of the CFB. The time-averaged pressure differences of circular, square and rectangular 2:1, 4:1, 8:1 and 16:1 are 10200, 5400, 7500, 8100, 6300 and 4700 Pa, respectively. Circular shape reactor has a maximum value, the values for square and rectangular rectors vary according to aspect ratio. As one increases the aspect ratio from 1(square) to 4, the pressure difference increases. However, if the aspect ratio is further increased to 16, the pressure difference decreases.

B. Gas-Solid Behaviors

Solid particle concentration shows where the solid particles is mainly concentrated in the reactor. Fig. 4 shows the cross-sectional solid particle concentration in the different cross-sectional shape. In common, at the center of the reactor, the solid particle concentration is dilute, and near the wall, the solid particle concentration is dense. This distribution of the solid particle is called the core-annular structure, which is a typical flow pattern of a turbulent fluidized bed. Core-annular flow means that solid particles flow upward in the core and down near the wall.

Fig. 4 shows that upward flow and downward flow is different depending on the cross-sectional shape. Especially, in downward annular flow, compared to the circular shape reactor in which the annular solid particle distribution appears to be connected, the rectangular shape reactor appears to be segmented. This tendency becomes clearer as the aspect ratio increases, and at rectangular with an aspect ratio of 16:1, the annular flow on the wide surface appears to have disappeared.

Gas solid mixing is an important component of fluidized bed reactors, which can be indirectly confirmed by solid particles distribution. In the circular shape, it exhibits a uniform distribution at all angles with respect to the center. However, for the square and the rectangular shape, the non-uniform distributions of solid particle appear due to the presence of corners. Solid particles flow toward the corners, and the extent of the flow depends on the aspect ratio. Also, as the aspect ratio increases, the particle distribution on the narrow surface increases. In other words, the non-uniformity of the solid particles distribution in the horizontal cross section becomes large.

C. Heat Transfer Characteristics

In a fluidized bed, the heat transfer mode is largely divided into three types; the convection heat transfer by gas, the convection heat transfer by solid particles and the radiation heat transfer. Up to 500 °C, the radiation heat transfer is so small that it is negligible. On the Geldart particle A, the bed-to-wall heat transfer is dominated by the convection heat transfer by solid particles. The convection heat transfer by solid particles is affected by the solid particles behaviors such as the solid particle concentration near the wall, clustering of particles, and particle contact cycle. Instantaneous local bed-to-wall heat transfer coefficient varies with time and location.

For quantitative comparative analysis, the time-averaged heat transfer coefficient is used. Fig. 5 shows the instantaneous local bed-to-wall heat transfer coefficient distribution in the heat transfer area. It shows that the different heat transfer occurs from location to location within the reactor. It is confirmed that the bed-to-wall heat transfer coefficient is higher in the circular reactor than in other shapes. In the rectangular reactor, compared to the wide surface, it can be confirmed that the heat transfer coefficient in the narrow surface is higher.

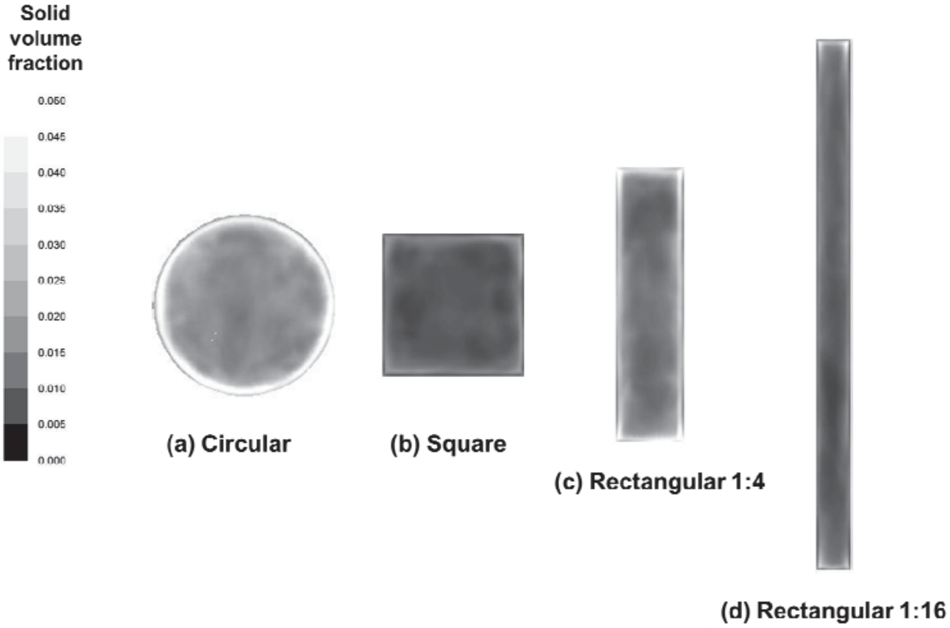

Fig. 4 The horizontal cross-sectional solid particle concentration in the different cross-sectional shape at 5 m height of the reactor

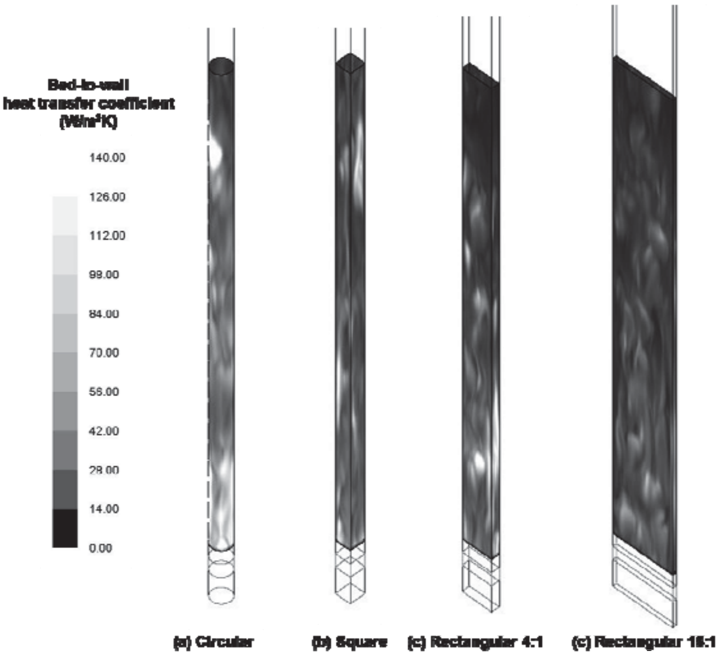

Fig. 5 Contour of the instantaneous bed-to-wall heat transfer coefficient distribution in the heat transfer area with the different cross-sectional shape reactor

IV. CONCLUSION

This study is about the effect of the cross-sectional geometry on heat transfer and particle motion of CFB riser for CO_2 capture using numerical simulation. In terms of gas-solid particle behavior and heat transfer, it is confirmed that the cross-sectional geometry is a significant critical point of the fluidized bed reactor. In the pressure difference, circular shape reactor has a maximum value, the values for square and rectangular rectors vary according to aspect ratio. Due to the difference in shape, the distribution of solid particles in the rectangular shape reactor becomes uneven as compared with the circular shape reactor. And, it was confirmed that the cross-sectional shape of the reactor affects the heat transfer owing to the change of the solid particle behavior. Particularly, it was confirmed that the rectangular shape reactor has a local difference of the bed-to-wall heat transfer.

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