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PARTIC-1008; No. of Pages 9
ARTICLE IN PRESS
Particuology xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Particuology
journal homepage: www.elsevier.com/locate/partic

A hydrodynamic model of loop seal with a fluidized standpipe for a circulating fluidized bed

Changjin Li[a], Zheng Zou[a], Hongzhong Li[a,b,*], Qingshan Zhu[a,b,*]

[a] State Key Laboratory of Multi-phase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 16 November 2016
Received in revised form 25 January 2017
Accepted 21 February 2017
Available online xxx

Keywords:
Circulating fluidized bed
Loop seal
Hydrodynamic model

ABSTRACT

Loop seals are among the most common non-mechanical valves used in circulating fluidized bed systems. In the present work, a fundamental study is conducted of a fluidized loop seal, which consists of a fluidized standpipe, a fluidized supply chamber, and a fluidized recycling chamber. Based on the principles of momentum, mass, and energy conservation, a hydrodynamic model for a loop seal is established, consisting of 13 equations. The effects of operating conditions such as the bottom aeration rate, total solid inventory, and fluidizing gas velocity in the riser on the solids flow rate and the performance of the loop seal are studied by a combination of model analysis and experiments. The experiments are carried out in a circulating fluidized bed with silica gel particles (Geldart group A). The model predictions show good agreement with the experimental data.

Introduction

The solids recycling system that controls the rate of solids recycling around a circulating fluidized bed (CFB) loop is an important component of a CFB. Pneumatically controlled non-mechanical valves are commonly used to transfer solids from the CFB standpipe to the riser because they are robust, inexpensive, and simple to construct. The L-valve, J-valve, V-valve, and loop seal are different types of non-mechanical valve.

Loop seals, which consist of a standpipe, a supply chamber, and a recycling chamber, are widely used as solids recycling valves in CFB boilers and reactors. Solid particles in the standpipe and both chambers can be fluidized by the gas flow from the gas distributor at the bottom. There are two operational types of loop seal. A loop seal with a non-fluidized standpipe is used in cases in which the flow of solids is in the moving-bed mode in the standpipe and the supply chamber, and in the fluidized-bed mode in the recycling chamber. A loop–seal with a fluidized standpipe is used in cases in which the flow of solids is in the fluidized-bed mode in the standpipe and in both chambers.

Loop seals have been investigated in many studies (Basu & Butler, 2009; Basu & Cheng, 2000; Cheng & Basu, 1999; Han, Cui, Jiang, & Liu, 2007; Kim & Kim, 2002; Kim, Kim, & Lee, 2002; Kim, Namkung, & Kim, 1999; Monazam, Shadle, & Mei, 2007). Han et al. (2007) performed an industrial cold experiment and obtained certain insights into the relationship between the solids flow rate and the bottom aeration of a loop seal. Kim and Kim (2002) and Kim et al. (1999) proposed empirical correlations to predict the solids flow rate by using dimensionless expressions of the operational parameters. However, their research was purely experimental and lacked any theoretical analysis. Therefore, it is highly necessary to develop hydrodynamic models of a loop seal to predict the solids flow rate, which would help improve the design and operation of such seals. In previous work (Li, Li, & Zhu, 2014), we studied the hydrodynamics of the non-fluidized loop seal experimentally and theoretically. We established a hydrodynamic model for predicting the solids flow rate that agreed satisfactorily with the experimental measurements.

In the present work, we develop a hydrodynamic model for the fluidized loop seal. The effects on the flow rate of solids (G_p) and the performance of the loop seal of operating conditions such as the bottom aeration rate, total solid inventory (M_t), and fluidizing gas velocity in the riser (U_r) are studied through a combination of model analysis and experiments. The results predicted by the model are compared with experimental data.

* Corresponding authors at: State Key Laboratory of Multi-phase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China. Fax: +86 1062536108.
E-mail addresses: hzli@ipe.ac.cn (H. Li), qszhu@ipe.ac.cn (Q. Zhu).

http://dx.doi.org/10.1016/j.partic.2017.02.005
1674-2001/

Please cite this article in press as: Li, C., et al. A hydrodynamic model of loop seal with a fluidized standpipe for a circulating fluidized bed. *Particuology* (2017), http://dx.doi.org/10.1016/j.partic.2017.02.005

Nomenclature

A	Cross-sectional area, m^2
C_D	Effective drag coefficient of gas–solid systems
C_d	Discharge coefficient
D	Equivalent diameter, m
d_p	Mean particle diameter, m
F	Force exerted on particles, N
F_d	Drag force for a single particle, N
F_D	Total drag force for all particles, N
G_p	Solids flow rate, kg/h
h_o	Height of opening connecting the two chambers, m
h_{rc}	Height of fluidized bed in recycling chamber, m
H	Height of solids in standpipe, m
L_{sc}	Height of supply chamber, m
M_t	Total solids inventory, kg
n	Richardson–Zaki exponent
p_s	Pressure at bottom of supply chamber, Pa
p_r	Pressure at bottom of recycling chamber, Pa
p_t	Pressure above solids in standpipe, Pa
p_x	Pressure at top of recycling chamber, Pa
Δp	Pressure drop, Pa
Q_1	Bottom aeration rate of supply chamber, m^3/h
Q_2	Bottom aeration rate of recycling chamber, m^3/h
Q_o	Air flow rate through the opening, m^3/h
Q_r	Air flow rate through recycling chamber, m^3/h
Q_s	Air flow rate through supply chamber, m^3/h
U_r	Superficial gas velocity in riser, m/s
U_s	Superficial gas–solid slip velocity, m/s
u	Actual velocity, m/s
u_{io}	Ideal particle velocity through the opening, m/s
u_{po}	Actual particle velocity through the opening, m/s
u_t	Terminal velocity of single particles, m/s
ε_{mf}	Voidage for minimum fluidization
ε_{min}	Minimum voidage of solids
ε	Voidage
ϕ_s	Shape factor of particles
μ_f	Gas viscosity, kg/m·s
ρ	Density, kg/m^3
λ_s	Friction coefficient

