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Hydrodynamics of a hybrid circulating fluidized bed reactor with a partitioned loop seal system

Dal-Hee Bae*, Minyoung Yun, Jong-Ho Moon*,†, Gyoung Tae Jin*, Dowon Shun*, Chan Seung Park**, and Joseph M. Norbeck****

*Low Carbon Process Laboratory, Korea Institute of Energy Research, 102, Gajeong-ro, Yuseong-gu, Daejeon 305-343, Korea
**Bourns College of Engineering, Center for Environmental Research and Technology (CE-CERT), University of California, Riverside, CA 92521, USA
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Abstract−A circulating fluidized bed (CFB) with a hybrid design has been developed and optimized for steam hydrogasification. The hybrid CFB is composed of a bubbling fluidized bed (BFB) type combustor and a fast fluidized bed (FB) type gasifier. Char is burnt in the combustor and the generated heat is supplied to the gasifier along with the bed materials. Two different types of fluidized beds are connected to each other with a newly developed partitioned loop seal to avoid direct contact between two separate gas streams flowing in each fluidized bed. Gas mixing tests were carried out with Air and Argon in a cold model hybrid CFB to test the loop seal efficiency. Increase in solid inventory in the loop seal can improve the gas separation efficiency. It can be realized at higher gas velocity in fast bed and with higher solid inventory in the loop seal system. In addition, bed hydrodynamics was investigated with varying gas flow conditions and particle sizes in order to obtain a full understanding of changes of solid holdup in the FB. The solid holdup in the FB increased with increasing gas velocity in the BFB. Conversely, increase in gas velocity in the FB contributed to reducing the solid holdup in the FB. It was observed that changing the particle size of bed material does not have a big impact on hydrodynamic parameters.

Keywords: Circulating Fluidized Bed, Hydrogasification, Hydrodynamics, Gas Mixing, Loop Seal

INTRODUCTION

Growing concerns about the depletion of oil resources and greenhouse gas emission have driven worldwide attention to alternative energy sources such as coal, biomass and refuse derived fuel. Among them, biomass is an attractive feedstock for producing transportation fuels as its use contributes little or no net carbon dioxide to the atmosphere [1]. In this respect, gasification is expected to be an important technology because it allows the conversion of biomass into storable and transportable fuel.

Gasification, which is the reaction of solid fuels with air, oxygen, and steam at a temperature over 700 °C, yields a gaseous product suitable for use either as a source of energy or as a raw material for the synthesis of chemicals, liquid fuels, or other gaseous fuels. There are roughly three types of generic gasifiers: entrained flow beds, fluidized beds, and fixed beds [2]. Among them, fluidized bed gasifiers have several advantages, such as relatively low operating temperature, high conversion efficiency with synthesis gas recycling, and durability for corrosive materials.

In a conventional fluidized bed gasifier, gasification and combustion reactions occur in one bed simultaneously. Therefore, synthesis gases are inevitably diluted by inert gases and combusted gases (CO_2). However, in specially designed gasifiers, such as a dual fluidized bed gasifier [3-6], internally circulating fluidized bed with draft tube [7], and compartmented fluidized bed [8], a partitioned fluidized bed gasifier [9-11], synthesis gases can be obtained without diluting or mixing with combusted gases. In addition, since the generated heat from the independent combustor is supplied to the gasifier along with the bed materials directly, thermal efficiency of the gasification reaction can be improved.

Hydrogasification is gasification in a hydrogen-rich environment, often used for the production of synthetic natural gas (SNG) from solid fuel. It does not require an oxygen plant, which can be a substantial cost to a gasification facility. However, it tends to have low carbon conversions and product yields and slow reaction rates without the use of catalysts. Steam hydrogasification (SH) presented as below is a thermochemical process operated at high temperature (750-850 °C) and pressure (50 bar) fed with steam and H_2 as gasifying agents, producing methane rich gas. Especially, SH shows high efficiency at low temperature and pressure with a direct input of water when compared to hydrogasification [12,13].

$$C+H_2O+2H_2 \rightarrow CH_4+H_2O+CO, CO_2, C_{2+}$$

Since gasification is a endothermic reaction, external heat is required for the process because the feedstock and gasifying agents must be heated to high reaction temperatures (750-850 °C). It is thus essential to develop a proper reactor to address the heat supply issue with SH. This external heat source can be addressed by adopting a specific type of fluidized bed reactor, and circulating fluidized bed (CFB) with a hybrid design was suggested for the pur-

†To whom correspondence should be addressed.
E-mail: moon_jongho@kier.re.kr

pose. The design of a hybrid CFB reactor consists of fast bed (FB) with a bubbling fluidized bed (BFB) connected with a cyclone.

