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A hydrodynamic model of loop-seal for a circulating fluidized bed

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ABSTRACT

Loop-seal is one of the most common valves used in circulating fluidized bed (CFB) system. In the present work, a hydrodynamic model is developed for the operation that the particles in the recycle chamber are fluidized by the air, while the particles in the standpipe are in moving bed condition. Through hydrodynamic analysis, a hydrodynamic model including three equations has been established, whose solution results in the actual gas velocity, particle velocity and bed voidage in the recycle chamber. The model also predicts the solids flow rate, gas flow rate and pressure drop in both standpipe and recycle chamber. Experiments were conducted in a circulating fluidized bed with silica gel particles (Geldart group A). The model predictions showed good agreement with experimental data.

1. Introduction

A typical circulating fluidized bed (CFB) system normally consists of a riser, a gas–solid cyclone, a standpipe and a solids recycle valve. Solids particles move consecutively through these components, and the solids recycle valve is a key device of the CFB system. The valve (mechanical or non-mechanical), usually installed at the lower end of the standpipe, is used to control the solids flow rate of the system. Mechanical valves are difficult to be applied to deal with fine powders in harsh environments under high temperature and pressure conditions. On the contrary, non-mechanical valves are commonly used because they are robust, inexpensive and simple in construction. Several types of non-mechanical recycle valves, like L-valve, V-valve, J-valve and loop-seal, have been developed and used successfully in industrial CFB units [1–5].

Loop-seal is one of the most common non-mechanical valves used in CFB boilers and reactors. Previously Basu et al. [6,7] explored the basic principle of loop-seal operation and the effect of operational parameters such as pressure and air flow-rate on the solids flow. Based on the free surface theory and pressure balance equations, Basu et al. developed a model based on the pressure drops across each section of the circulation loop to predict the solids flow rates with good accuracy. Kim et al. [8,9] investigated the influence of operating parameters and proposed an empirical equation to correlate the solids flow rate with the operating parameters, valve size, gas and particle properties. These investigations improve greatly the understanding of loop-seal performance. However, these models still rely on pressure drop measurements to predict the solids flow rate. It is therefore necessary to develop more sophisticated models for prediction of loop-seal operation in terms of simple measureable operation parameters.

In the present work, the hydrodynamics of a loop-seal was studied and a hydrodynamic model was developed for the operation that the recycle chamber alone was fluidized by the air while the standpipe was operated in a moving packed bed mode. This model was used to predict the solids flow rate, gas pressure drop and gas flow rate in satisfactory agreement with experimental measurements.

2. Experimental apparatus and methods

Experiments were conducted in a circulating fluidized bed test rig operated at room temperature, consisting of a riser, two cyclones, a standpipe connected to a butterfly valve and a loop-seal (Fig. 1). The loop-seal has a rectangular cross-section, 0.11 m wide, 0.23 m long and 0.41 m high. It consisted of a supply chamber (0.11 m × 0.11 m) connected to the standpipe and a recycle chamber (0.11 m × 0.11 m). The two chambers are connected with a thin partition (0.01 m thick) with the opening of 0.1 m in height, as shown in Fig. 1. The riser has an inner diameter of 0.07 m and a height of 6.9 m, and the standpipe has a height of 5.4 m and an inner diameter of 0.09 m. The test rig is made of Plexiglas for easy observation.

In experiment, air was fed from bottom to the riser and the recycle chamber of the loop-seal, the gas velocity was kept constant in the riser (U_r) while the bottom aeration of the loop-seal (Q_1) was varied, or vice versa. For normal operations, two rotameters, one (0.1–1.0 m^3/h) for the loop-seal aeration and the other (6–60 m^3/h) for the riser, were used for controlling and measuring the gas flow rate. To measure the solids flow rate (G_p), the butterfly valve in the standpipe was closed for certain time (t) and the height of the cumulated powder bed above the butterfly valve was measured, from which the solids flow rate was calculated [8,9] with the information of bulk density and the time t. U-type

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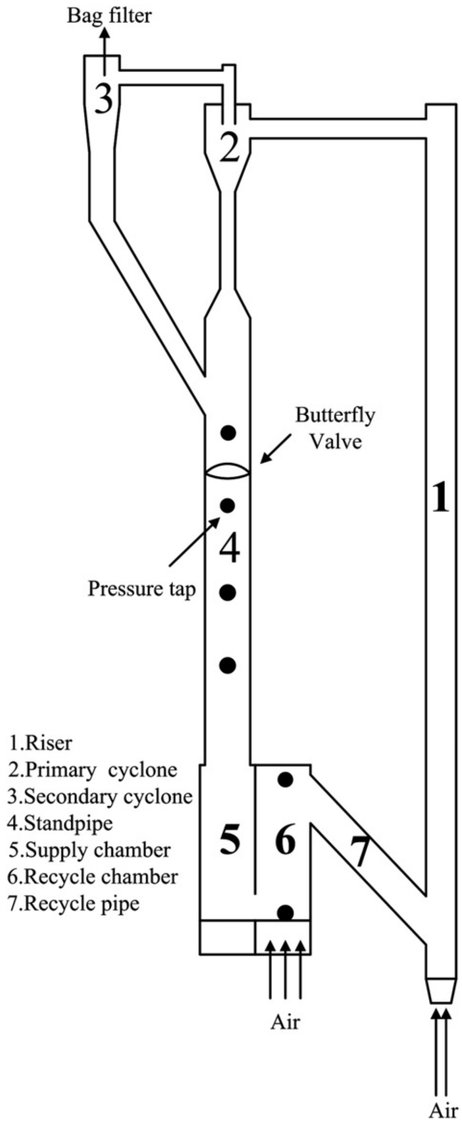

