Effect of Characterization of Powder on Particle Velocity in Dense-phase Pneumatic Conveying

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Abstract. Particle velocity is an important characteristic parameter in the process of evaluating dense-phase pneumatic conveying system. It relates to the properties of conveying materiel, system performance, operating conditions, physical properties of conveying gas etc, and has some noticeable effect on the conveying capacity, energy consumption, wear between particles and pipe. Of all influencing factors, characterization of powder is crucial to impact particle velocity. In this paper, pneumatic conveying experiments of four kinds of powdery material whose different solid physical properties are tested and taken are carried out using compress air in long distance pipe. The trend of particle velocity was achieved by the experimental data gained from Groups of differential pressure transmitters. Dimension analysis and mathematical analysis were adopted to obtain a theoretical correlation equation of particle velocity versus solid characteristics:

\[
u_s = 1.29 \times 10^{-3} p^{0.5} D^{0.408} L^{0.408} \rho_s^{-1.06} \rho_g^{0.56} d_s^{-0.196} \varepsilon^{6.55} w^{-0.559}\]

And this equation can be used to predict the tendency of particle velocity for different kind of solid precisely.

1. INTRODUCTION
With widespread application of technology of dense phase pneumatic conveying, its effect factors has been focused in recent research. It was found that the factors of effecting dense phase pneumatic conveying are many and also complex, mainly including performance of powder, feature of conveying pipeline, operated condition in conveying processing(such as pressure), etc(Mainwaring et al, 1987; Pan,1999). The effects of performance of powder on characteristic of dense phase pneumatic conveying which has greater effect on flow mode, characteristic parameter and pressure drop are critical (Pan, 1999). In this paper, the effects of characterization of powder on particle velocity are researched by testing powders on properties and dense phase pneumatic conveying experiments. Theoretical correlation equation of particle velocity versus powder performance is obtained.

2. INTRODUCTION OF EXPERIMENT

2.1 Experimental System
The pneumatic conveying system in this paper is a dense-phase pneumatic conveying and circulating experimental bench with long-distance pipeline whose length is 203m and diameter is 80mm. The measuring instrument and data collected system consist of GP /DP(Differential Pressure) transmitters, Weight balance, Vortex Flowmeter and Paperless Recorder, as shown in Fig.1.

![Fig.1 Schematic diagram of experimental system](image)

1. Air compressor 2. Gas container 3. Oil and water separator 4. Desiccator 5. Surge tank 6. Flowmeter 7 – 12. Gauge pressure transmitter 13 – 16. Differential pressure transmitter 17. Feeder 18. Collecting bin 19. Weight balance 20. Dust collector

2.2 Experimental Material and Characterization
The fly ash, gypsum, cement and desulfurization gypsum are used for conveying materials, Whose performance such as granularity, density, shape, angle of repose, void fraction and moisture content are characterized, as shown in table.1.

| Material                  | mean particle diameter (μm) | median particle diameter (μm) | particle density (kg/m³) | packing density (kg/m³) | shape      | angle of repose (°) | void fraction (%) | percent moisture content (%) |
|---------------------------|-----------------------------|-------------------------------|--------------------------|-------------------------|------------|---------------------|-------------------|--------------------------|
| fly ash                   | 58.73                       | 50.51                         | 2078                     | 771.5                   | spherical  | 36                  | 66.8              | 0.68                     |
| gypsum                    | 40.3                        | 30.65                         | 2703                     | 910.9                   | horny      | 41                  | 65.9              | 1.07                     |
| cement                    | 47.57                       | 27.24                         | 2881                     | 1001.2                  | cluster    | 39                  | 63.2              | 0.7                      |
| desulfurization gypsum    | 13.46                       | 5.751                         | 2476                     | 663.6                   | granular   | 44                  | 66.2              | 0.86                     |

It can be seen from photos of SEM that shape of fly ash is nearly spherical whose degree of sphericity is maximal. So its fluidity is better than other materials.

2.3 Experimental Procedure
The whole experimental to be divided four phases are materials being put into the feeder, being fluidized by compressed air(as shown t1 in Fig.2), conveying materials (as shown t2 in Fig.2) and cleaning pipe(as shown t3 in Fig.2). The whole process can be operated circularly.

Variable curve of data of each measurer in conveying process is shown in Fig.2. It can accurately reflect changed trends of pressure in the feeder, gas instantaneous mass flow and solid mass flow in the conveying process.
2.4 Experimental Scheme
Five test segments along horizontal pipeline were employed averagely to analyze the tendency of velocity, pressure and pressure drop. A differential pressure transmitter and a gauge pressure transmitter were assembled in the place of 52.2 m–53.4 m, 90.5 m–91.7 m, 126.5 m–127.7 m, 176 m–177.2 m. And two gauge pressure transmitter were separately assembled at the point of the initial and terminal of pipe. The layout of transmitters was shown in Fig.1.

