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Regime Classification of Geldart B Food Particles in Circulating Fluidized Bed

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Abstract: The flow characteristic velocities with respect to flow regime classification have been estimated. Flow characteristics in CFB mainly depend on gas velocity, in which the regimes include bubbling, turbulent, fast and pneumatic fluidization. The flow characteristics depend on particle characteristics, bed geometry and gas velocity. Furthermore, in a CFB, the flow regime depends on gas velocity and solid circulation rate. Circulating fluidized bed operates under fast fluidization regime. A cold model of a CFB with column height of 1200 mm and diameter of 50 mm is operated under wide range of gas velocity and solid concentration. Transport velocity is regarded as the boundary dividing the gas–solids up flow into two states and it is estimated by extrapolation technique. It has been observed that slip velocity attains maximum in fast fluidization and it decreases with increase in bed porosity. In the present work it is observed that the transport velocity for sand is higher than terminal velocity, while the transport velocity is more or less close to the terminal velocity Geldart B materials. A flow regime map has been developed for semolina, poppy seeds and sand.

Keywords: Flow regime, transition velocity, circulating fluidized bed, solid concentration.

1 Introduction

Solid and gas contacting in chemical industries by using CFB has more advantages than conventional fluidized bed. The significance of CFB includes effective contact, high amount of material passing per unit cross section, elimination of bubbles, facility to handle cohesive materials, temperature uniformity within the bed, high degree of mixing for solids, and high processing capacity. It finds successful application for gas-solid reactions such as calcinations, combustion catalytic cracking, etc. The riser has different flow regimes and it depends on operating gas velocity [1, 2]. In the design of CFB flow regime plays an important role. Numerous studies have been carried out to define the flow regimes in bubbling and turbulent fluidization [3]. Regime classification for Geldart B materials are very few and literally no report has been found food material behaviour in CFB. The present work mainly focuses on the flow behaviour of food materials in CFB and establishes the flow regime.

Most of the work has been carried out to understand high-velocity fluidization, which is featured by solid flow, riser pressure drop, slip velocity, solid circulation rate and gas velocity and flow regime that has been studied by several researchers [1, 3, 11]. Transition velocities and flow properties are reported for sand and FCC, for Geldart A material transport velocity is greater than terminal velocity. For B-type material transport velocity is much closer to terminal velocity [4]. The particles which are finer in size have less transport velocity and higher solid circulation rate [5]. The mass ratio of solid particle increases, the mixing of upward and down flow of particles gets in contact. The flow regime in the riser was classified as dense, transition and dilute region based on solid holdup [6]. To examine the effect of Geldart B material shape and density on solid flow, the work proposed that particle shape has more impact on riser hydrodynamics [7]. The CFB flow regime differs from convention regimes. It has some unique properties including rigorous gas–solid mixing and contact efficiency [8]. The minimum fluidization velocity decreases with increase in temperature. This can be measured by bed pressure drop and gas velocity. By emptying time method, the transport velocity increases with increase in temperature [9].

It concludes that the transport velocity plays a vital role in operation of circulating fluidized bed. The research committed to transport velocity is very few for food materials. Numerous studies have been reported on

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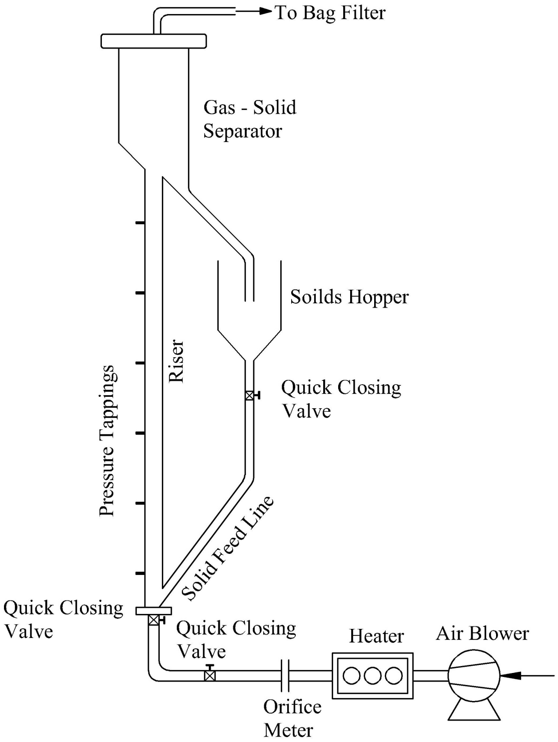

