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Young-ju Seo
Korea Institute of Energy Research, Daejon

Solim Kang
Korea Institute of Energy Research, Daejon

Seung-Yong Lee
Korea Institute of Energy Research, Daejon

Young Cheol Park
Korea Institute of Energy Research

Ho-Jung Ryu
Korea Institute of Energy Research, Daejon, hjryu@kier.re.kr

See next page for additional authors

Authors
Young-ju Seo, Solim Kang, Seung-Yong Lee, Young Cheol Park, Ho-Jung Ryu, Gyoung Tae Jin, and Jong-Ho Moon

A STUDY OF SOLID AND GAS MIXING IN A PARTITIONED FLUIDIZED BED

Jong-Ho Moon, Young-Ju Seo, Solim Kang, Seung-Yong Lee,
Young-Cheol Park, Ho-Jung Ryu, and Gyoung-Tae Jin
Korea Institute of Energy Research, Greenhouse Gas Research Center
71-2 Jang-dong, Yuseong-gu, Daejon 305-343, Korea
T: +82-42-860-3676. F: +82-42-860-3134. E: gtjin@kier.re.kr

ABSTRACT

A partitioned fluidized bed gasifier has been developed for improving coal gasification performance. The basic concept is to divide a fluidized bed into two parts, a gasifier and a combustor, by a partition. Char is burnt in the combustor and generated heat is supplied to the gasifier by solid mixing. Therefore, solid mixing should be maximized whereas gas mixing between syngas and the combusted gas should be minimized. In this study, gas and solid mixing behaviors were verified in cold model acrylic beds. For monitoring solid mixing behavior, transient temperature trends in the beds were analyzed. A heat source and a heat sink were installed in each bed. Dozens of thermocouples were used to monitor temperature distribution.

INTRODUCTION

Since the world recoverable oil resources will be depleted within the next few decades, a search for alternatives to oil is an urgent task. In the post-oil era, coal technologies are of great interest as a practical alternative to oil, due to their cost, availability and versatility. However coal causes 40% of global CO_2 emissions. CO_2 is considered as a representative green-house gas and increased levels of CO_2 with other green-house gases in the atmosphere contribute to global warming. To sum up, mankind will have to use coal, but at the same time restrain CO_2 emissions. Therefore, clean coal technologies should be developed.

The solid residence time depends on solids feed rate in a fluidized bed. In a dual bed system, the solid residence time depends on the sum of the solid feed rates and solid circulation rates. If the heat requirement is increased, it is necessary to increase the solid circulation rates. This shortens the residence time of solids and reduces the solid conversion. To overcome this, a “partitioned fluidized bed” concept for low rank coal gasification has been developed (figure 1). The upper part of the bed is blocked by a partition, but the lower part of the partition is open to connect the two beds. Endothermic reactions (coal gasification) and exothermic reactions (coal combustion) occur simultaneously in a gasifier and combustor. For coal gasification, a high temperature of over 900^{o}C is needed. Most of the heat is generated by coal combustion. Therefore, the generated heat should be supplied from a combustor to a gasifier using the bed materials.

In this study, cold model experiments in a “partitioned fluidized bed (transparent acrylic bed)” were executed at atmospheric conditions to understand solid and gas mixing behavior. N_2, CO_2 and compressed air were introduced as fluidizing gases into each partitioned fluidized bed. For the gas mixing experiments, glass beads with an average diameter of 150 microns and particle density of 2.5 g/cm^3 were used. As can be seen in figure 2(a), CO_2 and N_2 were introduced into each distributor in the bed. Outlet gas flow rates and concentrations for each bed were analyzed by gas flow meters and FT-IR respectively. The gas exchange ratios between the reactors were then calculated. For the solid mixing experiments, 1000-micron polypropylene particles with a density of 0.883 g/cm^3 were continuously fed into the reactor. As a fluidizing gas, compressed air was introduced into each bed. For improving solid mixing, newly developed distributors and plenums were installed. The objectives of this study were to understand gas and solid mixing characteristics and to quantify the solid flux between the reactors under various operating conditions.