In this experiment, operating condition is mainly controlled by changing the pressure of feeder. Feeder pressure was set from 0.26 MPa to 0.42 MPa and each 0.02 MPa interval is as work condition. The experiments of 9 operating conditions were carried out in total and several repeated experiments were carried out in each operating condition.

3. EXPERIMENTAL RESULT

3.1 Average Particle Velocity
Particle velocity is one of the most important conveying characteristic parameter in dense phase pneumatic conveying. It was found that as a result of speed-variable moving of particle in the pipe (Peter et al., 2003), average particle velocity in whole pipeline is researched firstly. The average particle velocities is defined by the ratio of total length of pipe to total time of conveying. The relationship between average particle velocity of four materials and feeding pressure was shown in Fig.3.

From Fig.3, it can be seen that average particle velocity is low at the range of 3–8 m/s. And the solid loading ratio of all materials is more than 25, up to maximum 47. It is shown that the conveying process is dense phase pneumatic conveying. Particle velocity increase gradually with pressure increasing. Because the driving power to particles of gas in pipe increases as the continuous increase of pressure. When feeding pressure is constant, particle velocity increase with reduction of density, and decrease with decreasing of void fraction. It is shown that density and void fraction affect average particle velocity obviously. However, about the effect of particle size, average particle velocity of fly ash with maximum particle size is higher than other three material, and average particle velocity of desulfurization gypsum with minimum particle size is higher than gypsum and cement. It was shown that particle diameter have not obvious effect on average particle velocity.
3.2 Particle Velocity along Pipeline

About long distance pneumatic conveying, particle velocity is changed along pipeline. The particle velocity is changed with the distance of along pipeline changing which is analyzed by using gauge pressure transmitter.

All signals from each pressure transmitter were transmitted to MultiFR4000 recorder in the conveying process. The reading of each gauge pressure transmitter changing with time is shown in Fig.4. The six curves from left to right express the changes of static pressure of 7-12 in Fig.1.

Based on time interval of signal emergence of every pressure transmitter in different place (Fig.4), particle average velocities were achieved as follows:

\[ u_{ij} = \frac{L_{ij}}{t_{ij}} \]

Variable curve of four material particle velocity along pipeline with the feed pressure 0.32MPa was shown in Fig.5. It can be seen that particle velocity increase gradually along pipeline because of the continuous decrease of pressure and the expansion of gas. When feeding pressure is a constant, on the same point, particle velocity increase with the reduction of density.
4. CORRELATION BETWEEN CHARACTERIZATION OF POWDER AND PARTICLE VELOCITY

4.1 Deduction of Theoretical Correlation Equation

It was found that complexity of gas-solid flow makes particle velocity be difficult to calculate (Liu et al, 2006). And it should be related to physic characterization of powder (such as size, shape, density and void fraction of powders), system performance and operating conditions, physical properties and velocity of conveying gas (Gilbertson et al, 2003; Luis Sanchez et al, 2003). In this section, theoretical correlation equation of particle velocity versus powder performance is deduced base on the assumption.

As mentioned previous, influencing factors of particle velocity $u_s$ are $p, L, D, \rho_g, \rho_s, d_s, \varepsilon, \sigma, w$, etc. Suppose the expression of $u_s$ as follows:

$$u_s = f \left( p, L, D, \rho_s, \rho_g, d_s, \varepsilon, \tan \sigma, w \right) \quad (2)$$

The expression of power product can be expressed as follows:

$$u_s = K p^a L^b D^c \rho_s^d \rho_g^e d_s^f \varepsilon^g \left( \tan \sigma \right)^h w^i \quad (3)$$

Base on the dimensional analysis, it can be expressed as follows:

$$LT^{-1} = (ML^{-1}T^{-2})^a (L)^b (\rho_g)^c (\rho_s)^d (\tan \sigma)^e (w)^f \quad (4)$$

Equations set was obtained.

$$\begin{align*}
M & : a + d + e = 0 \\
L & : a + b + c - 3d - 3e + f = 1 \\
T & : -2a - 1 = 0
\end{align*} \quad (5)$$

Undetermined coefficients are $b, c, e$. Then

$$a = 0.5, d = -0.5e, f = -b - c \quad (6)$$

Eq. (6) was substituted into Eq. (4).
where 

$$E = L / d_s; \quad \psi = D / d_s; \quad Y = \rho_g / \rho_s$$

Eq. (7) can be changed as followed:

$$u_s = \frac{K \rho_s^{0.5}}{\rho_s} \left( \frac{L}{d_s} \right)^b \left( \frac{D}{d_s} \right)^c \frac{1}{\rho_s^{0.5}} \left( \frac{\rho_g}{\rho_s} \right)^e \left( \tan \sigma \right)^h w^i$$

Eq. (8)

Base on the mathematical analysis, substituting 144 groups of data into Eq.(8) and adopting linear regression analysis in seven unknown, regression equation was obtained as follows:

$$\ln u_s = -3.375 + 0.153 \ln E + 0.662 \ln Y + 1.563 \ln \psi + 8.55 \ln \varepsilon - 1.47 \ln (\tan \sigma) - 1.118 \ln w$$