Fig. 1: Schematic diagram of the experimental set-up

Table 1: Properties of the materials

Material	Size (μm)	Particle Density (kg/m^3)	Ar	Geldart clause
Semolina	550	1429	8559	B
Semolina	388	1429	3005	B
Poppy seeds	550	1112	6659	B
Sand	231	2778	1233	B
Sand	165	2778	449	B

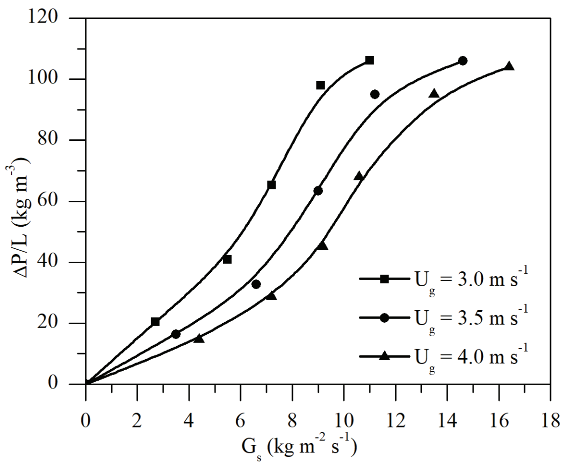

Fig. 2: Variation of pressure drop with solid and gas velocity, Material: Semolina; d_p: 388μm, Density: 1429 kg/m^3

transition velocities for granular materials. The intention of the present work is to study riser hydrodynamics of a CFB involving the estimation transport velocity, slip velocity, flow characteristics and pressure drop for semolina, poppy seeds and sand.

2 Experimental details

Experiments are carried out in a CFB as shown in Fig. 1. It consists of riser, with provision of continuous feed of solids through a hopper and separator with fabric filter. Air enters to the riser through a distributor plate placed at the bottom of the column. The riser with 50 mm internal diameter and height of 1200 mm made out of acrylic. The solid is fed to the bottom of the riser through a down comer. The solids are returned to the hopper from the gas-solid separator. A quick closing valve is provided above the solids inlet for the measurement of solids holdup in the riser. To measure the axial pressure drop in the riser pressure tapings are provided. The top portion of the riser is connected with gas-solids separator. A bag filter is connected to the gas-solids separator to prevent material loss. The return leg facilitates the solids to the hopper.

Air is introduced at the desired flow rate and the solids are initially allowed at low rate into the riser. The solid rate is gradually increased in small increments to the desired value. The circulation rate of solids is measured by collecting solids at steady state at the outlet of the riser for a given time. The pressure drop across each tap is read on the manometer under steady-state operation. The properties of food materials and sand are presented in

3 Result and Discussions

Fig. 2 shows the variation of pressure drop with solids circulation rate. Pressure drop along the length of the riser is insignificant at moderate solids rate corresponding to homogenous flow in the riser. The change in pressure drop with solid concentration for the given gas rate is thus 'S' shaped curve. It is observed that, pressure drop decreases with increase in gas velocity. The hydrodynamic results obtained are similar to those reported in the literature [10–12]. Hence the present observations are in agreement with Semolina also.

Transport velocity

The transport velocity is evaluated for the materials of the present study using linear extrapolation technique [13, 14]. As shown in Fig. 3, maximum solid circulation rate is plotted against gas velocity to find transport velocity. A tangent drawn to the curve gives the transport velocity (U_{tr}). The value of transport velocity for sand particle 231