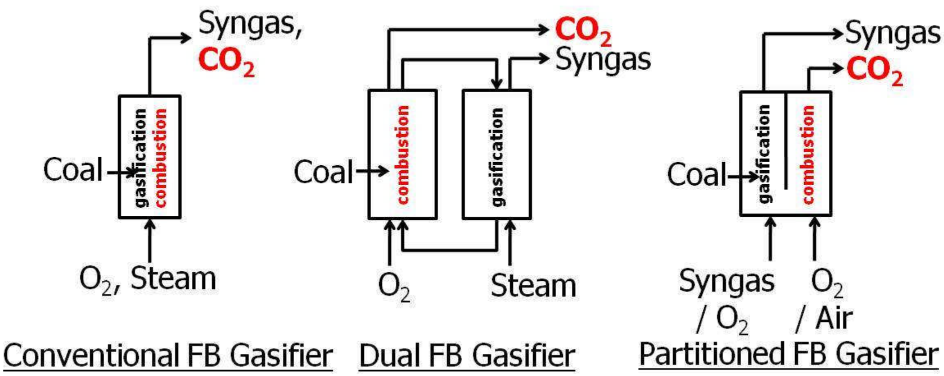


Figure 1. Schematic diagrams of coal gasifiers:
conventional, dual, and partitioned fluidized bed gasifiers

EXPERIMENTAL

Experimental Method (1): Gas Mixing

For gas mixing experiments, CO_2 and N_2 were introduced into each distributor. Experimental procedure was (Figure 3): step 1. Initially, introduce N_2 into each partitioned bed (L, C, R) to fluidize the solids, step 2. Switch N_2 to CO_2 in the center bed by using a 3-way valve, step 3. Measure flow rates and concentrations. Outlet gas flow rates and concentrations of each fluidized bed were analyzed by gas flow meters and IR respectively. Then, the gas exchange rates between the reactors were calculated.

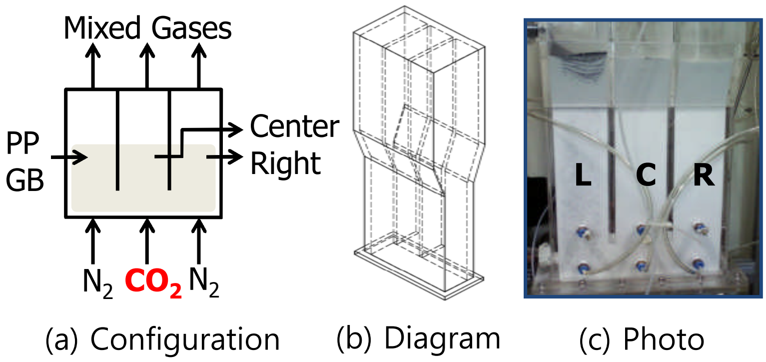


Figure 2. Schematic diagram of a partitioned fluidized bed: (a) Cold model configuration, (b) Diagram, and (c) Apparatus for cold mode run

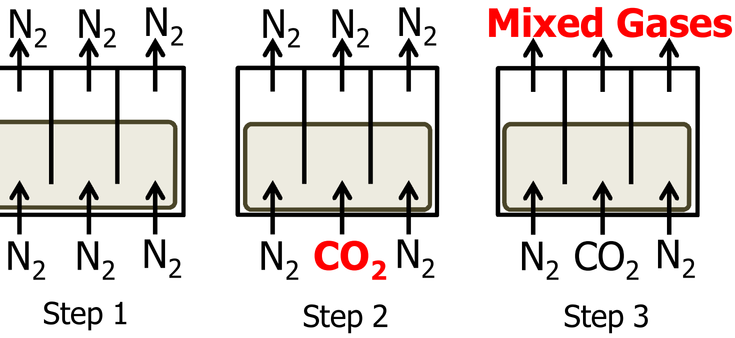


Figure 3. Experimental procedure for gas mixing evaluation

At first, CO_2 and N_2 compositions and flow rates at the inlet and the outlet of each bed were measured and/or calculated respectively. Then, they were substituted into the following equations;