For the optimal design of fluidized bed gasifiers, the understanding of gas mixing behavior is recognized as one of the most important factors. These behaviors affect heat and mass transfer rates in the bed dominantly. In addition, better understanding of gas mixing in the bed can improve the unit operation efficiencies. Therefore, cold model experiments should be done before running real mode operation from the viewpoint of economics. Up to now, a number of researchers have reported gas mixing behaviors in various cold model fluidized beds [3,12,14-17] and those numerical modeling [18-23].

In this study, cold model experiments in a circulating fluidized bed (CFB) with a hybrid design were executed to understand gas mixing behavior and hydrodynamics of bed particles. Two different types of fluidized beds were connected to each other with a newly developed partitioned loop seal to avoid direct contact between two separate gas streams flowing in each fluidized bed. Gas mixing tests were carried out with Air and Argon in a cold model hybrid CFB to test the loop seal efficiency. Bed hydrodynamics was investigated with varying gas flow conditions and particle sizes in order to obtain a full understanding of changes of solid holdup in the FB. The objective of this study was to understand gas mixing characteristics under various operating conditions.

BASIC CONCEPT

1. Gas Mixing in the Cold Model Hybrid CFB

An important feature of the hybrid CFB is the separation of gases in the loop seal in BFB aimed at preventing the contamination of a valuable gasification product gas with flue gas from combustion. Since, the gasification reaction needs more reaction time than combustion reaction. In this system, some part of reactants, such as coal, is gasified in the riser section and the rest part is transferred to the bubbling fluidized section as char state. The transferred char is converted to thermal energy via combustion reaction in the bubbling fluidized section, and then the thermal energy is transferred to the riser along with the bed materials to enhance gasification reaction

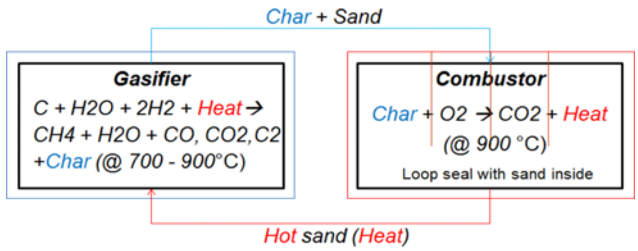

Fig. 1. Circulation of heat and mass in the hybrid CFB.

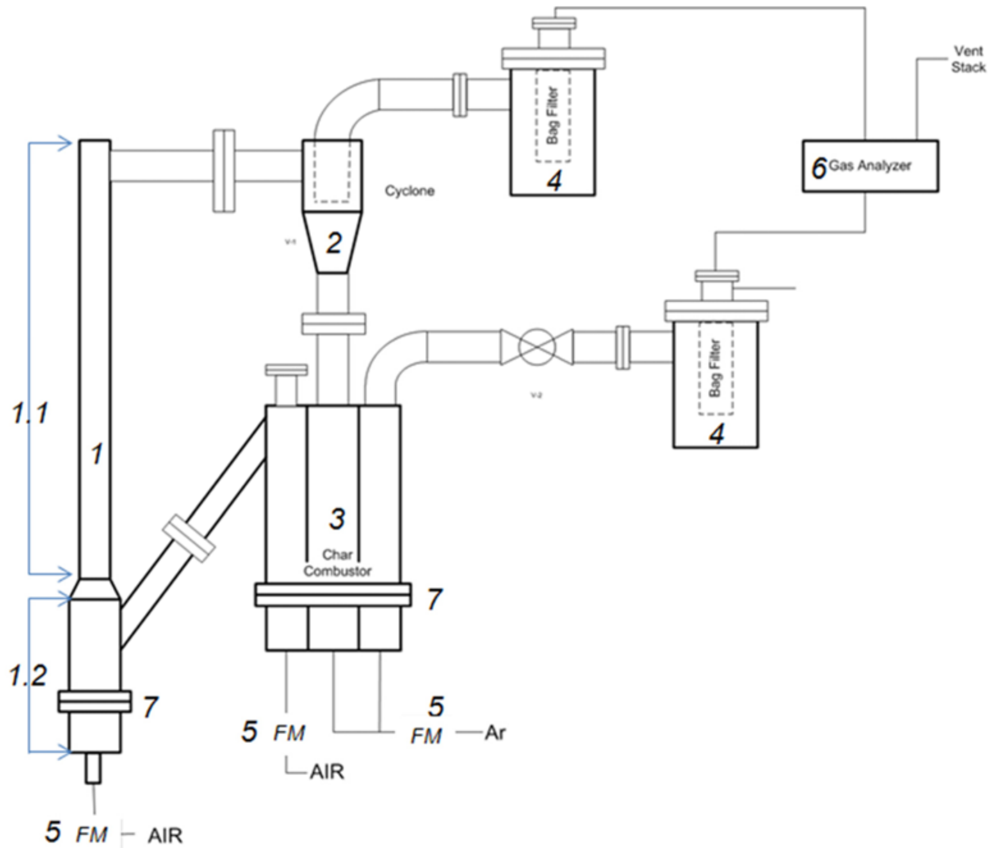

Fig. 2. Experimental apparatus of cold model hybrid fluidized bed.