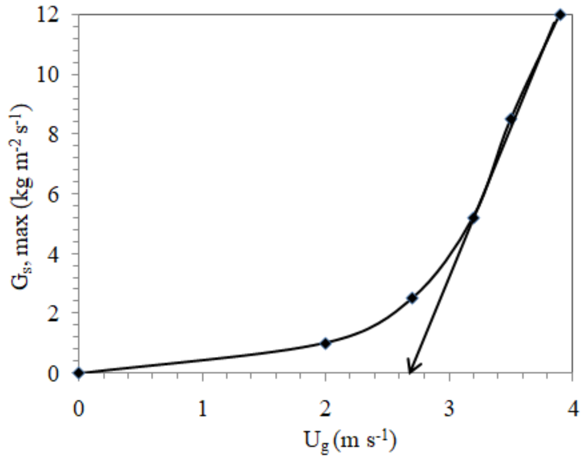

Fig. 3: Evaluation of transport velocity by extrapolation technique. Material sand: d_p: 231μm, Density: 2777 kg/m^3

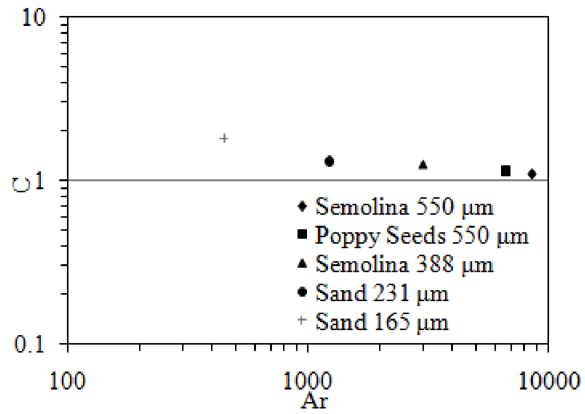

Fig. 4: Variation of the factor C with Archimedes number

μm is 2.7 m/s. In the present study the transport velocity is measured for all the particles and is listed in Table 2.

Table 2 shows that transport velocity is approximately equal to terminal velocity for higher values of Archimedes number and the values of transport velocity match acceptably with 10 % deviation.

Slip velocity

Velocity ratio in gas-solid flow is the ratio of velocity of gas phase to that of solid phase. The solids concentration depends on relative velocity [15].

$$\text{Slip velocity } U_{\text{slip}} = \frac{U_g}{\varepsilon} - \frac{U_g}{1-\varepsilon} \tag{1}$$

By including buoyancy, momentum and hindrance effects [16] in Eq. (1), we get

$$\frac{U_{\text{slip}}}{U_0} = \frac{\varepsilon}{\left[1+(1-\varepsilon)^{1/3}\right]\exp\frac{5(1-\varepsilon)}{32}} \tag{2}$$

Eq. (2) may be written as:

$$\frac{U_{\text{slip}}}{U_0} = \frac{\varepsilon^n}{\left[1+(1-\varepsilon)^{1/3}\right]^m} \tag{3}$$

For creeping flow $n = 1$ and for transition Reynolds number $[1 < \text{Re} < 10^3]$. Putting U_0 in Eq. (3) and rewriting for Stokes and Reynolds numbers:

$$U_{\text{slip}} = \left[\frac{(\rho_s-\rho_g)gd_p^2}{18\mu_g}\right]\frac{\varepsilon^n}{\left[1+(1-\varepsilon)^{1/3}\right]^m}, \quad \text{Re} < 1 \tag{4}$$

and

$$U_{\text{slip}} = \left[\frac{4(\rho_s-\rho_g)g}{30\rho_g^{0.5}\mu_g}\right]^{2/3} d_p\frac{\varepsilon^{2/3}}{\left[1+(1-\varepsilon)^{1/3}\right]^{2m/3}},$$

$$1 \le \text{Re} < 10^3 \tag{5}$$

It has been reported that the fine particles form agglomerates while moving upwards.

Eq. (5) has been modified in [17] to incorporate the cluster formation as,

$$U_{\text{slip}} = \left[\frac{(\rho_s-\rho_g)\,g\,(cd_p)^2}{18\mu_g}\right]\frac{\varepsilon^n}{\left[1+(1-\varepsilon)^{1/3}\right]^m} \tag{6}$$

and

$$U_{\text{slip}} = \left[\frac{4\,(\rho_s-\rho_g)\,g}{30\rho_g^{0.5}}\mu_g\right]^{2/3} cd_p\frac{\varepsilon^{2/3}}{\left[1+(1-\varepsilon)^{1/3}\right]^{2m/3}} \tag{7}$$