$$X_{RC} = \frac{V_C \times y_{C,CO_2}}{F_R \times x_{R,CO_2}} \tag{1}$$

$$X_{CR} = \frac{V_R \times y_{R,N_2}}{F_C \times x_{C,N_2}} \tag{2}$$

Where, X_{RC} (Eq. 1) is the gas exchange ratio from the right side bed to the center bed and the X_{CR} (Eq. 2) is the gas exchange in the opposite direction. F and V are inlet and outlet flow rates respectively. Small x and y are inlet and outlet mole fractions respectively. Subscripts R and C mean left and center beds.

Experimental Method (2): Solid Mixing

For the solid mixing experiments, the 1000-micron polypropylene particles with a density of 0.883 g/cm^3 were continuously fed into the left bed (L). Mixed solid particles were withdrawn from the center bed (C) and the right bed (R) (figure 4). As a fluidizing gas, compressed air was introduced into each partitioned fluidized bed by controlling input flow rates. Outlet gas flow rates of each fluidized bed were measured by gas flow meters. Withdrawn mixed solid particles (GB/PP) were separated by sieves. The solid particle distributions were measured by weighing the separated particles.

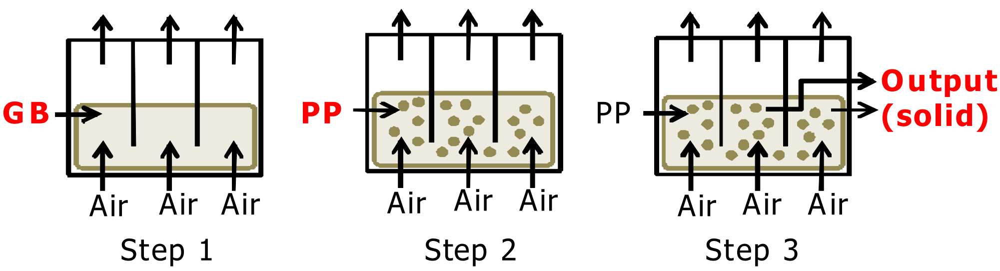


Figure 4. Experimental procedure of solid mixing at a three partitioned fluidized bed gasifier.

Center and right side solid discharge ratio could be controlled by the fluidizing gas velocity in each side bed. The discharge percentage of center was mainly affected by the ratio of U_C (input fluidizing velocity at center bed) to U_R (right bed). As can be seen in figure 5, solid mixing in a three partitioned fluidized bed can be considered the same as in a CSTR.

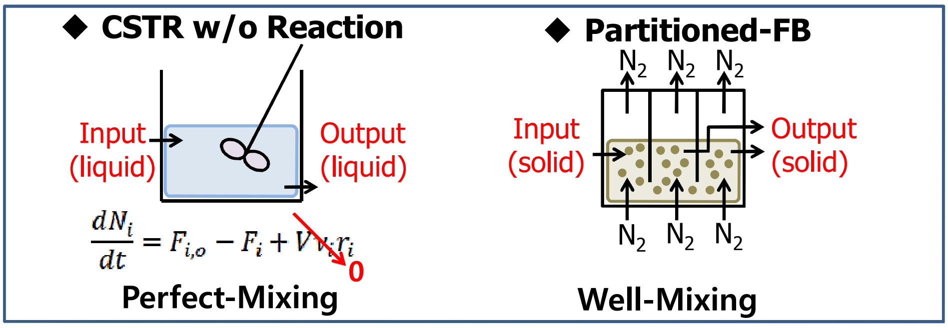
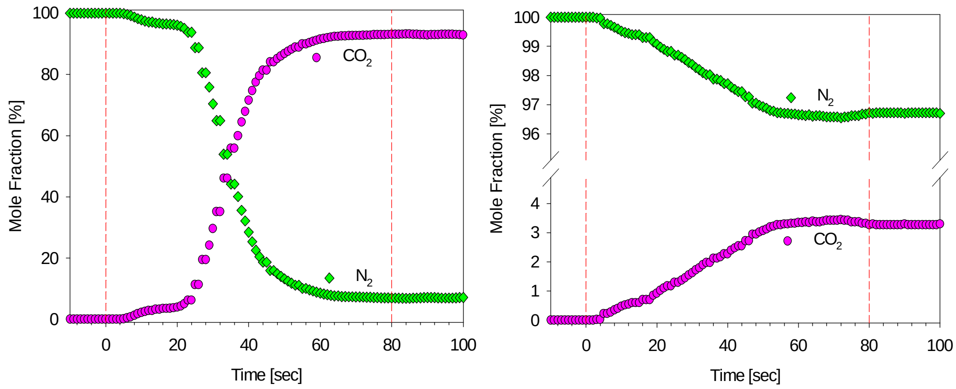