Subscripts

a	Acceleration
f	Frictional or gas
g	Gravitational
o	Loop–seal opening
p	Particle
rc	Recycling chamber
sc	Supply chamber
sp	Standpipe

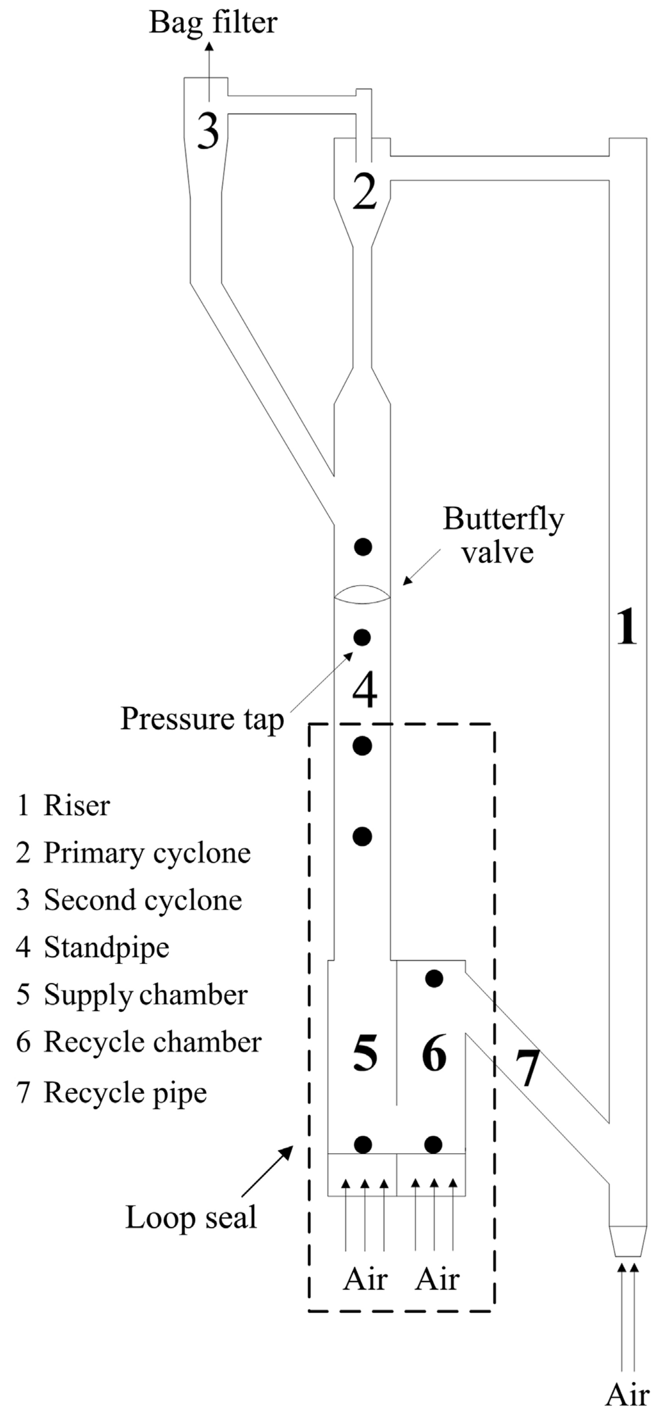

Fig. 1. Schematic diagram of the apparatus.

Experimental apparatus and methods

Experiments were conducted in a CFB test rig that is the same as in our previous work (Li et al., 2014), consisting of a riser, two cyclones, and a loop seal (Fig. 1). The riser is a cylindrical tube with an inner diameter of 0.07 m and a height of 6.9 m. The standpipe of the loop seal has an inner diameter of 0.09 m and a height of 5.4 m. The dimensions of each chamber are 0.41 m (height) × 0.11 m (width) × 0.11 m (depth). As shown in Fig. 1, the two chambers are connected by a thin partition (0.01 m thick) with an opening, the height of which can be changed. The test rig is made of Plexiglas for ease of observation, and the experiments were conducted at room temperature.

In the experiments, air is fed from the gas distributor at the bottom of the riser and the two loop–seal chambers. Solids in the riser are transported upward by high-velocity gas and are separated from the gas in the cyclones. They then drop from the cyclone via gravity into the standpipe and the subsequent supply chamber. After this, they pass through the inter-connecting opening into the recycling chamber for upward transport in the dense phase, finally passing into the riser via a recycling pipe. The gas velocity in the riser (U_r) and the aerations for the supply chamber (Q_1) and the recycling chamber (Q_2) are variable and are measured by flow meters. The solids flow rate (G_p) is measured by closing a butterfly valve in the standpipe and recording the time (t) needed to collect