1. Fast bed	1.2. Mixer	3. Bubbling fluidized bed	5. Flow meter	7. Gas distributer
1.1. Upper bed	2. Cyclone	4. Bag filter	6. Gas analyser (RGA)	

in the riser section. Also, a mixing zone with wide diameter was equipped in the bottom of the riser section to increase the solid residence time. In this process, residence time for gasification reaction can be guaranteed by controlling flow rates and loop seal operation.

The loop seal is filled with bed materials (sand) to minimize the degree of contact between gas streams in FB and BFB. To test the critical function of the loop seal, a mixing test was carried out with Air and Argon in the cold model hybrid CFB. The less mixing is observed the better.

2. Hydrodynamics of Bed Particles in the Cold Model Hybrid CFB

Bed hydrodynamics was investigated at various gas flow conditions in order to obtain a full understanding of dynamic changes of solid holdup in the FB. Understanding bed hydrodynamics in the configuration is important because it is deeply related to not only the heat circulation in the system for endothermic SH but also great gas-solid mixing to improve mass and heat transfer.

Necessary heat for the endothermic gasification reaction is delivered by means of circulation of bed materials. High mass and heat transfer rates can be achieved by active gas-solid mixing behavior. Therefore, the distribution of the solid inventory in FB governs reaction rate and thus carbon conversion during SH operation in a hybrid CFB. For these reasons, the solid inventory in the FB was closely observed under diverse fluidization conditions in BFB and FB utilizing pressure manometers to study the influence of the fluidization conditions on hydrodynamics parameters.

3. Configuration of the Cold Model Hybrid CFB

A cold model hybrid CFB was designed and built with a transparent acrylic plastic for the purpose of studying the gas mixing and hydrodynamics of bed material in the configuration. The cold model hybrid CFB corresponds to a pilot demonstration unit (PDU) hybrid CFB that is currently under development and construction at center for environmental research & technology (CE-CERT), University of California Riverside (UCR). The particular feature of the design is the two types of fluidized beds connected to each other with a partitioned loop seal to avoid direct contact between two separate gas streams flowing in each fluidized beds. The design is well described in Fig. 2. The FB, unit 1, is designed for SH with an active solid-gas mixing with a stream of steam and H_2 as gasifying agents while the BFB, unit 3, is for combustion of residual char from gasification with Air. These two different gas streams in two fluidized beds exhaust the configuration separately, one stream from FB through upper bag filter and the other stream from BFB through lower bag filter. As can be seen in Fig. 1, the necessary heat for SH

Table 1. Dimension of the cold model CFB

Fast bed (FB)		
Diameter (D_{mixer})	5.08	cm
Diameter ($D_{upper\ bed}$)	4.20	cm
Height ($h_{fast\ bed}$)	200	cm
Bubbling fluidized bed (BFB)		
Diameter ($D_{downcomer}$)	4.20	cm
Width ($w_{loopseal}$)	5.08	cm
Depth ($d_{loopseal}$)	5.08	cm
Height ($h_{loopseal}$)	100	cm

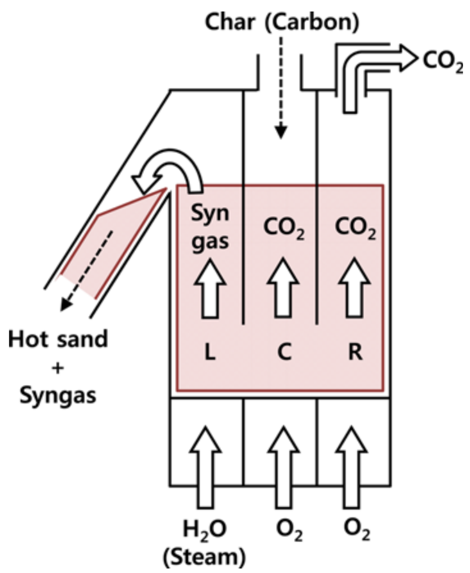

Fig. 3. Conceptual design of a partitioned loopseal (L: left bed, C: center bed, R: right bed).

can be provided from an exothermic reaction (combustion) and supplied by a means of circulation of bed material between FB and BFB. The two partitioned walls in BFB serve as a loop seal in the bubbling fluidized bed (BFB), which is a unique feature. Dimensions for the reactor are given in Table 1. Many researchers have studied the hydrodynamics of bed particles in a fluidized bed recently. Kaiser et al. [12] studied the circulation of bed material in a CFB gasification system with a dual fluidized bed concept, and the changes of the solid holdup under different fluidization conditions.