Figure 5. Analogy between a CSTR and a Partitioned fluidized bed.

RESULTS AND DISCUSSION

Gas Exchange Experiments

The effect of gas velocity on gas mixing is shown in figures 6 and 7. In this experiment, the gas velocity of each reactor was same.



(a) Center Bed (b) Right Bed

Figure 6. Transient gas mixing behavior (U_L=U_C=U_R=2U_{mf}): (a) Center Bed and (b) Right bed

The left side, center and right side gas velocities were 2, 3, and 4 times the minimum fluidizing velocity (U_{mf}). Figure 6 shows transient gas mixing behavior for the center and right beds. It reached a steady state within 80 sec. After reaching steady state, CO_2 mol% in the center bed was 93.5% (X_{CR}=0.032) and N_2 mol% in the right bed was 97.0% (X_{RC}=0.0.032). This means that the effect of gas mixing in the partitioned fluidized bed was very small. Increasing the gas velocity from 2.0 to

4.0 U_{mf}, caused the gas exchange rates from the center to left(X_{CL}) and right(X_{CR}) to decrease while the gas flows from the left and right to center (X_{LC} and X_{RC}) increased.

At the same gas velocity in each bed (figure. 7 (a)), the gas exchange ratios, from center to right and from right to center, had similar values. At higher flow rates, gas mixing was slightly enhanced. At a low gas velocity condition in the center (figure. 7(b)), X_{CR} was far higher than X_{RC}. The exchanged CO_2 amount from center to right decreased, whereas the exchanged N_2 amount from right to center increased. X_{RC} was not affected by the center flow rate. At low flow rates in right and left beds (figure 7 (c)), the exchanged CO_2 amount from the C to R bed linearly increased, while the exchanged N_2 amount from the right to center bed decreased. That means the flow from the side to the center became dominant. X_{CR} was not affected by flow rate in the center bed.