The terms c and m are related to particle agglomeration and particle–particle and –wall effects. The corresponding equation for drag is given by,

$$C_D = \left[\frac{4\,(\rho_s-\rho_g)\,g\,(cd_p)}{3\rho_g U_{\text{slip}}^2}\right]\frac{\varepsilon}{\left[1+(1-\varepsilon)^{1/3}\right]^m} \tag{8}$$

The index m is evaluated from experimental data and c depends on material characteristics. Factor c is related to Archimedes number by,

$$C = 5.2Ar^{-0.172} \tag{9}$$

The present study's slip velocity has been found for the material used. The experimental data has been compared with Eq.(9). Fig. 4 shows that variation of factor c with Archimedes number. These observations qualitative match with the experimental observation given in literature [4]. That shows that the materials also behave very similarly to non-porous materials such as sand reported in literature [4].

U_{slip} and C_D are calculated using Eqs. (6)– (8) for the experimental data of the present study as well as that

Table 2: The food material characteristics used in present study

Material	Size (µm)	ρ_s (kg/m^3)	Ar	U_{mf} $\times 10^{-2}$ (m/s)	U_t (m/s)	U_{tr} (m/s)	Geldart clause
Semolina	550	1429	8559	13.30	2.98	3.2	B
Semolina	388	1429	3005	6.91	2.10	2.6	B
Poppy seeds	550	1112	6659	10.49	2.52	2.8	B
Sand	231	2778	1233	4.84	1.95	2.7	B
Sand	165	2778	449	2.48	1.39	2.2	B

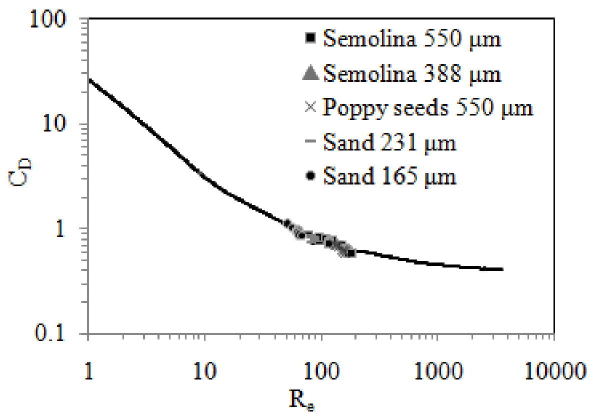

Fig. 5: Comparison of experimental data with the C_D-Re relationship

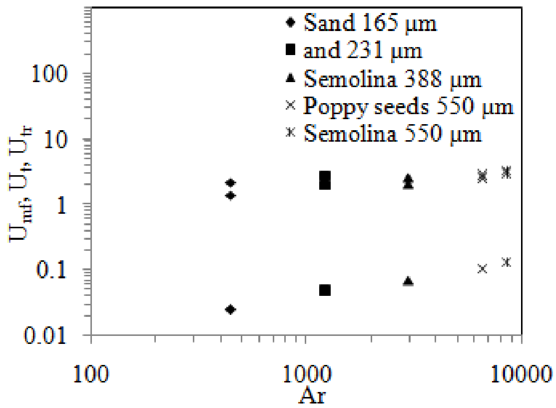

Fig. 6: Variation of terminal minimum fluidization velocity, terminal velocity and transport velocity with Archimedes number

reported in literature and presented in Fig. 5. It is noticed that the comparison is satisfactory for the wide range of variables covered in the analysis and the results are similar to those obtained in previous study [4].

The minimum fluidisation velocity, terminal velocity and drag coefficient are calculated using the following equations [18, 19].

Minimum fluidization velocity:

$$\frac{d_p\rho_g U_{mf}}{\mu_g} = \left[(33.7)^2 + 0.0408\frac{d_p^3\rho_g(\rho_s-\rho_g)g}{C\mu_g^2}\right]^{1/2} - 33.7 \tag{10}$$

Terminal velocity:

$$U_t = \frac{g(\rho_s-\rho_g)d_p^2}{18\mu_g}, \text{ for Re } < 0.4 \tag{11}$$

$$U_t = \left[\frac{4}{225}\frac{(\rho_s-\rho_g)^2 g^2}{\rho_g\mu_g}\right]^{1/3} d_p \text{ for } 0.4 < \text{Re} < 500 \tag{12}$$

$$U_t = \left[\frac{3.1(\rho_s-\rho_g)gd_p}{\rho_g}\right]^{1/2} \text{ for } 500 < \text{Re} \tag{13}$$

Drag coefficient:

$$C_D Re^2 = \frac{4gd_p^3\rho_g(\rho_s-g)}{3\mu_g^2} \tag{14}$$

From Fig. 6 it has been noticed that the transport velocity for finer particles is much higher, whereas for coarse materials the terminal velocity is equal to that of a single particle.

