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Dynamic characteristics of solids circulation establishment in laboratory and industrial circulating fluidized beds with sweeping bend return

Can Zi, Musango Lungu, Jingdai Wang, Zuiwei Liao, Zhengliang Huang *, Yongrong Yang, Yong Li, Jian Yang

State Key Laboratory of Chemical Engineering, College of Chemical and Biological Engineering, Zhejiang University, Hangzhou 310027, PR China

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A B S T R A C T

Solids circulation establishment in a cold model and industrial scale reactor has been investigated via visual observation, bed density, pressure drop, particle loss and acoustic emission (AE) techniques. The gas-solid flow pattern in the cold model and industrial unit share similar features based on the visual observation and bed density detection respectively. The circulating fluidized bed (CFB) with sweeping bend return initially exhibits stable fluidization in the riser and downer. As time elapses, the resistance fluctuation in the riser and downer is induced by the imbalance between the inlet and the outlet solids flow in the downer, leading to the unstable gas-solids flow pattern in riser and downer. The alternation between fluidized bed and moving bed is observed in the downer during the unstable stage, and further induces high-pressure drop fluctuations, heavy particle loss. Besides, the detection of pressure drop, particle loss rate and corresponding AE energy could be used to determine the time range of unstable stage.

1. Introduction

Circulating fluidized beds (CFBs) are widely applied in numerous gas-solid contacting processes such as combustors and fluid catalytic cracking (FCC) reactors to mention but a few. The circulation loop in these reactors mainly consists of a riser, a cyclone, a downer and a solid recycle valve. In the riser section, solid particles flow upwards by means of a gas stream under the condition of fast fluidization. In the downer section, the solid particles flow downward under gravity, forming a packed-bed at the bottom. Solid particles are transported from the downer to the riser thereby preventing gas bypassing in the riser. The quality of solids circulation in such a loop will directly influence the particles concentration, temperature distribution, and final the performance of the CFB [1,2]. Moreover, stable solids circulation is essential for the equipment's long period operation. Unstable solids circulation of CFB during solids circulation has been studied by many researchers, unbalance pressure loop [1,3,4] and high aeration rates in the downer [5–9] are considered as the reasons for the unstable solids circulation. However, there is still lack of research in the area of solids circulation establishment, especially for its dynamics characteristics.

In establishing solids circulation, the bed inventory is always placed in the downer without the supplication of primary gas flow in order to prevent riser gas bypass. However, this method is difficult and labor intensive [10] for a completely closed system. Besides, the empty downer is essential for the start-up of large CFB boiler [4] and multi-zone circulation reactor. For large CFB boiler, the failure of solids return in the loop-seal during the start-up process will make the operation costs increase significantly. If a certain amount solids have been put into the downer, the aeration gas flow in the loop-seal would flow into the riser directly because of the large gas resistance in the downer. The pressure head of the aeration flow in loop-seal may not be sufficient to transport the solids. Therefore, the start-up of a large CFB boiler should be kept with an empty downer in order to avoid the failure of solids return in the loop-seal. The flow pattern transition from fluidized bed to moving bed in the downer has been reported [11] during the start-up of a CFB boiler. Riser gas bypass is considered as the reason for the flow pattern variation based on the pressure drop fluctuation. Multi-zone circulation reactor(MZCR) is a kind of circulating fluidized bed with a butterfly valve equipped at the bottom of the downer, which is used for the polymerization of polypropylene(PP). If the solids circulation is established with initial bed inventory, a lot of unqualified transitional PP products would be generated. As a consequence, empty downer is essential for the start-up of MZCR. An unstable solids circulation stage during start-up process was also put forward by the detection of the solids velocity and solids concentration in the bottom of the downer [12]. In addition, the start-up procedure of MZCR exhibits pressure drop fluctuations in the riser and the downer according to the operation experience. Longer start-up time and significant entrainment was induced by pressure drop fluctuation, which made the risk of emergency shutdown and recycle gas heat exchanger blockage increased [13]. However, the flow pattern variation and particle loss mechanism during the solids circulation establishment are still not clear, which deserves further investigation.

* Corresponding author.

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In the present study, the solids circulation establishment is realized in a cold model set-up and corresponding industrial scale reactor. The cold model and industrial unit are equipped with sweeping bend return which is different from the loop-seal structure in CFB Boiler. The solids circulation establishment in the cold model is analyzed by visual observation, pressure drop analysis and the change of particle loss. Meanwhile, flow pattern variation during start-up in the industrial reactor is investigated by monitoring the bed density in the riser and downer bottom. The pressure drop of riser and downer is also monitored to characterize the solids establishment process. In addition, the AE sensor is placed at the cyclone tube wall of cold model and industrial unit to measure the particle loss. The typical CFB structure will bring about the limitations of the research results. Further research with other solids control section, such as loop-seal, would be investigated.

2. Experiment apparatus

A CFB industrial unit with sweeping bend return, producing polypropylene (PP), is considered as the research project, which is equipped with mechanical valve to control the solids circulation rate. The riser and downer consist of multistage pipeline connected by the reducer transition part. The relevant particle size distribution of the PP solids and its properties are listed in Tables 1 and 2 respectively. It is worth noting that the characteristic velocities of PP in Table 2 are calculated from empirical formulas [14], and the air is considered as the fluidized gas.