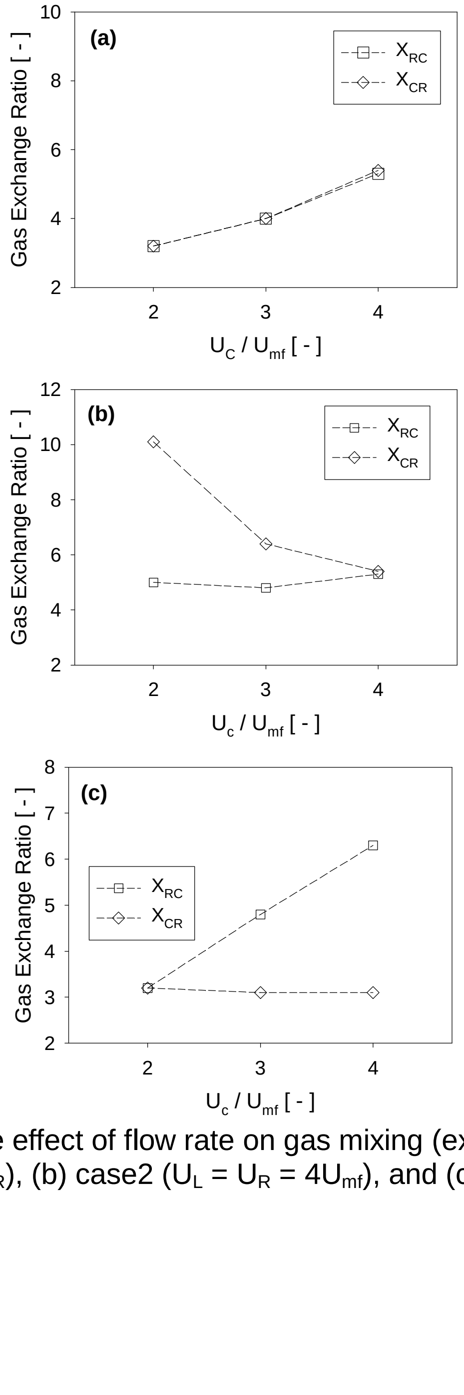


Figure 7. The effect of flow rate on gas mixing (exchange ratio):
(a) case1 ($U_L = U_C = U_R$), (b) case2 ($U_L = U_R = 4U_{mf}$), and (c) case3 ($U_L = U_R = 2U_{mf}$)

Solid Mixing Experiments

Figure 8 shows analogies between a CSTR and a partitioned fluidized bed. CSTR behaviors are based on perfect mixing. That is, as soon as reactants are introduced into a reactor, mixing and reaction occurs immediately. For no reaction, a CSTR is a perfect mixer. Similarly, if solids are well mixed in a three-partitioned fluidized bed, the solid concentration in each partitioned bed will be the same. Figure 8(a) shows a comparison between calculated CSTR behavior and experimental data from a partitioned fluidized bed. The calculated line is CSTR behavior and the squares are experimental data from a partitioned fluidized bed, where the x-axis is time and the y-axis is PP (polypropylene) concentration in the mixtures.

The second figure indicates PP concentration dispersion between the center and right beds. The x-axis is PP concentration in the center bed and the y-axis is that in the right bed. The diagonal line shows the case when the PP concentration in the center and right beds are exactly same, i.e. CSTR behavior. The squares are the experimental data.

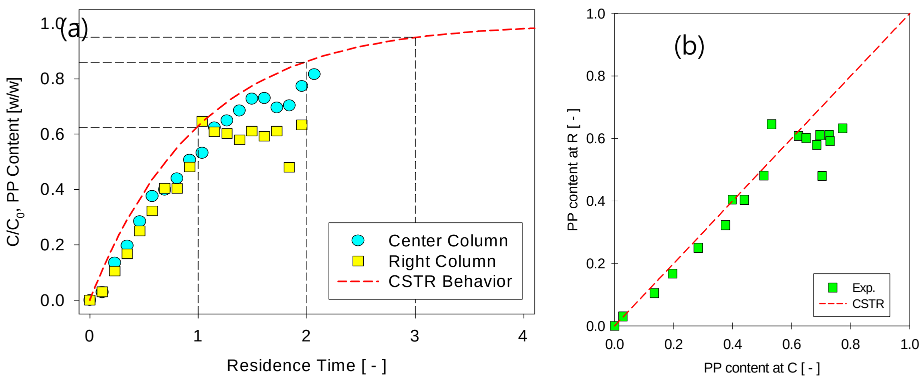


Figure 8. Experimental vs. theoretical results of solid mixing behavior ($U_L = U_C = U_R = 2U_{mf}$):
(a) Comparison between CSTR and partitioned fluidized bed, and
(b) Particle distribution at the partitioned bed fluidized bed

Temperature Trend

As can be seen from the above results, the solid mixing behavior in a three partitioned bed is analogous to liquid mixing behavior in a CSTR. These results were be confirmed by analyzing temperature distribution. Dozens of thermocouples were added to the beds for monitoring temperature distribution. (See Figure. 9) For improving solid mixing, newly-developed distributor systems were installed.

