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Study on the flow behavior in spout-fluid bed with a draft tube of sub-millimeter grade silicon particles

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HIGHLIGHTS

- Cylindrical spout-fluid bed with a draft tube investigates at cold bed conditions.
- The effect of fluidizing gas and geometrical parameters of flow behavior are examined.
- A new correlation is proposed to predict minimum spout-fluidizing velocity.
- The regime map based the measured data is presented.
- The introduction of sub-millimeter grade silicon particles lays a basis for potential applications.

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ABSTRACT

An experimental study on gas-particle flow behavior in a spout-fluid bed with a draft tube was performed in a 182 mm diameter cylindrical column with a flat distributor. Sub-millimeter grade silicon particles with wide particle size distribution were used as bed materials to investigate the effect of operating conditions and geometrical parameters on the flow behavior. The pressure drop and its standard deviation were recorded using a capacitive differential pressure transducer, which can be applied to evaluate the hydrodynamic properties. The effects of fluidizing gas and geometrical parameters of the bed on the hydrodynamic characteristics were analyzed. The results show that the minimum spout-fluidizing velocity increases with increasing the length of entrainment zone and the draft tube diameter, but it decreases with the increasing of fluidizing gas flow rate and static bed height. Furthermore, a correlation on the minimum spout-fluidizing velocity which has practical value is proposed based on the present experimental data, and the calculated data is in good agreement with the experimental results. In addition, seven flow regions can also be observed in different spouting and fluidizing gas velocity, and a new flow regime map for a spout-fluid bed is established with the consideration of the influence of flow regime on geometrical parameters. Such results mentioned above can provide important information on the flow behavior in the spout-fluid bed with a draft tube for process design.

1. Introduction

Effective production processes for polysilicon, which is the basis of electronic and photovoltaic industry, has attracted considerable research interest in the last few decades. The production methods [1–5] mostly include Siemens Process, Metallurgical Process, Silane Process, etc. Polysilicon produced by Siemens methods accounts for about 80% of the total output, however, one of the shortcomings of Siemens Process is the large quantity of silicon tetrachloride produced as a byproduct. The method of hydrogenating reduction of silicon tetrachloride [6–8] is explored to address the above problem. In the hydrogenation reduction process, the conventional fluidized or fixed bed is widely used in the hydrogenation reaction of silicon tetrachloride [9–12].

The spout-fluid bed with a draft tube (DTSFB), combining the favorable properties of both spouted and fluidized beds, is widely applied in physical and chemical processes such as reaction, drying, granulation, and coating [13–16]. It provides a good gas-particle mixing and contacting process by introducing fluidizing gas and draft tube. On the base of observation and data analysis, the stable spouting state can be established for finer particles in a spouted bed with a draft tube. The introduced fluidized gas increases the contact area of gas-particles and makes it possible to eliminate the dead zone in the bottom of the bed. A draft tube inserted in the bed reduces the interaction of particle flow between spout region and annular region, enabling the formation of a good inner particle circulation. In addition, the draft tube enables the bed to overcome the limits of maximum spoutable height. The particle flows become more uniform and easier to form a stable fountain.

In order to be applied in the industrial process, the DTSFB needs further investigation on the influence of pressure drop, the

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Nomenclature

D_C	bed diameter (mm)	u_s	spouting gas velocity (m/s)
D_i	Spout nozzle diameter (mm)	u_{mf}	minimum fluidizing velocity (m/s)
D_D	draft tube diameter (mm)	u_{msf}	minimum spout-fluidizing velocity (m/s)
d_p	mean diameter of particles (mm)		
H_0	static bed height (mm)	*Greek letters*	
H_t	length of entrainment zone (mm)	ρ_p	particle density (kg/m^3)
ΔP_S	pressure drop of spout region (Pa)	ρ_f	gas density (kg/m^3)
ΔP_A	pressure drop of annular region (Pa)	σ_S	standard deviation in the spout region (Pa)
Q_f	fluidizing gas flow rate (m^3/s)	σ_A	standard deviation in the annular region (Pa)
Q_s	spouting gas flow rate (m^3/s)	ε	particles bulk voidage
u_f	fluidizing gas velocity (m/s)		

minimum spout-fluidizing velocity, and flow pattern on hydrodynamic characteristics. In recent years, a number of published articles have reported valuable results about the hydrodynamics characteristics of spout bed [17–23] and spout-fluid bed [24–30] with a draft tube. Link et al. [31] mapped the spout-fluid flow regimes in spout-fluid bed, the data of which was compared with the simulation result. Zhong et al. [32] studied gas mixing in a rectangular spout-fluid bed between the spout and annular region by introducing a tracer gas, and made a preliminary research of gas-mixing mechanism. Moreover, hydrodynamic characteristics of spout-fluid bed were studied, such as solids circulation, velocity profiles, and pressure drop [33–36]. Nagashima et al. [28] investigated the pressure fluctuation and solid conveying in a spout-fluid bed with a conical bottom. Unlike conical distributor in earlier works, the flat distributor in this paper leads to the variation of flow pattern and flow characteristics. In addition, few reports focus on the field of spout-fluid bed with finer particles, such as sub-millimeter grade silicon particles, which are important raw materials using in the silicon tetrachloride reaction process. The flow characteristics between coarse particles and finer particles are significantly different. Compared with coarse particles flow, there is some particulate fluidization phenomenon in the finer particles flow.