Significance test of regression equation showed that $\ln(\tan \sigma)$ has no obvious effect on $\ln u_s$. So it is eliminated from equation and quadratic linear regression should be performed. Result was gained as follows:

$$\ln u_s = -6.653 + 0.408 \ln E + 0.561 \ln Y + 0.488 \ln \psi + 6.55 \ln \varepsilon - 0.559 \ln w$$

Significance test of previous equation was performed again. It was found that significant probability of each coefficient is less than 0.05. Linear regression of the equation wasn’t needed again. The multiple correlation coefficient of the equation $R$ is 0.964 which means regression result is good. Regression equation of particle velocity $u_s$ was gained as follows:

$$u_s = 1.29 \times 10^{-3} p^{0.5} D^{0.488} L^{0.408} \rho_s^{-1.06} \rho_g^{0.56} d_s^{-0.896} \varepsilon^{6.55} w^{-0.559}$$

From Eq.(11), it can be seen that particle velocity was affected by some parameters such as feeding pressure, pipe diameter, pipe length, particle diameter, density, void fraction, moisture content. Comparing each parameter of the theoretical formula, it can not be directly compared, because each parameter has different units and orders of magnitude. In this paper, we get partial regression analysis of Eq.(11) and standardize the coefficients, making it easy to compare. From all of the standard partial regression coefficient, the standard partial regression coefficients of the density, size, void fraction, moisture content were obtained:

$$b_i'(\rho_s)=-0.763, \quad b_i'(d_s)=-0.496, \quad b_i'(w)=-0.235, \quad b_i'(\varepsilon)=3.256$$

where $b_i'<0$ shows that independent variable increase a standard deviation unit, dependent variable will reduce $b_i'$ standard deviation units. It introduced the increasing of density has greater effect than moisture content and particle size on particle velocity reducing and the increasing of void fraction has more obvious effect than other influencing factors on the increasing of particle velocity.

For this experimental system, particle velocity increase gradually with the increase of pipe diameter and feeding pressure, while system operated parameters are invariable, particle velocity increase with the reduction of density and the increasing of void fraction. That is consistent with experimental result.

### 4.2 Error Analysis

We compared theoretical value with experimental value. It was found that good accuracy is achieved with the relative error range -13.6%—12.38% between academic fitting equation and experiment.
The relationship of particle velocity between theoretical and experimental value was shown in Fig.6. It can be seen that theoretical result of particle velocity is consistent with trend of particle velocity along pipeline in experiment, and the theoretical arithmetic value is identical with experiment data. Therefore, it can be used to predict trends of particle velocity in the conveying process for different kinds of powder materials preferably.

![Fig.6 Relationship of particle velocity between theoretical and experimental value(0.36MPa)](image)

5. CONCLUSIONS

1) Average particle velocity and particle velocity along pipeline can be measured by Gauge Pressure transmitters.
2) Average particle velocity increase with the increase of feeding pressure. When feeding pressure is a constant, average particle velocity increase with the reduction of density of materials, while particle velocity decreases with the reduction of void fraction.
3) Particle velocity increase gradually along pipeline conveying direction and feeding pressure. When feeding pressure is a constant, on the same point, particle velocity increase with the reduction of density, while high void fraction increase particle velocity.
4) Theoretical correlation equation of particle velocity versus powder characterization has been obtained with dimensional analysis and mathematical analysis as follows:

\[ u_s = 1.29 \times 10^{-3} p^{0.5} D^{0.488} L^{0.408} \rho_g^{-1.06} \rho_s^{0.56} d_s^{-0.896} \varepsilon^{6.55} w^{-0.559} \]

It was shown that good accuracy is achieved by Error analysis. Therefore, it can be used to predict trends of particle velocity in the conveying process for different kinds of powder materials precisely.

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NAMENCLATURE

- \( u_s \) = particle velocity \[ \text{[m/s]} \]
- \( L_{ij} \) = distance between two gauge pressure transmitters \[ \text{[m]} \]
- \( t_{ij} \) = the time interval of signal emergence of two gauge pressure transmitters \[ \text{[s]} \]
| Symbol | Description                               | Unit          |
|--------|-------------------------------------------|---------------|
| $p$    | conveying pressure                        | [MPa]         |
| $L$    | length of pipeline                        | [m]           |
| $D$    | diameter of pipeline                      | [mm]          |
| $\rho_g$ | gas density                                | [kg/m$^3$]    |
| $\rho_s$ | particle density                           | [kg/m$^3$]    |
| $d_s$  | diameter of particle                       | [$\mu$m]      |
| $\varepsilon$ | void fraction                              | [%]           |
| $\sigma$ | angle of repose                            | [$^\circ$]    |
| $w$    | moisture content                           | [%]           |

$E$ the ratio of pipe length and particle diameter

$\Psi$ the ratio of pipe diameter and particle diameter

$Y$ the ratio of gas density and particle density

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