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Solid Circulation Rate and Gas Leakage Measurements in an Interconnected Bubbling Fluidized Beds

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***Abstract*—**Two-interconnected fluidized bed systems are widely used in various processes such as Fisher-Tropsch, hot gas desulfurization, CO_2 capture-regeneration with dry sorbent, chemical-looping combustion, sorption enhanced steam methane reforming, chemical-looping hydrogen generation system, and so on. However, most of two-interconnected fluidized beds systems require riser and/or pneumatic transport line for solid conveying and loopseals or seal-pots for gas sealing, recirculation of solids to the riser, and maintaining of pressure balance. The riser (transport bed) is operated at the high velocity fluidization condition and residence times of gas and solid in the riser are very short. If the reaction rate of catalyst or sorbent is slow, the riser can not ensure sufficient contact time between gas and solid and we have to use two bubbling beds for each reaction to ensure sufficient contact time. In this case, additional riser must be installed for solid circulation. Consequently, conventional two-interconnected fluidized bed systems are very complex, large, and difficult to operate. To solve these problems, a novel two-interconnected fluidized bed system has been developed. This system has two bubbling beds, solid injection nozzles, solid conveying lines, and downcomers. In this study, effects of operating variables on solid circulation rate, gas leakage between two beds have been investigated in a cold mode two-interconnected fluidized bed system. Moreover, long-term operation of continuous solid circulation up to 60 hours has been performed to check feasibility of stable operation.

***Keywords*—**Fluidized bed, Gas leakage, Long-term operation, Solid circulation.

I. INTRODUCTION

TWO interconnected fluidized bed systems are widely used in various processes to accomplish simultaneous dual reactions in one process such as Fisher-Tropsch, hot gas desulfurization, CO_2 capture-regeneration with dry sorbent, chemical-looping combustion, sorption enhanced steam methane reforming, chemical-looping hydrogen generation system, and so on. Most of these processes need two or more reactors and need non-mechanical valves for solid conveying and gas sealing between two reactors such as loopseal, seal pot, J-valve, L-valve, U-valve, and so on [1]. Fig. 1 shows a conceptual diagram of conventional two interconnected circulating fluidized bed systems [2]-[4]. Fig. 1(a) represents bubbling-bubbling-transport mode. This mode consists of two bubbling beds, one transport bed, two loopseals and three cyclones. Two bubbling beds are used as reactors for each reaction and transport bed is used for solid conveying. This mode is usually applied when two reactions are slow and longer contact time between gas and solid is favorable. However, this mode is difficult to operate because maintaining of pressure balance for three fluidized beds and loopseals is difficult, and a back flow of solid is main problem. Indeed, this mode requires much solid inventory in loopseals and many gas injection ports, at least five. If one reaction rate is fast enough, the transport bed can be used for reaction and solid conveying, simultaneously, as shown in Fig. 1(b). This mode consists of one bubbling beds, one transport bed, two loopseals and two cyclones. One bubbling beds is used as reactor and transport bed is used for reaction and solid conveying, simultaneously. This mode is also difficult to maintain pressure balance for two fluidized beds and loopseals (or other non-mechanical valves). The main disadvantages of bubbling-bubbling-transport and bubbling-transport mode are complexity and huge system volume. Actually, these two systems contain four or five vessels contains gas-solid mixture (two or three fluized beds and two loopseals), and therefore, many gas flows are required and volume of systems are huge. To solve these problems, two bubbling beds mode (Fig. 1(c)) has been proposed. This mode consists of two bubbling beds and two cyclones. Two bubbling beds are used as reactors for each reaction and gases for each reaction are switched periodically. This mode is usually applied when two reactions are slow and longer contact time between gas and solid is favorable. However, there is pressure shock during gas switching and this system requires purging to clean each bed before gas switching. Indeed, this mode is difficult to operate when two reactions take place at different temperatures.

