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RESEARCH NOTES

Incipient Condition of Hang-up in a Long Standpipe-Hopper System for Geldart-D Powders

JING Shan(景山)[a,*], CAI Guobin(蔡国斌)[b], HUANG Sheng(黄晟)[b], WANG Jinfu(王金福)[b] and JIN Yong(金涌)[b]

[a] Institute of Nuclear Technology, Tsinghua University, P. O. Box 1021, Beijing 102201, China

[b] Department of Chemical Engineering, Tsinghua University, Beijing 100084, China

Abstract The incipient condition of hang-up for three Geldart-D powders has been experimentally studied in a 21 m long standpipe hopper system. Experimental results show that the pressure gradient for hang-up to occur is independent of the materials height in the hopper and the diameter of orifice and equals to $(dp_w/dl)_s$, which can be predicted by Eq. (7). While the corresponding gas velocity in the standpipe equals to the incipient fluidized velocity of particles at the high pressure and can be predicted by Kwauk's equation.

Keywords hang-up regime, standpipe-hopper system, Geldart-D powder

1 INTRODUCTION

The circulating fluidized bed (CFB) with a moving-bed standpipe having an orifice valve at the bottom for controlling the solid flow rate is popularly employed in industry. For Geldart-B powder in CFB, the flow of the circulating solids stops when a hemispherical bubble surface just bridges the orifice. In this situation, the gas velocity in the standpipe is given by Zhang[1] as follows

$$U_g = 2\left(\frac{D_o}{D_t}\right)^2 U_{mf}, \text{ If } D_o < 0.707D_t \tag{1}$$

$$U_g = U_{mf,0}, \text{ If } D_o > 0.707D_t \tag{2}$$

The pressure gradient in the standpipe can be calculated by the Ergun equation[2]. The no particle flow state of powder in the standpipe is also termed the hang-up regime[3] and Eqs. (1) and (2) are termed the incipient condition of hang-up in the standpipe-hopper system. For stable flow, the gas velocity should be below than that estimated from Eqs. (1) and (2).

For Geldart-D powder, the standpipe-hopper system acts as a valve without mechanical part, which is named as "particle plug valve", in the gas-conveying system[3]. However, the length of the standpipe, which was used in those experiment for determining the incipient condition, is less than 2.0 m[1,3]. In this paper, in order to re-examine the incipient condition of hang-up for Geldart-D powder, experiments are carried out in a 21 m long standpipe-hopper system.

2 EXPERIMENTAL SETUP AND PROCEDURE

The experimental apparatus is made of stainless steel as shown in Fig. 1. It consists basically of a ID 0.05 m standpipe, which includes 0.6 m high vertical transparent section above the orifice, 3.25 m high vertical pipe, 4.15 m long inclined pipe with 45° and 13 m high vertical pipe, a hopper with cone angle of 60° located at the top of the standpipe, an orifice installed at the bottom of the standpipe and a ball valve located between the orifice and a solid collector. The transparent section allows visual observation of the occurrence of the incipient hang-up state in the standpipe. The diameters of the orifices used in this experiment are 0.02 m, 0.025 m, 0.03 m and 0.035 m, respectively. The conical and cylindrical height of the hopper at the top of the standpipe are 0.3 m and 0.35 m, respectively. The gas flow rate is determined by a rotameter with the wide range from 6 to 50 $m^3 \cdot h^{-1}$. Three differential pressure transducers are arranged along the wall of the hopper-standpipe system and connected to a personal computer for recording the measurements. The properties of powders used in the experiments are shown in Table 1.

In the experiments, firstly air is allowed to pass through the orifice, the rate of gas increases progressively so as to reach the state in which the powder is hung up above the orifice in the system. The state in the system is observed and the values of pressure and gas flow rate are recorded.