Detailed unique features of a loop seal system are shown in Fig. 3. In this study, a 3-partitioned loop seal system was established to prevent gas mixing between syngas and combusted gas. Char is introduced from riser and O_2 is introduced into center and right bed for combustion reaction. H_2O is also introduced into left bed for gasification reaction. As Moon et al. [10] stated in the previous paper, solid mixing is maximized whereas horizontal gas mixing is minimized in the partitioned fluidized bed. Therefore, highly concentrated combusted gas, mostly CO_2, is emitted from the right bed and syngas in the left bed is transferred to the mixer, bottom of the riser. Heated bed material by combustion reaction is also transferred to the mixer with carrying thermal energy.

EXPERIMENTS

1. Gas Mixing Test

Gas mixing tests examined the level of mixing of gases from two reactors under different fluidization conditions using Air and Argon (Ar). As for gas flow inlet, Air was injected into FB and through left gas inlet into BFB, while Ar entered system through right gas inlet into BFB. In the configuration, a pure stream of Air from FB and Ar from BFB can be expected without any degree of mixing of gases. The exhausting gas streams, respectively, from FB and BFB were analyzed utilizing a residual gas analyzer (RGA). Silica sand with 150 μm average diameter (OK-75, US Silica) was used as bed

Table 2. Properties of bed material and fluidizing gases

Bed material (silica sand, OK-75)		
Particle diameter (D_p)	150-242.5	μm
Skeletal density (ρ_s)	2650	$kg\cdot m^{-3}$
Bulk density (ρ_b)	1250	$kg\cdot m^{-3}$
Fluidizing gas (Air and Ar at atmospheric condition)		
Density ($\rho_{g, Air}$)	1.18	$kg\cdot m^{-3}$
Viscosity ($\mu_{g, Air}$)	1.76×10^{-5}	$kg\cdot m^{-1}\cdot sec^{-1}$
Density ($\rho_{g, Ar}$)	1.78	$kg\cdot m^{-3}$
Viscosity ($\mu_{g, Ar}$)	2.23×10^{-5}	$kg\cdot m^{-1}\cdot sec^{-1}$

material for the gas mixing experiments. Detailed properties of bed material and fluidizing gases are listed in Table 2.

Variables for the gas mixing test were determined based on a calculation of minimum fluidizing velocity (U_{mf}) and terminal velocity (U_t) for bed material with a specific particle size of 150 μm. As mentioned above, the volumetric flow rate of Air and Ar was chosen on the basis of U_{mf}, U_t of bed material of 150 μm silica sand.

$$\frac{1.75}{\varepsilon_{mf}^3 ø_s}\left(\frac{d_p U_{mf}\rho_g}{\mu}\right)^2 + \frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3 ø_s^2}\left(\frac{d_p U_{mf}\rho_g}{\mu}\right) = \frac{d_p^3\rho_g(\rho_s-\rho_g)}{\mu^2} \quad (1)$$

$$d_p^* = d_p\left[\frac{\rho_g(\rho_s-\rho_g)g}{\mu^2}\right]^{1/3} \quad (2)$$

$$U_t^* = \left[\frac{18}{(d_p^*)^2} + \frac{2.335-1.744ø_s}{(d_p^*)^{0.5}}\right]^{-1} \quad (3)$$

$$U_t = U_t^*\left[\frac{\mu(\rho_s-\rho_g)g}{\rho_g^2}\right]^{1/3} \quad (4)$$

U_{mf} for 150 μm sand in the BFB is calculated by Eq. (1), while U_t in the FB reactor is obtained from Eqs. (2)-(4) [24], where, d_p means particle diameter of the sand (m), ρ_g is gas density (kg/m^3), ρ_s is particle density (kg/m^3), μ is gas viscosity (kg/m·s), ε_{mf} is void fraction at minimum fluidization (-), Φ_s is sphericity of a particle (-), d_p^* is dimensionless particle diameter (-), U_t^* is dimensionless terminal velocity of a falling particle (-) for calculating terminal velocity (U_t). Minimum fluidizing velocities and terminal velocities of silica sands with various sizes for Air and Ar are calculated in Table 3.

Minimum fluidizing velocities of the bed material were measured experimentally and then compared with theoretical values. Optimal εmf values were obtained by minimizing the objective function, the sum of squared residuals between experimental data and calculated data. On the other hand, sphericity of bed materials (Φ_s) was assumed as 0.86, the conventional value.