In this study, a novel two interconnected fluidized bed system has been developed. The compact two-bed system has two bubbling beds, solid injection nozzles, solid conveying

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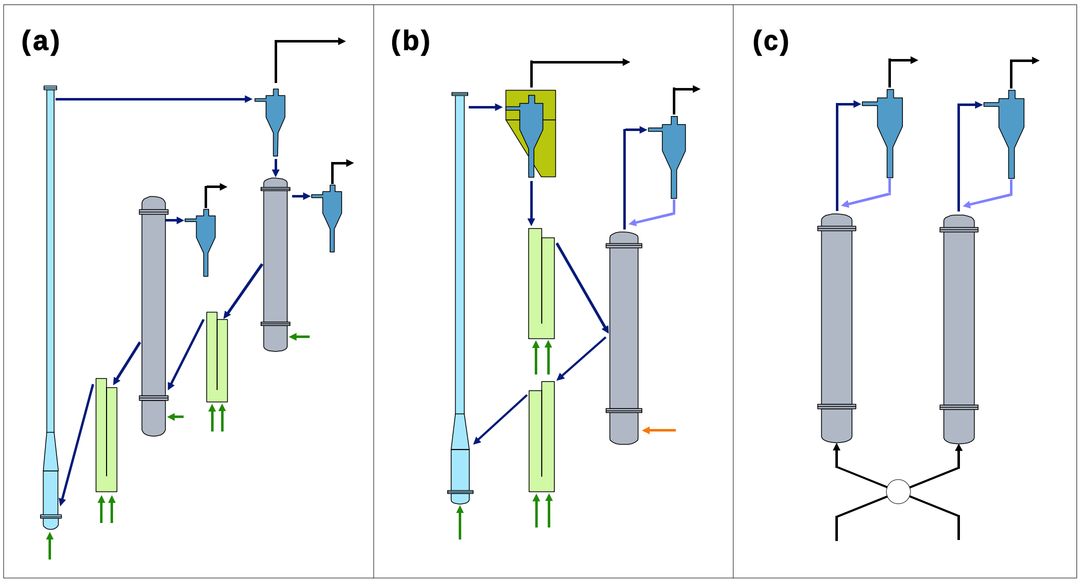

Fig. 1 Schematic of conventional two interconnected circulating fluidized bed system

lines, and downcomers. By using this system, effects of operating variables on solid circulation rate, gas leakage between two beds have been investigated and long-term operation of continuous solid circulation up to 60 hours has been performed to check feasibility of stable operation.

II. EXPERIMENTAL SECTION

The solid circulation rate measurements, gas leakage tests, and long-term operation test were carried out in a two bubbling beds interconnected circulating fluidized bed system. A schematic of the system is shown in Fig. 2. The major components consist of plenums, bubbling beds, solid injection nozzles, risers, cyclones, and downcomers. The bubbling bed above the plenum is 0.8 m high with an internal diameter of 0.15 m and the dimensions of two bubbling beds are exactly same. The inside diameters of riser and downcomer are 0.016 m. Two cyclones have standard proportions with an internal diameter of 0.055 m. The particles are sharp sand with a density of 2575 kg/m^3 and an average size of 0.159 mm (106-212 μm). The fluidizing gas was air except for gas leakage tests and all experiments were carried out at room temperature. The fluidizing gases (Q_1, Q_2) are added in the bottom of the bubbling fluidized beds through perforated plates which have 25 holes with a diameter of 1 mm. The gases for solid injection (Q_3, Q_4) are added in the bottom of the bubbling fluidized bed through the solid injection nozzles. The gases going to the plenums and solid injection nozzles are controlled by four mass flow controllers. The gas flow rate to the plenum (for fluidization) and the solid injection nozzle, inside diameter of the solid injection nozzle, the number of holes on the solid injection nozzle, solid height above the holes were considered as the experimental variables.

The solid circulation rate was measured by particle weight measurement technique [5]. At the steady-state condition, we diverted solid flow from downcomer to solid hopper by using diverter. After capturing of the solids, solid circulation rate was calculated based on the weight of solids and time.

For gas leakage measurements a tracer gas method was used [6]-[7]. The CO_2 was replaced with air, and the concentration of CO_2 in the gases from four ports (P1, P2, P3, P4 in Fig. 2) was measured by on-line gas analyzer. Solving the mass balances of the CO_2 yields the leakage flow between the beds and nozzles. The leakage is defined as the fraction of gas added to the each gas adding point. The leakages measured at four measuring points indicate different gas leakage. The leakages measured at P1, P2, P3, P4 indicate gas mixing between Q1 and Q3 in the left bubbling bed, (Q1+Q3) and (Q2+Q4) in the cyclone and downcomer, Q2 and Q4 in the right bubbling bed, and (Q2+A4) and (Q1+Q3) in the cyclone and downcomer, respectively.