A scaled down cold model has been constructed to study the unstable solids flow during solids circulation establishment. Fig. 1 displays the Plexiglas cold model CFB, which consists of a riser, a cyclone, a downer and a solid control section. The riser has a diameter of 0.15 m and a height of 3.0 m with a smooth exit at the top. The feed inlet is located 0.3 m above the riser bottom. The 2.3-m-long standpipe consists of two transition sections and one butterfly valve which is equipped at the end. Polypropylene (PP), stored in the storage tank, is employed as the bed material, since the particle properties are considered as important parameters to keep the hydrodynamic similarity between industrial unit and scaled model [15,16]. Primary air (Q_{in}) and aeration air (Q_a) are supplied by an induced draft fan and measured with air rotameters calibrated in m^3/h. The primary air flows into the riser, which is used to transport the particles in the riser. Meanwhile, the aeration air is injected at the solid control section in order to promote the solids flow in the solids control section. The superficial gas velocity in the industrial unit riser is triple of the particle transport velocity, while the superficial gas velocity in cold model riser is only 1.1 times particle transport velocity because of the fan's limited capacity, however the gas flow velocity in the cold model riser is sufficiently high enough to keep the riser solids in fast fluidization. Two differential gauge transducers are used to measure the pressure drop in the riser and downer. The entrained particles are captured by the external cyclone and weighed by an electronic balance. An AE sensor installed at the central tube wall of the cyclone acquires the signals at a sampling frequency of 600 kHz. Afterwards, the AE signals are analyzed in order to quantify the particle loss from the system.

The bed density in the riser and downer bottom of industrial unit is detected to investigate the gas-solid flow pattern variation. Meanwhile, the pressure drop in the riser and downer and the AE energy at the cyclone central tube wall are monitored to verify the experimental results in the cold model. Fig. 2 illustrates the locations of the density instrument, pressure taps and AE sensor. The low-pressure point in the downer of industrial equipment is located in the cyclone, while the low pressure point is located at the top of the downer in the cold model. The sampling frequency of the AE signals in industrial unit is 600 kHz.

Table 1
Properties of PP.

Property	Value
ρ_p (kg/m^3)	900
d_p (mm)	2.38
U_{mf} (m/s)	0.64
U_{tr} (m/s)	4.5
U_t (m/s)	7.0

Table 2
Particle size distribution of PP.

Size (μm)	Mass fraction (wt%)
2800	26.8
2000	43.2
1000	27.9
500	1.7
75	0.4

3. Results and discussion

3.1. The experimental results of cold model

3.1.1. The gas-solid flow pattern variation

At $t = 0$ s, the CFB cold model is operated with 300 m^3/h primary air (Q_{in}), 15 m^3/h aeration air (Q_a) and fully opening butterfly valve. Riser gas bypass is observed in the empty downer at beginning. At $t = 380$ s, solids are introduced into the riser with a constant mass rate (M_{in}) of 27.6 g/s. Part of the injected solids are fluidized in riser with the upward gas flow; the other part are transported into the downer through the solids control valve and behave as fluidized bed as shown in Fig. 3(a). The solid transfer between two connected fluidized beds is considered as a function of the solids concentration difference [17,18], which is verified as shown in Fig. 4. Based on the experimental observation, the gas-solid flow pattern in the riser and the downer is in stable fluidization during 380 s < t < 540 s. Meantime, the amount of solids in the riser and the downer increases gradually and leads to the increase of flow resistance in the riser and the downer. However, the increase rate of flow

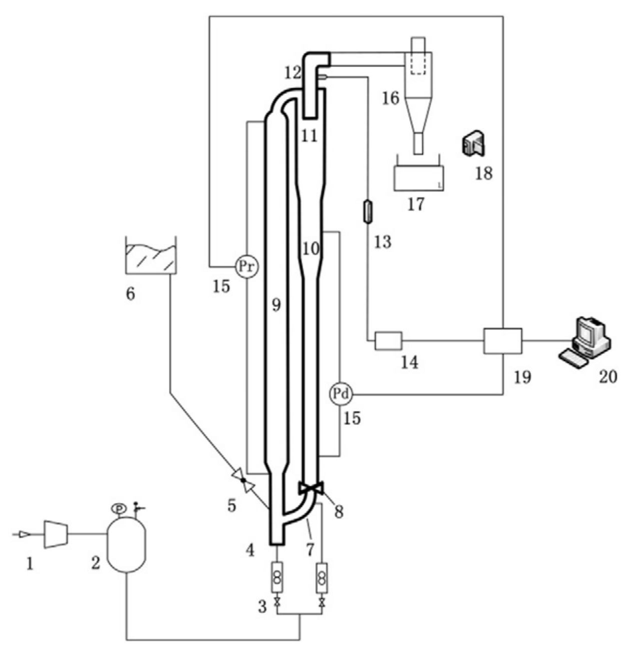

Fig. 1. Schematic diagram of the experimental apparatus: (1) induced draft fan; (2) buffer tank; (3) rotameters; (4) circulating fluidized bed; (5) globe valve; (6) solids storage tank; (7) "L"-valve; (8) butterfly valve; (9) riser; (10) downer; (11) cyclone; (12) AE sensor; (13) pre-amplifier; (14) main-amplifier; (15) differential pressure gauge; (16) external cyclone; (17) electronic balance; (18) video camera; (19) analog-to-digital converter; (20) computer.