Table 3. Minimum fluidizing velocities and terminal velocities for silica sand with various sizes

Particle size (μm)	150		200 (214.4)		250 (242.5)	
Fluidizing gas (-)	Air	Ar	Air	Ar	Air	Ar
u_{mf} (cm·sec^{-1})	2.38	1.87	4.87	3.83	6.22	4.90
u_t (cm·sec^{-1})	55.00	50.30	89.11	86.46	103.49	102.61

2. Hydrodynamics of Bed Particles

The test of the hydrodynamics was carried out in the cold model CFB with a hybrid design built with acrylic plastic. Air was injected into FB and BFB and Ar was injected into BFB at ambient temperature, pressure. The flow rates were controlled by flow meters. The FB is composed of two parts, a mixer (section 1.2 in Fig. 2) and an upper bed (Section 1.1 in Fig. 2). The solid holdup in the mixer and upper bed was measured by pressure manometers connected to the FB under various fluidization conditions. The investigation of distribution of solid holdup in each part of the FB helps learning how to control the movement of the bed material in the system effectively. The FB is operated at two fluidization regimes, which are turbulent regime for the mixer and fast regime for upper bed. A cyclone, gas-solid separator, placed after FB, separates the entrained solids, such as char, ash, and bed material, from the gas flow exiting FB.

The study in hydrodynamic behavior of solid holdup in FB was carried out by measuring pressure difference in pressure manometers installed 4.1, 32.4, and 217.2 centimeters high from the distributor. Measured pressure differences were later used to estimate the solid holdup in each sector of the FB. Before each test, a fresh batch of sand was weighed and introduced into BFB. The designed tests were performed at different flow rates of Ar and Air in the BFB and the FB.

In this study, solid inventories (kg) up were calculated by Eqs. (5) and (6) [24]. First, differential pressures at static condition were measured and then converted to solid inventories.

$$L_{mf} = \frac{\Delta P_b}{(1-\varepsilon_{mf})(\rho_s-\rho_g)}\cdot\frac{g_c}{g} \quad (5)$$

$$\text{(solid inventory)} = L_{mf}\cdot\text{(cross sectional area)}\cdot\rho_s \quad (6)$$

where L_{mf} is height of minimum fluidized bed (m), ΔPb is pressure drop across the bed (Pa), ρ_s is density of solid (kg/m^3), ρ_g is density of gas (kg/m^3), g is acceleration of gravity (9.8 m/s^2), and g_c is gravity conversion factor (1 kg·m/N·s^2).

Silica sand (OK-75, US Silica) was used as bed material for the gas mixing and bed hydrodynamic experiments. The tests were run with three different groups of sands classified by the mass-average particle size of 150, 214, and 242 μm. The different sizes were used in order to gain a deep understanding of the influence of particle size on hydrodynamic parameter, solid holdup in the FB. The influence of varying particle size of bed material on bed hydrodynamics is of importance since this has to be taken into account when determining the range of particle size of bed material and feedstock for the gasification tests in a hybrid CFB. Understanding bed hydrodynamics behavior under different flow rates of gases into the BFB and FB can also help find optimum flow rates for gasification tests in terms of residence time, heat and mass transfer.

RESULTS AND DISCUSSION

1. Gas Mixing Test in the Cold Model Hybrid CFB

To evaluate gas mixing, pure Ar gas (99.99%+) was introduced into the left bed in BFB and the mixer in FB. Ambient air was introduced into the center and the right beds in BFB by using a com-