III. RESULTS AND DISCUSSION

A. Minimum Fluidization Velocity (U_{mf})

To determine gas flow rate through two bubbling fluidized beds, minimum fluidization velocity was determined by bed pressure drop measurement [8]. Fig. 3 shows trend of bed pressure drop versus gas velocity in the bed. For the relatively low flow rates in a fixed bed, the pressure drop is approximately proportional to gas velocity, and usually reaching a maximum value. With gas velocities beyond minimum fluidization, the bed expands and gas bubbles are seen to be present. Despite this rise in gas flow, the pressure drop remains practically unchanged. Usually, the gas velocity when the pressure drop shows the maximum value is considered as the minimum fluidization velocity and it was 0.018 m/s for sharp sand.

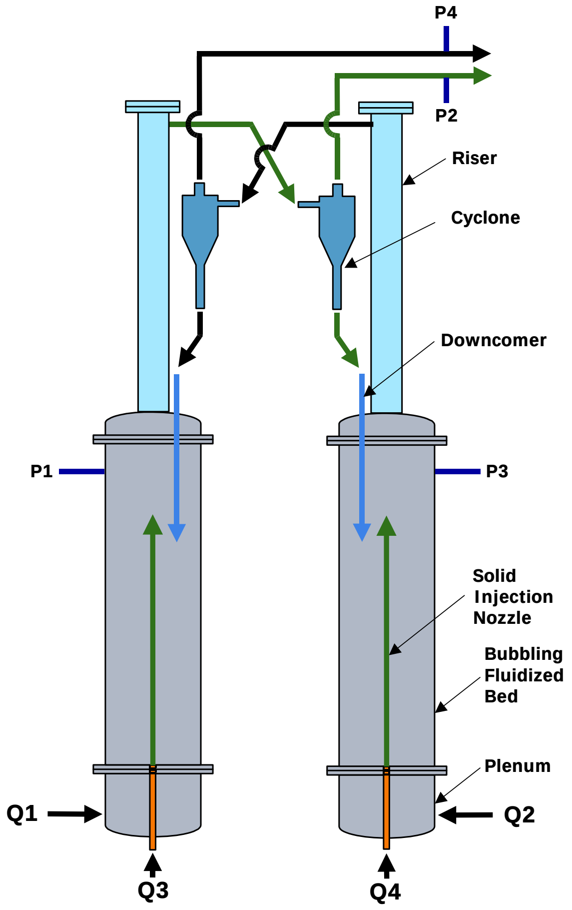

Fig. 2 Schematic of two bubbling beds interconnected circulating fluidized bed system

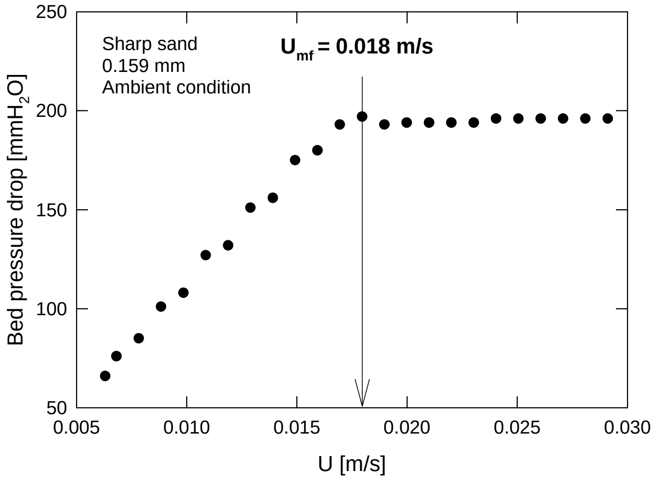

Fig. 3 Bed pressure drop versus gas velocity for sharp sand

B. *Solid Circulation Rate*

Fig. 4 shows effects of gas velocities through the solid injection nozzles in the left and right bubbling fluidized beds (U_3, U_4), fluidizing velocity in the left and right bubbling fluidized beds (U_1, U_2), the number of holes on the solid injection nozzle on solid circulation rate from left to right bed. The measured solid circulation rate increased as the gas velocity through the solid injection nozzle increased. However at high gas velocity, solid circulation rates were maintained at almost constant values. At the same U_3, the change of fluidizing velocities (U_1, U_2) does not affect solid circulation rate, and this results indicate that gas velocity through the solid injection nozzle (U_3 or U_4) is the main parameter to control the solid circulation rate. Moreover, gas velocity through the injection nozzle in right bed does not affect solid circulation rate from left bed (compare ● and ○, ■ and □, ♦ and ◊ in Fig. 4). Fig. 4 also indicates that more holes on the solid injection nozzle gives higher solid circulation rate at the same condition.