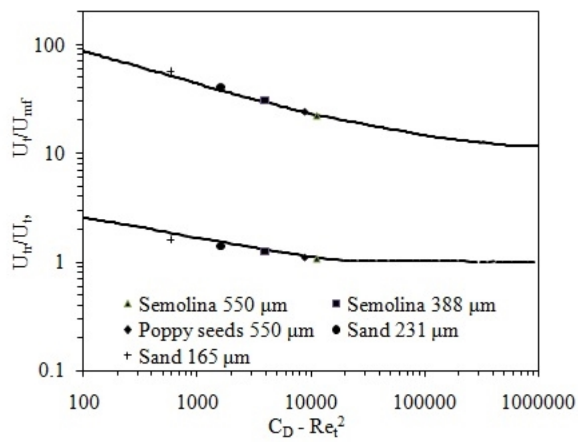

Fig. 7: Variation of U_{tr}/U_t and U_t/U_{mf} with C_D–Re_t^2

Fig. 7 presents variation of U_{tr}/U_t and U_t/U_{mf} against C_D Re_t^2. It is noticed that U_{tr}/U_t decreases with increase in C_D Re_t^2. This validates that in high–velocity fluidization, finer particles tend to form agglomerates, while coarser particles move as individual particles. These results obtained for food materials are similar to those existing in previous study [4].

Fluidization map

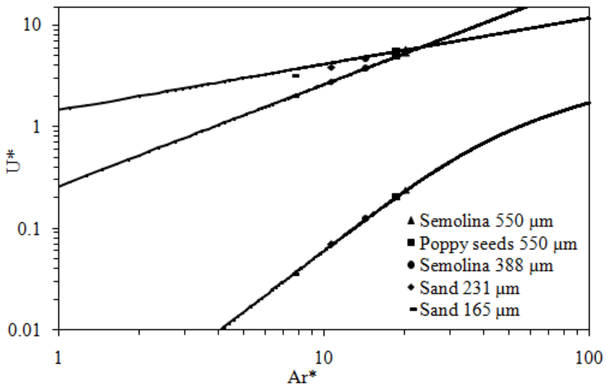

Fig. 8: Flow regime map of gas–solids flow in a CFB

Fig. 8 shows the flow regime map for materials composed of transition velocities for gas-solid circulating fluidized bed. The dimensionless parameters U^* and Ar^* are calculated as $U^* = \mathrm{Re}^{1/3}$ and $\mathrm{Ar}^* = \mathrm{Ar}^{1/3}$, where, $\mathrm{Re} = \frac{d_p \rho_g U}{\mu_g}$ and $\mathrm{Ar} = \frac{\rho_g(\rho_s - \rho_g) g d_p^3}{\mu_g^2}$

From the above equations transition velocities can be estimated. It is noticed from Fig. 8 the value of transport velocity overlaps with the terminal velocity at higher Reynolds number for Geldart B materials. These results obtained are similar to those obtained in previous study [4, 20].

4 Conclusion

In this research, a new approach to find regime classification for food materials and their effect on particle properties in a CFB has been developed. Slip velocity attains maximum in fast fluidization and it decreases with increase in bed porosity [17]. Transport velocity has been estimated by extrapolation technique. Transport velocity is regarded as the boundary dividing the gas–solids up flow into two states. Below the transport velocity, the bubbling and turbulent fluidization occur, while fast fluidisation and pneumatic transport occur above the transport velocity [4]. Pressure drop and solids concentration in CFB vary with solid flux, giving a ‘S’-shaped curve which decreases with higher gas velocity. In the present work it is observed that the transport velocity for sand is higher than terminal velocity, while the transport velocity is more or less close to the terminal velocity Geldart B materials. These results obtained are similar to those obtained in previous study [4].

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