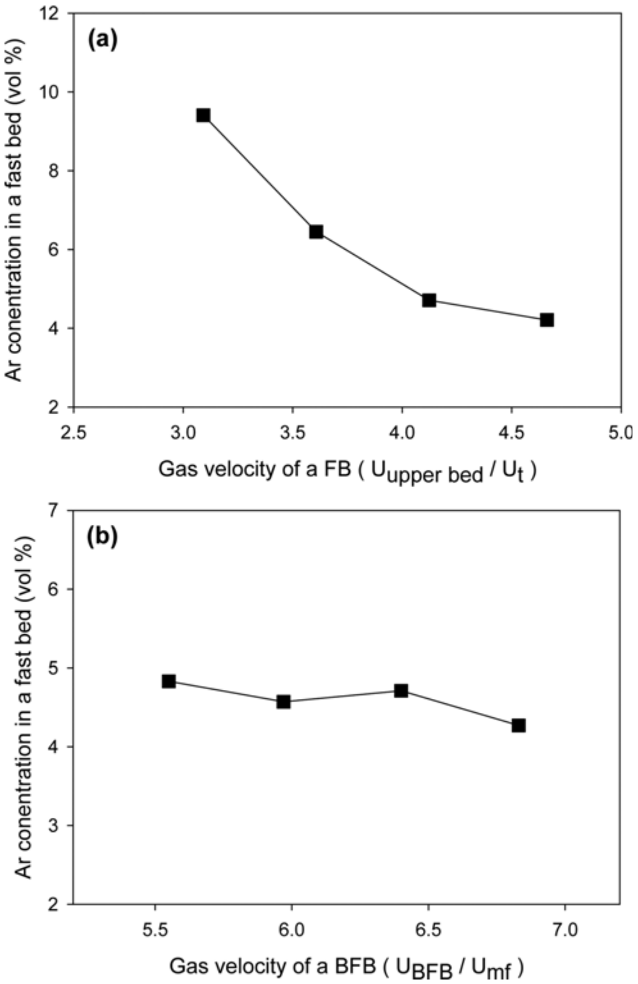

Fig. 4. Effect of inlet gas velocities of (a) a fast bed and (b) a bubbling fluidized bed on gas mixing behaviors: Ar concentration in the gas stream exiting from a fast bed.

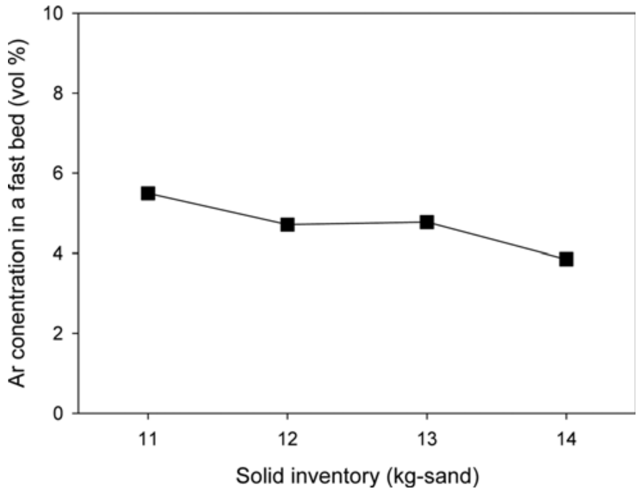

Fig. 5. Effect of solid inventory in the loop seal (BFB) on gas mixing behaviors: Ar concentration in the gas stream exiting from a fast bed.

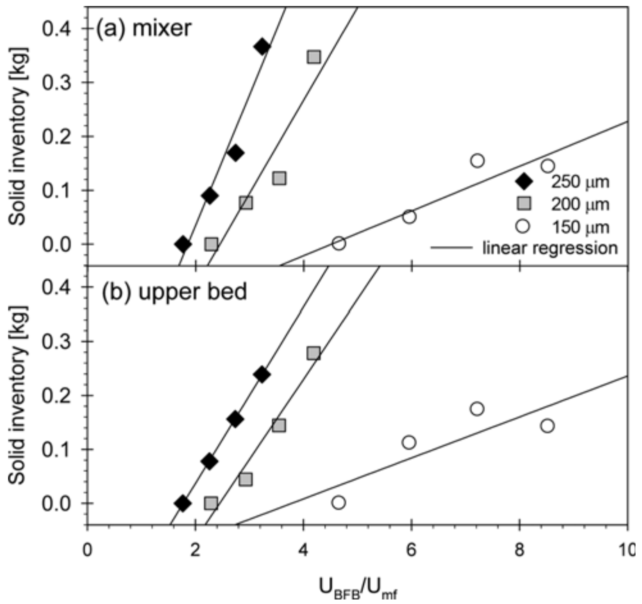

Fig. 6. Hydrodynamics of bed particles at flow rate of 9.91 Nm^3/hr at (a) the mixer and (b) the upper bed.

pressor and flow controllers. As can be seen in Fig. 4(a), increasing Air flow rate in FB resulted in a decrease in the Ar amount mixed in the exiting gas from the FB, which means lower degree of mixing of gases. This can be explained as that the higher Air flow rate transported more amount of bed material into BFB for the same period of time, resulting in improved loop seal efficiency. Namely, more amount of bed material circulation causes more amount of thermal energy supply into the riser. It can also improve the gasification efficiency. Furthermore, the effect of the change in Air flow rate in the BFB was investigated. The result in Fig. 4(b) displays an insignificant influence but slightly decreasing trend of mixing level. This result can be speculated such that as the flow rate of Air increases, the vigorous Air flow in the BFB prevented Ar transportation to FB, which resulted in lower Ar amount in the FB. Note that the change in Air flow in the FB plays a bigger role in a sealing effect than in BFB.

As mentioned above, the loop seal was designed and filled with sand for the purpose of preventing the contamination of valuable product gas with flue gas exiting from combustion part in a hybrid CFB when gasification reaction occurs. In the cold model hybrid CFB, the result of the mixing test with change in the solid inventory in the loop seal proved that increase in solid inventory in the loop seal has a positive effect on efficiency of gas separation in the system. It can be seen that percentage of Ar decreases from 5.49% to 3.85% in Fig. 5 with increasing solid inventory in the system.