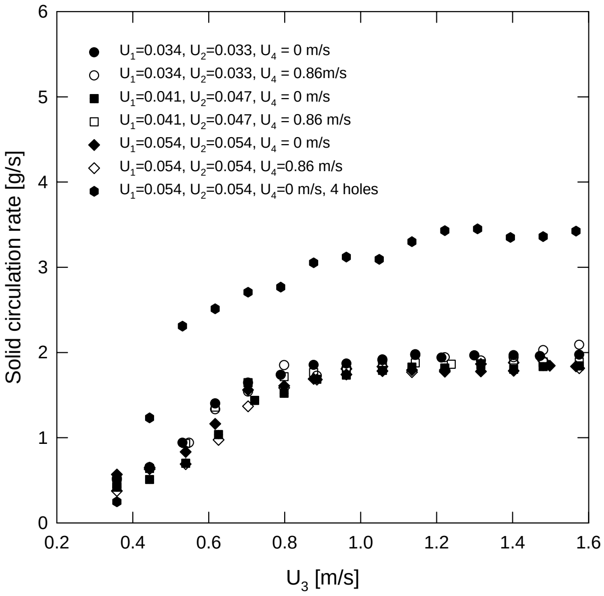

Fig. 4 Solid circulation rate versus gas velocity through the solid injection nozzle at different conditions (injection nozzle diameter: 0.0037 m, hole diameter: 2mm, solid height: 0.2 m)

Fig. 5 shows effects of gas velocity through the solid injection nozzle, solid height (H_{bed}), and the number of holes on the solid injection nozzle on solid circulation rate. The measured solid circulation rate increased as the gas velocity through the solid injection nozzle increased. Moreover, at the same condition, the solid circulation rate increased as the number of holes increased and solid height above hole increased.

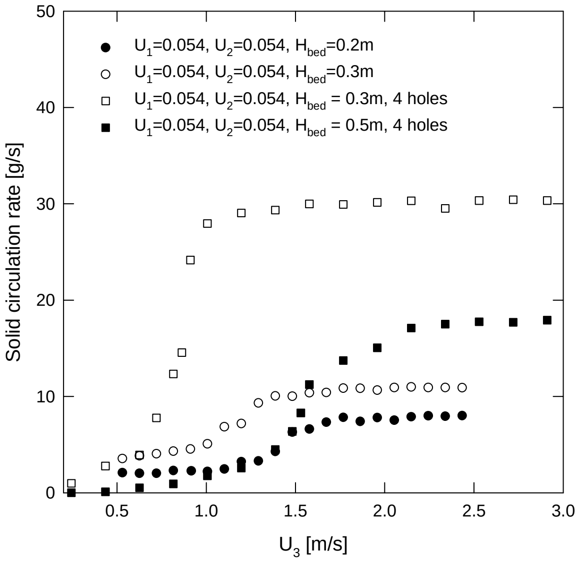

Fig. 5 Solid circulation rate versus gas velocity through the solid injection nozzle at different conditions (injection nozzle diameter: 0.0075 m, hole diameter: 4 mm)

Fig. 6 shows effects of gas velocity through the solid injection nozzle, solid height (H_{bed}), and the number of holes on the solid injection nozzle on solid circulation rate. The measured solid circulation rate increased as the gas velocity through the solid injection nozzle, the number of holes, and the solid height above hole increased, consistent with Fig. 5. Comparison of Fig. 4, 5, and 6 indicates that the solid circulation rate increased as the diameter of solid injection nozzle increased and as the hole diameter increased. Moreover, we can control solid circulation rate with wide range from 0 to 60 g/s.