Fig. 1. Schematic diagram of apparatus.

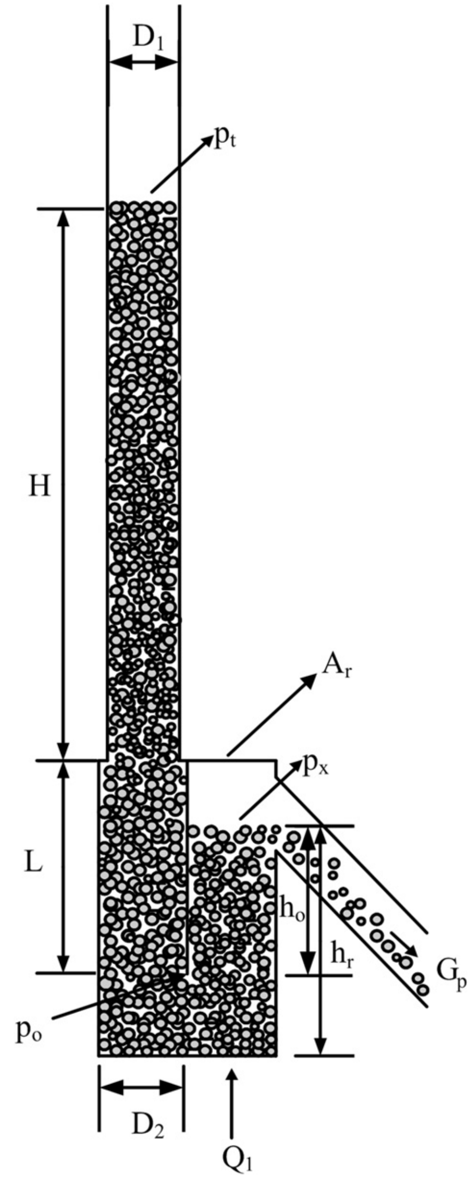

Fig. 2. Schematic diagram of loop-seal.

tube pressure meters were used to get the pressure readings. As illustrated in Fig. 2, several parameters, like the pressure at top of the recycle chamber (p_x), the pressure at top of solids in the standpipe (p_t), the height of solids in the standpipe (H) were measured simultaneously during experiments.

The fluidizing gas was air (20 °C, 101 kPa), with density 1.21 kg/m^3 and viscosity 1.79×10^{-5} kg/m · s. Silica gel, whose properties are listed in Table 1, was used as the solid particles. Silica gel is a kind of Geldart group A particles, which has good fluidizable ability.

3. Hydrodynamic modeling for the loop-seal

For operations in this study, the recycle chamber alone is fluidized by the air. The air flow rate in the moving bed standpipe can be calculated by Lewis equation, air flow rate through the recycle chamber can be obtained by adding the gas flow rate in the standpipe to the bottom aeration Q_1. In the recycle chamber, voidage is correlated with gas–solid slip velocity. The drag force exerted on the particle is balanced with the gravitational force of particle, particle-wall friction force and particle acceleration force. With above analysis, a hydrodynamic model including three equations has been established.

3.1. Gas flow rate equation

The gas velocity in standpipe, u_{fs}, can be obtained by solving the following Lewis equation [10]:

$$\frac{\Delta p}{\Delta z} = 154\left(\frac{1-\varepsilon_s}{\varepsilon_s}\right)^2 \frac{\mu_f}{\left(\phi_s d_p\right)^2}\left(u_{ss}-u_{fs}\right) \quad (1)$$

Table 1
Physical properties of silica gel particles.

Property	Value
Mean diameter, d_p (μm)	68
Particle density, ρ_p (kg/m^3)	765
Bulk density, ρ_b (kg/m^3)	410
Minimum fluidization velocity, U_{mf} (m/s)	0.0010
Terminal velocity, u_t (m/s)	0.067
Voidage at minimum fluidization, ε_{mf}	0.489
Minimum voidage, ε_{min}	0.431
Sphericity, ϕ_s	0.617