For monitoring solid mixing behavior, transient temperature trends in the beds were analyzed. A heat source (right bed) and a heat sink (left bed) were installed in each bed at a height of 55 cm. Dozens of thermocouples were equipped for monitoring temperature distribution. Figure 10 shows the transient temperature trend at the heat source (combustor) and the heat sink (gasifier). Initially, fluidizing air was not introduced into the beds. Therefore, the temperatures at the heat source and the heat sink could be kept constant at 24℃ and 19℃, respectively. After introducing fluidizing air (U_L = U_R = $2U_{mf}$) into the beds, generated heat was transferred from the right bed (heat source) to the left bed (heat sink). Temperatures at all positions reached steady state within 50 seconds. This means that the solids (or temperature) can be dispersed well in spite of a partition in the bed.

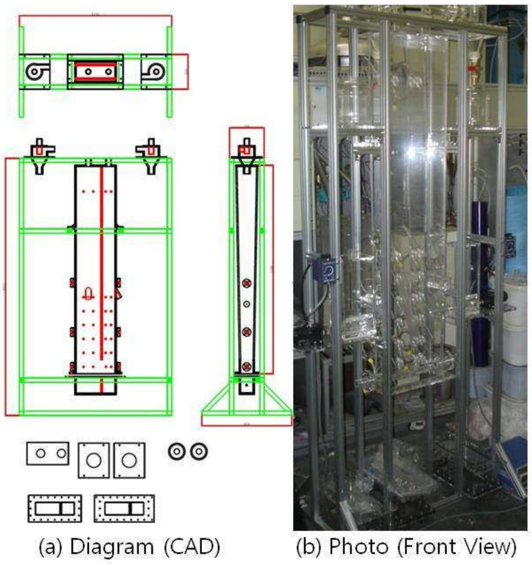


Figure 9. Cold mode partitioned bed for analyzing temperature distribution.

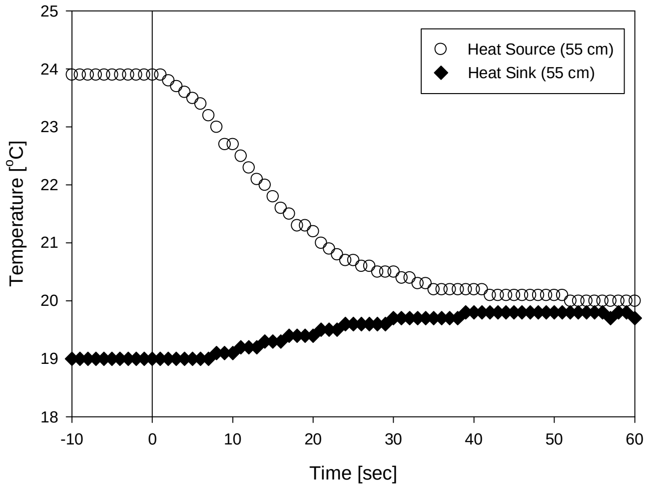


Figure 10. Transient temperature trend in a partitioned fluidized bed (U_L = U_R = $2U_{mf}$); temperature at heat source (white circles) and heat sink (black diamonds)

CONCLUSIONS

Gas and solid mixing experiments in partitioned fluidized beds were conducted. Gas mixing between the partitioned fluidized beds can be minimized by controlling the gas velocity in the beds.

The center and right side solid discharge ratio can be controlled by the fluidizing gas velocity in each side bed. The discharge percentage in the center bed is mainly affected by the ratio of U_C to U_R. Solid mixing in partitioned fluidized beds can be considered well mixed as in a CSTR.

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NOTATIONS

F	inlet mass flow rates respectively (g s^{-1})
r	rate of reaction (g cm^{-3} s^{-1})
t	time (s)
U	gas velocity (cm s^{-1})
V	outlet mass flow rates (g s^{-1})
X_{CR}	gas exchange ratio from the center to the right side (-)
x	inlet mole fraction (-)
y	outlet mole fraction (-)

Subscripts

L, C, R	left, center and right respectively
mf	minimum fluidization conditions

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