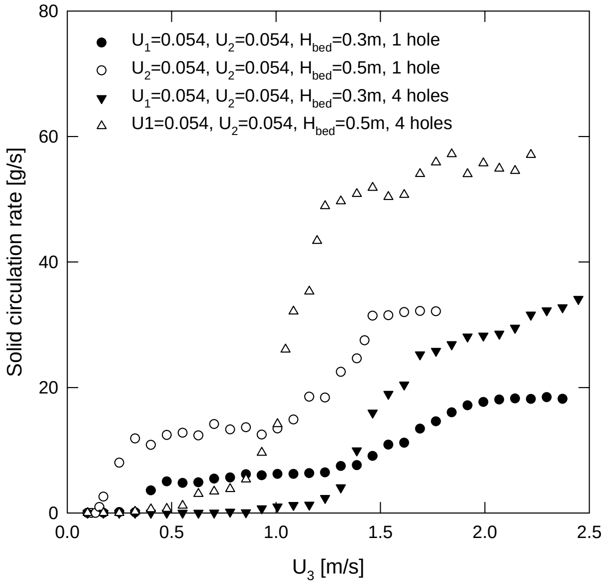

Fig. 6 Solid circulation rate versus gas velocity through the solid injection nozzle at different conditions (injection nozzle diameter: 0.0104 m, hole diameter: 6 mm)

C. Gas Leakage

In order to investigate the leakage from the hole on the solid injection nozzle to bubbling fluidized bed, CO_2 gas was added as the tracer gas to solid injection nozzle in the left fluidized bed. The detail experimental conditions are provided in Table 1. Fig. 7 shows measured CO_2 concentration in four ports. As explained in the experimental section, the leakages measured at P1, P2, P3, P4 indicate gas mixing between Q1 and Q3 in the left bubbling bed, (Q1+Q3) and (Q2+Q4) in the cyclone and downcomer, Q2 and Q4 in the right bubbling bed, and (Q2+Q4) and (Q1+Q3) in the cyclone and downcomer, respectively. In Fig. 7(a), the measure CO_2 concentration at P_2 increased as the CO_2 flow rate in the solid injection nozzle increased because gas mixing between air from the bubbling bed and CO_2 from solid injection nozzle, as expected. However, the measure CO_2 concentration at P_1 shows different results with gas velocity in the solid injection nozzle. At relatively low gas velocity, solid flow through the solid injection nozzle is unstable and CO_2 detected at P2, but at higher gas velocity, solid flow through the solid injection nozzle is stable and CO_2 was not detected at all. These results indicate that we can avoid gas leakage from the hole on the solid injection nozzle to bubbling fluidized bed by using this system during steady-state operation. Fig. 7(b) indicates that there is no gas mixing between two bubbling fluidized beds.

TABLE I
EXPERIMENTAL CONDITIONS FOR GAS LEAKAGE TESTS

Test No.	Variable	Value
1	Injection nozzle diameter (left)	0.0075 m
	Hole diameter (left)	4 mm
	Number of holes (left)	4 ea
	Injection nozzle diameter (right)	0.0075 m
	Hole diameter (right)	6 mm
	Number of holes (right)	2 ea
	Solid height	0.5 m
	Q1	Air, 0.072 m/s
	Q2	Air, 0.072 m/s
	Q3	CO_2, change
	Q4	Air, 2.68 m/s
2	At the same condition of injection nozzle, hole and solid height,	
	Q1	CO_2, 0.072 m/s
	Q2	Air, 0.072 m/s
	Q3	CO_2, 2.9 m/s
	Q4	Air, 2.9 m/s

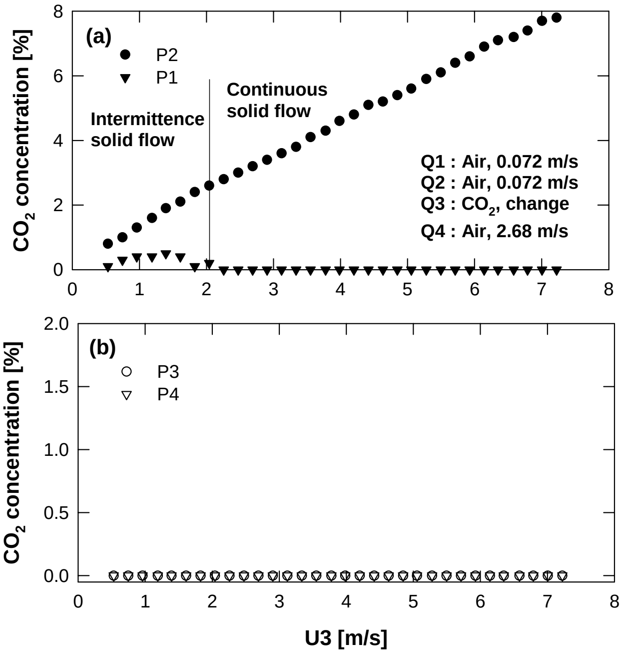

Fig. 7 CO_2 concentration versus gas velocity through the solid injection nozzle at different measuring points (Test No. 1)