Table 1 Properties of powders

Material	d_p, m	ε_{mf}	ρ_s, $kg \cdot m^{-3}$	$U_{mf,0}$, $m \cdot s^{-1}$	m	ϕ_s
ceramic ball 1 (C1)	1.81×10^{-3}	0.447	1650	1.08	1.46	1.0
ceramic ball 2 (C2)	5.6×10^{-3}	0.412	2254	2.80	1.76	1.0
polypropylene ball (A)	3.0×10^{-3}	0.382	965	1.70	1.68	0.88

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* To whom correspondence should be addressed. E-mail: shanjingts@263.net

Figure 1 Experimental setup
1—hopper; 2—13 m high vertical pipe;
3—4.15 m long inclined pipe; 4—3.85 m high vertical pipe;
5—orifice; 6—ball valve; 7—solids collector;
8—manometer; 9—rotameter

3 RESULTS AND DISCUSSION

3.1 Effect of H_c on the incipient condition

The effect of H_c in the hopper located at the top of the standpipe on the values of pressure gradient, $(dp/dl)_h$, of the long standpipe at incipient hang-up state for powder A is shown in Fig. 2. From Fig. 2, it can be seen that the values of $(dp/dl)_h$ remain constant with increasing of the values of H_c, which is in the agreement with that obtained from the short standpipe[3]. For powder C2, the particles in the standpipe are hung-up although $D_o/d_p = 3.57 < 5.0$.

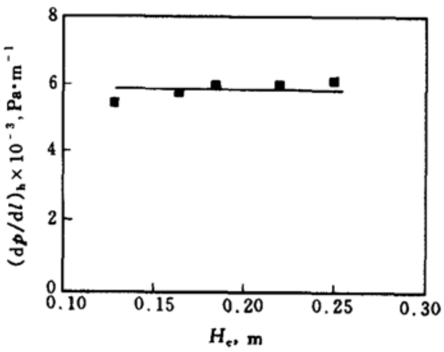

Figure 2 Effect of H_c on the incipient condition of hang-up for the long standpipe
(polypropylene ball, $D_o = 0.025$ m, $l = 21$ m)

3.2 Effect of D_o on the incipient condition

For powders C1, C2 and A, the effect of orifice diameter, D_o, on the values of $(dp/dl)_h$, in the long standpipe at the incipient hang-up state is shown in Fig. 3. From Fig. 3, the values of $(dp/dl)_h$ almost approach the corresponding constants for different powders with increasing D_o for the long standpipe. In other words, D_o has little influence on the incipient condition of hang-up regime for the long standpipe. However the conclusion differs from that for the shorter standpipe observed from Eq. (1)[3].

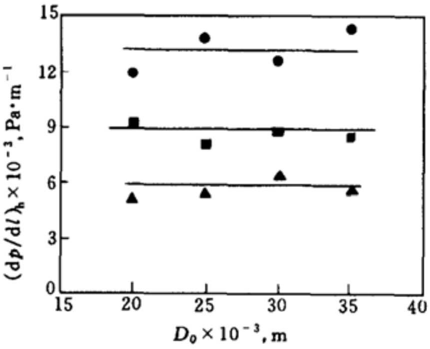

Figure 3 Effect of D_o on the incipient of hang-up for the long standpipe ($l = 21$ m)
Material: ■ C1; ● C2; ▲ A

3.3 U_g at incipient hang-up point

For the long standpipe, the value of D_o has little influence on the incipient condition, that is the same as that for the short standpipe when $D_o > 0.707D_t$[1,3]. Therefore, the values U_g in the standpipe equals to those of U_{mf} at the incipient point of hang-up regime for Geldart-D powder as suggested by Zhang[1]. However, by considering the effect of pressure on the values of U_g due to the long standpipe, the following equation presented by Kwauk[4] is chosen to estimate the values of U_g.

$$U_g = U_{mf} = U_{mf,0}\left(\frac{p}{p_0}\right)^{\frac{1}{m}-1} \tag{3}$$

where U_{mf} is the incipient fluidized velocity at p; $U_{mf,0}$ is the incipient fluidized velocity at p_0; m is the function of ε and Re_t, the calculation method is given by Kwauk[4].

Here, by substituting the values of m and $U_{mf,0}$ in Table 1, $p_0 = 1.0135 \times 10^5$ Pa and the values of p at the incipient hang-up state into Eq. (3), the values of U_g is obtained in Table 2. From Table 2, the values of U_g calculated from Eq. (3) are quite close to those measured in experiment.