2. Hydrodynamics of Bed Particles in the Cold Model Hybrid CFB

Fig. 6 shows the results of bed hydrodynamic test at 9.91 Nm^3/hr of Air injected into FB with different flow rate of Air and Ar injected into BFB. The flow rates of gases are shown in the form of dimensionless velocity (u_{BFB}/u_{mf}). First, an increase in solid holdup was observed in both the upper bed and the mixer with increasing gas velocity in BFB for all three types of sand. Second, the rate of the increase varies depending on particle size of sand. That is, whereas the solid holdup of 150 μm sand increases slowly with increase in gas velocity in BFB, the one of 200 μm and 250 μm increases relatively steeper. It can be explained that superficial gas velocity reached u_t of most of particles in the 150 μm sand group which resulted in immediate migration of most of the particles out of the FB. Therefore, less solid holdup in FB was observed for 150 μm group compared to other groups of sand. As for the other sand groups (212 and 242 μm), once the group of sand was transported from BFB to FB, a large portion of the group of sand failed to exit FB due to bigger particle size, which led to increasing solid holdup in FB.

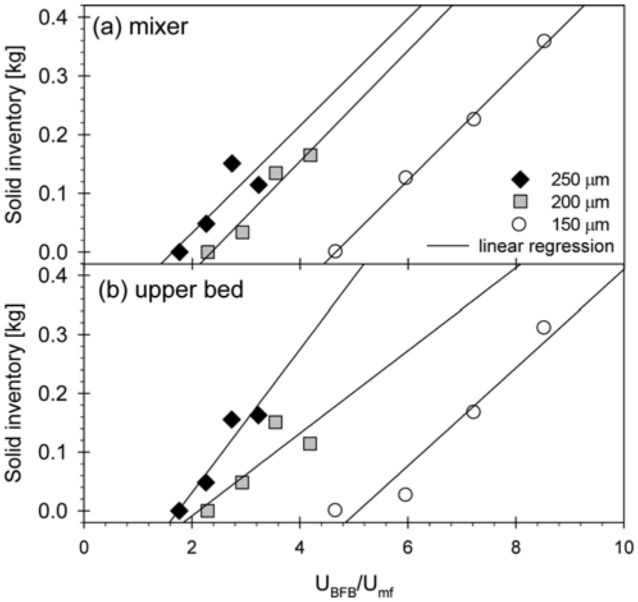

Fig. 7. Hydrodynamics of bed particles at flow rate of 11.33 Nm^3/hr at (a) the mixer and (b) the upper bed.

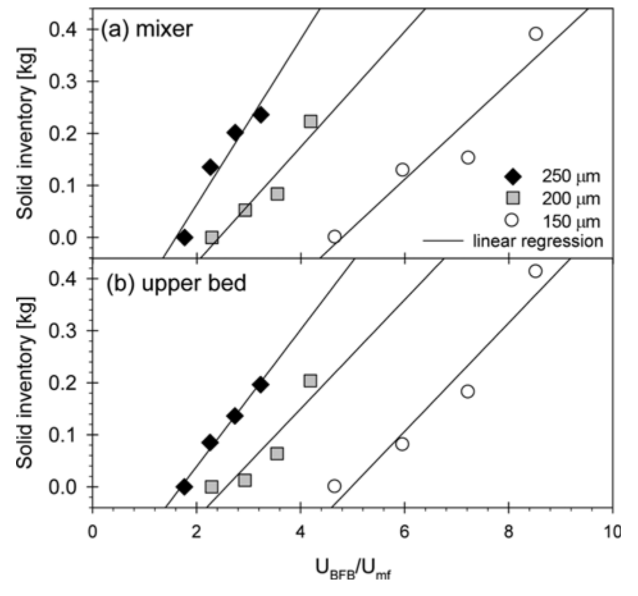

Fig. 8. Hydrodynamics of bed particles at flow rate of 12.74 Nm^3/hr at (a) the mixer and (b) the upper bed.

Fig. 7 and Fig. 8 show the results of bed hydrodynamic test at 11.33 and 12.74 Nm^3/hr of Air injected into FB, respectively. Overall increasing trend of solid holdup for all three types of sand was observed in both the upper bed and mixer with increasing gas velocity in BFB. As for the solid holdup for different size of sand (150, 200, and 250 μm), the bigger particle group overall showed higher solid holdup. Also, the slope of the graphs for all types of sand is almost the same as can be seen in Fig. 7 and Fig. 8. During the tests the circulation of the groups of sand (200, 250 μm) was intermittently interrupted during the tests at 11.33, 12.74 Nm^3/hr in FB. The circulation of sand can be achieved when the particle flow in the direction from the cyclone to BFB is strong enough to suppress the other uprising flow from BFB to FB or the cyclone. Furthermore, relatively heavier sand particles in the groups settled down to form a saltation layer of bed material at the bottom of the pipe between FB and cyclone. Therefore, the volumetric flow reduced in the result of smaller available cross sectional area of the pipe. This can explain the reduced solid holdup for the groups at the flow rate of 11.33, 12.74 Nm^3/hr in the FB. Simply, transportation of sand from BFB to FB was reduced in the situation. This interruption did not appear to happen with the smallest sand group of 150 μm.