As the second test, we fed CO_2 not only through the solid injection nozzle but also through bubbling fluidized bed to check gas mixing between two bubbling fluidized beds. The detail experimental conditions are also provided in Table I (see test No. 2). The measured CO_2 concentrations at P1, P2, P3, P4 were 100, 100, 0.3, 0.5 %, repectively. This result indicates that the gas leakage between two bubbling fluidized beds is negligible. Consequently, the gas leakage from the solid injection nozzle to bubbling fluidized bed and between two fluidized beds can be avoided by using this system.

D. Long-Term Operation

To check feasibility of stable operation of developed system, long-term operation with minimum adjustment of operating variables has been performed. The long-term operation test was carried out in the same facility and dimensions of injection nozzles and holes were the same that used in the gas leakage tests. Solid height above the holes was 0.5 m for both beds. Air velocities through bubbling fluidized bed were set at 0.07 m/s and air velocities through solid injection nozzles were set at 1.5 m/s at first.

Fig. 8 shows traces of gas flow rates and pressure drop profiles in the left bed, right bed, left bed downcomer, right bed downcomer, and pressure difference between two beds. We adjusted gas flow rate through the solid injection nozzle to maintain solid heights in both bubbling fluidized beds and only three times adjustment were required during 60 hours operation. The pressure drop profiles in the left bed, right bed, left bed downcomer, right bed downcomer, and pressure difference between two beds were maintained steadily throughout operating hours. It is evident from these results that the solid circulation between two bubbling fluidized beds is smooth and stable. Moreover, Fig. 8 also indicates that the new system is very easy to operate for long-term with minimum adjustment of operating conditions.

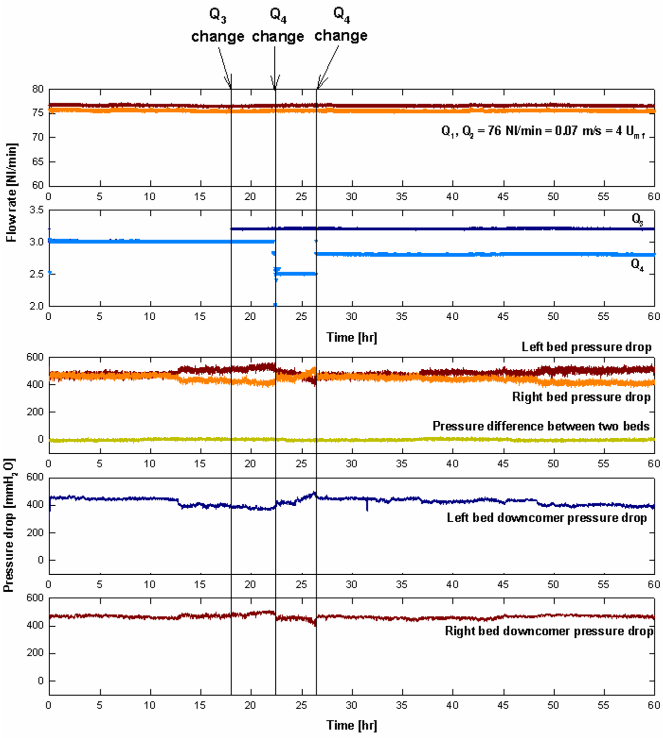

Fig. 8 Traces of gas flow rates and pressure drop profiles during 60 hours long-term operation

IV. CONCLUSION

The novel two-interconnected fluidized bed system which has two bubbling beds, solid injection nozzles, solid conveying lines, and downcomers has been developed. In this system, effects of operating variables on solid circulation rates, gas leakage between two beds have been investigated in a cold mode two-interconnected fluidized bed system. The solid circulation rate increased as the holes diameter on injection nozzle, the diameter of injection nozzle, the solid height above the holes, the number of holes on injection nozzle increased. The gas leakage between the beds was measured by CO_2 tracer gas methods. The results indicated that gas leakage between two beds is negligible and do not need to supply inert gas to prevent gas leakage. Moreover, long-term operation of continuous solid circulation has been performed to check feasibility of stable operation. The pressure drop profiles in the system loop were maintained steadily throughout 60 hours run and solid circulation between two reactors was smooth and stable with minimum adjustment of operating variables.

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