Table 2 Comparison of U_g at the incipient hang-up state

Materials	$U_{g,exp}$ m·s^{-1}	$U_{g,cal}$ m·s^{-1}	Relative error %
C1	0.70	0.775	−9.7
C2	1.68	1.59	5.7
A	1.09	1.205	−9.5

3.4 Pressure gradient of standpipe at incipient hang-up point

The pressure drop, which results from the interaction between gas and particles, at the incipient hang-up point can be divided into two parts: one of the vertical standpipe, and the other of the inclined standpipe. Especially for the inclined packed standpipe, the experiment results by O'Dea[5] have shown the pressure drop and gas velocity are coincident on the same straight line as those for the corresponding vertical one. Therefore, the values of $(dp/dl)_h$ are calculated by

$$\left(\frac{dp}{dl}\right)_h = \frac{p - p_0}{l_v + l_i} \quad (4)$$

If neglecting the friction between the particles and the wall of the standpipe, the pressure drop of the inclined standpipe due to the gravity of particles[5] is

$$\Delta p_i = \rho_s(1 - \varepsilon_{mf})gl_i \sin\alpha \quad (5)$$

and that of the vertical standpipe is

$$\Delta p_v = \rho_s(1 - \varepsilon_{mf})gl_v \quad (6)$$

Then, the values of $(dp_w/dl)_s$ including the vertical and inclined standpipes due to the gravity of particles are given as follows

$$\left(\frac{dp_w}{dl}\right)_s = \frac{\Delta p_v + \Delta p_i}{l_v + l_i} = \rho_s(1 - \varepsilon_{mf})g\frac{l_v + l_i \sin\alpha}{l_v + l_i} \quad (7)$$

The comparison of the values of $(dp/dl)_h$ estimated from Eq. (4) and $(dp_w/dl)_s$ from Eq. (7) is shown in Table 3. As shown in Table 3, the values of $(dp/dl)_h$ equal to those of $(dp_w/dl)_s$ at the incipient hang-up state in the long standpipe within the range of relative error of ±15%. These experimental results show that the pressure drop by the interaction between gas and particles at the incipient hang-up point for a long-standpipe hopper system equals to that due to the gravity of particles.

Table 3 Comparison of the values of $(dp/dl)_h$

Materials	d_p m	D_o m	$(dp/dl)_h$ Pa·m^{-1}	$(dp_w/dl)_s$ Pa·m^{-1}	Relative error, %
		0.02	9195		9.0
C1	0.00181	0.025	8032	8432	−4.7
		0.03	8733		3.6
		0.035	8505		0.9
		0.02	11870		−3.0
C2	0.0056	0.025	13750	12244	12.3
		0.03	12557		2.6
		0.035	14225		16.1
		0.02	5060		−8.2
A	0.003	0.025	5382	5510	−2.3
		0.03	6320		14.7
		0.035	5616		1.9

NOMENCLATURE

D_o	diameter of orifice, m
D_t	diameter of standpipe, m
d_p	diameter of particles, m
g	gravity acceleration, ($g = 9.81\,m\cdot s^{-2}$)
H_c	stagnant height of powder in the hopper, m
l	length of standpipe, m
l_i	length of inclined standpipe, m
l_v	length of vertical standpipe, m
m	expanded factor of gas
p	absolute pressure, Pa
p_0	atmospheric pressure, ($p_0 = 1.0135 \times 10^5$ Pa)
Δp_i	pressure drop of inclined standpipe, Pa
Δp_v	pressure drop of vertical standpipe, Pa
dp/dl	pressure gradient in the standpipe, Pa·m^{-1}
$(dp/dl)_h$	pressure gradient at incipient hang-up state, Pa·m^{-1}
$(dp_w/dl)_s$	pressure gradient due to the gravity of particles, Pa·m^{-1}
U_{mf}	incipient fluidized velocity at p, m·s^{-1}
$U_{mf,0}$	incipient fluidized velocity at p_0, m·s^{-1}
U_g	superficial gas velocity, m·s^{-1}
α	cone angle of hopper, (°)
ε_{mf}	voidage at incipient fluidization
ρ_s	density of particles, kg·m^{-3}
ϕ_s	shape factor of particles

Subscripts

exp	experimental
cal	calculated

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