The solid residing in the FB at fixed flow rate of 12.74 Nm^3/hr increased with increase in U_{BFB}. This is thought to be due to bed material transported to the FB faster at higher U_{BFB} with fixed U_{fast}, resulting in the increased solid holdup. When comparing the solid holdup for different size of sand (150,200, and 250 μm), the bigger particle group overall showed higher solid holdup. Also, the slope of the graphs for all types of sand is almost the same as can be seen in Fig. 7 and 7. As explained previously, the relatively lower solid holdup of the 200, 250 μm groups of sand can be explained by the reduced flow rate leaving FB. The results above show that the flow rate which determines the superficial gas velocity in the BFB is highly influential to the circulation of bed material in the hybrid CFB.

Bed hydrodynamics behavior tests overall suggest the importance of studying the trend of increase in solid holdup under certain flow rates under which it shows the steeper increase than the others. It is because the steep increase in solid holdup in the FB during gasification test at high temperature and pressure can mean excessive amount of bed material moved to the FB. And this can result in several unfortunate scenarios such as cyclone flooding or poor heat and mass balance in the system.

CONCLUSIONS

A cold model hybrid CFB was designed and built with a transparent acrylic plastic for the purpose of studying the hydrodynamics of bed material. The hybrid CFB for SHR will be developed with a better understanding of this specific type of reactor based on the research carried out in the cold model reactor. Mixing tests examined the level of mixing of gases from two beds using Air and Argon. The result of the first mixing test was that the gas stream exhausting combustor showed 100% pure Argon content, while the other gas stream exiting FB contained 95.3% of Air and 4.7% Argon. The result of the second mixing test under different fluidization conditions in BFB proved that increase in solid inventory in the loop seal (BFB) can improve the gas separation efficiency which can be realized at higher gas flow into FB and with higher solid inventory in the cold model CFB. The study of hydrodynamic behavior of solid holdup in the FB was carried out with different groups of sand, U_{fast}, and U_{BFB}. The solid holdup in the FB increased with increase in U_{BFB}. Conversely, increase in U_{fast} contributed to reducing the solid holdup in the FB. It was observed that changing the particle size of bed material did not have a big impact on hydrodynamic parameters. The U_{fast} should reach U_t for the biggest particle in a group of sand in the FB in order to enable a reliable analysis with the test data. The solid holdup in the FB is deeply related to kinetics of gasification reaction since bed material represents the mixing of solid and gas and furthermore heat and mass transfer. Therefore, it is necessary to know the changing trend of solid holdup in FB for interpretation of gasification reaction results in the configuration.

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NOMENCLATURE

D_{mixer} : diameter of mixer [cm]
$D_{upper\ bed}$: diameter of upper bed [cm]
D_{BFB} : diameter of bubbling fluidized bed [cm]
h_{fast} : height of fast bed [cm]
h_{BFB} : height of bubbling fluidized bed [cm]
d_s : average diameter of sand [μm]
U_t : terminal velocity [cm/sec]
U_{mf} : minimum fluidization velocity [cm/sec]
$Q_{fast,AIR}$: air flow rate injected into fast bed [Nm^3/hr]
$Q_{BFB,AIR}$: air flow rate injected into bubbling fluidized bed [Nm^3/hr]
$Q_{BFB,Ar}$: argon flow rate injected into bubbling fluidized bed [Nm^3/hr]
$U_{upper\ bed}$: superficial gas velocity in upper bed [cm/sec]
U_{mixer} : superficial gas velocity in mixer [cm/sec]
U_{fast} : superficial gas velocity in fast bed [cm/sec]
U_{BFB} : superficial gas velocity in bubbling fluidized bed [cm/sec]
m_{SYS} : sand inventory in the system [kg]

Greek Symbols

ρ_s : particle density of sand [kg/m^3]
ρ_G : density of gas (air) [kg/m^3]

Abbreviations

GHG : greenhouse gas
CE-CERT : center for environmental research & technology (CE-CERT)
UCR : University of California, Riverside
SH : steam hydrogasification
CFB : circulating fluidized bed
BFB : bubbling fluidized bed
FB : fast bed
RGA : residual gas analyzer

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