To further understanding the flow behaviors in spout-fluid beds for more sufficient applications, flow regime profiles and flowing parameters in all distinct regions of beds are required. In this study, a spout-fluid bed with a draft tube is adopted to investigate the hydrodynamic characteristic of sub-millimeter grade silicon particles at cold bed conditions. The finer particles with wide particle size distribution are used in the experiments in order to accord with actual condition. The pressure drop, the minimum spout-fluidizing velocity and flow regime map are studied at the influence of static bed height, draft tube diameter, length of entrainment zone and existence of fluidizing gas. A new correlation for predicting the minimum spout-fluidizing velocity based on the present experimental data is developed. Moreover, a new map of flow regime is developed by the analysis of pressure fluctuation signal and visual observation. This research investigates the system applying to the demand of silicon tetrachloride hydrogenation reduction process, and the conclusions have certain generality under this operating conditions and geometrical parameters.

2. Experiments

2.1. Apparatus

The experimental system is schematically shown in Fig. 1, and the experimental conditions are summarized in Table 1. The spout-fluid system consists of a spout-fluid bed, a gas supply system, and a detection system. The bed is a 182 mm diameter column with a flat bottom that is made of organic glass with the thickness of 10 mm. As shown in Fig. 2, silicon particles which are measured by grain size analyzer have wide particle size distribution in these experiments. The relationship between bulk density, particle density and bed voidage is $\rho_b = \rho_P(1 - \varepsilon)$. The particles properties are listed in Table 2. The particles passed through the entrainment zone and the spout region successively. Then, it returned to the annular region after forming a spouting state in the fountain region. A gas distribution plate is located at the bottom of the bed, which is divided into two parts: central zone and annular zone (as shown in Fig. 3). The orifice diameter in the annular zone is 2.2 mm, and the distance between every orifice is 10 mm. The percentage of open area in the annular zone is 4.39%. The central zone in the gas distribution is 20 mm in diameter. Double layer screens with the mesh number of 160 are placed on the distribution plate to prevent the particles drain from the bottom plate; meanwhile the mesh number is small enough to not affect the gas flow. A draft tube, 633 mm long, is installed above the gas distributor. The length of the entrainment zone, which describes the distance between the gas inlet plate and the bottom of the draft tube, is varied from 10 to 35 mm.

The experiment was conducted in ambient air. The spouting gas and the fluidizing gas were fed into the spout-fluid bed through a

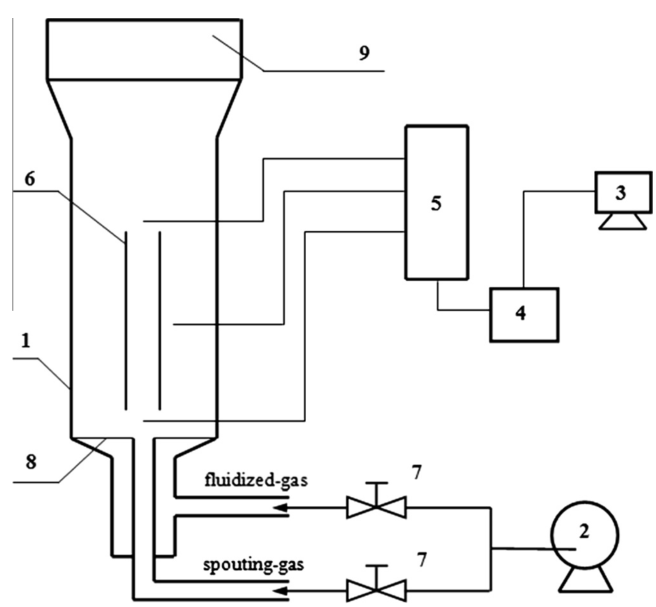

Fig. 1. Schematic diagram of the spout-fluid bed experimental system. (1) spout-fluid bed; (2) air blower; (3) personal computer; (4) A/D converter; (5) capacitive differential pressure transducer; (6) draft tube; (7) control valve; (8) gas distribution plate; and (9) expanding section.