Journal of the Taiwan Institute of Chemical Engineers 000 (2018) 1–5

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

journal homepage: www.elsevier.com/locate/jtice

Powder characteristics for index of powder unit operation☆

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ARTICLE INFO

Article history:
Received 17 October 2017
Revised 17 January 2018
Accepted 25 January 2018
Available online xxx

Keywords:
Powder characterization
Unit operation
Adhesion
Dispersion
Compression

ABSTRACT

It is said that designing a powder unit operation device is difficult. Hence, many of the devices are being manufactured by trial and error. The lack of correlation or connection between the output of the unit operation and the physical properties and/or characteristics of powders is the anticipated reason for this trial and error process to be needed. To advance this process, many have attempted to make a connection between the particle properties and/or powder characteristics with the result of the operation. In this manuscript, some attempts to make the connection were introduced.

The oldest attempt was reported by the pioneer of powder technology. This original approach gives us many suggestions on how to best proceed. Thus, outlines of the pioneer's investigation will be introduced. Following the investigation, a concept of "Powder operational characteristics" will be explained. An example of the definition and measurement of the powder operational characteristics relating to the disruption of particle aggregate by air flow is introduced. Another example of the definition of powder operational characteristics obtained through "analysing the basic powder science in a practical and applicable way" is also introduced.

1. Background

Particulate materials and powders are used as raw materials, intermediate products, and products in many processes such as food, medicine, and ceramic manufacturing processes. The operating conditions of the process are mostly decided based on experience. For this reason, when the lot of raw materials or the specifications of the product are changed, the operating conditions are set by trial and error every time. In order to avoid such trial and error and to decide the operating conditions according to the initial conditions such as the properties of raw materials and the performance or specification of products, it is necessary to connect the particle properties and/or the powder characteristics of the raw materials or products with the result of the operation. This is the basis of the device design method which has a long history of also being attempted in powder processes. However, it is hard to say that designing methods of powder handling operation or equipment is established.

On the other hand, with the development of measurement technology, many characterisation methods such as particle size distributions, properties, or characteristics of materials consisting of the particles, chemical, or physical properties of a surface can be made available. In addition, powder characterisation methods such as fluidity index and shear testing have been proposed and various powder characteristic values can be measured. Although various physical properties and characteristics can be evaluated, a trial and error accumulation of experience is required for designing and decision making for the operating conditions of powder processes. In this paper, instead of considering the reason why the trial and error experience is required, "What is the required evaluation of particle properties and powder characteristics" is reconsidered. This introduces some attempts to connect the particle properties and/or the powder characteristics with the result of the operation.

2. Pioneer's trials for systematisation of powder technology

In 1964, Professor Iinoya, who established The Society of Powder Technology, Japan and The Association of Powder Process Industry and Engineering, Japan, posted a paper entitled "Powder Engineering from the View of Chemical Engineering [1]". In the paper he proposed a classification of powder technology as shown in Table 1. The subjects are separated into a fundamental subject named "Powder science" and applications named "Powder technology". Based on this classification, he mentioned that "Since the powder science has not been analysed and/or experimented with practical application, the present powder technology has become rootless like a floating grass on water surface". This description on the relation between fundamentals and applications of

☆ Please note that the words of the pioneers are originally written in Japanese. The words shown in this manuscript are translations by the author of this manuscript.

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https://doi.org/10.1016/j.jtice.2018.01.033
1876-1070/

Table 1
Classification of subject of powder technology.

Category	Branch	Subject
Powder Science (Fundamental)	Powder dynamics	Movement, Repulsion, Friction, Flow, Forming etc.
	Powder physics	Adhesion, Packing, Moisture adsorption, Electrostatics etc.
	Powder chemistry	Adsorption, Agglomeration, Catalyst, Reaction etc.
	Powder measurement	Characteristics (Size, Concentration etc.), Level, Flow rate, Degree of Mixing, Sampling etc.
Powder Technology (Application)	Dry separation	Dust collection, Classification etc.
	Wet separation	Settling, Centrifugal sedimentation, Filtration etc.
	Powder mixing	Dry mixing, Wet mixing etc.
	Powder production	Comminution, Granulation, Spray drying etc.
	Powder conveying	Fluid conveyance, Mechanical conveyance etc.
	Powder process control	Powder process control, process dynamics
	Others	Combustion, Drying, Reactor etc.

powder technology is the same as our present day situation and must be one of the causes for trial and error or empirical designing of powder unit operation. There are several problems in powder technology, including adhesion, repulsion of particles, friction coefficient or friction angle of the powder layer, particle size distribution, particle shape and electrostatic and magnetic properties [1]. These points are related to the properties of the particles and powder characteristics. Some of them have progressed from the days of Professor Iinoya, but many of them are still under investigation. In other words, powder technology has still not been systematised.

At almost the same time as the Iinoya's paper [1], the classification of various powder behaviour for the systematisation of powder technology was proposed [2]. In the classification (Fig. 1), the behaviour of the powder is divided into the stationary state and the flow state. Each of them is roughly divided into the behaviour of the dry powder and wet powder. In this table, examples of devices and operations in powder processes for each of the categories defined here are also shown. The examples cover representative powder operations which can be seen in the process. Although various powder behaviours are also classified in detail, the relationship or connection of the properties of the particles or powder characteristics with each behaviour was not discussed.

3. Powder operational characteristic

Professor Masuda also emphasised the importance of "powder characteristics" when considering an operation in real powder processes [3]. Here, the "powder characteristics" means the powder characteristics correlated with the operational result. Later, he named the characteristics as "Powder operational characteristics" in the sense of distinguishing it from the characteristics for identification of the powder. According to Masuda's definition of the powder operational characteristics, among the measurable physical properties or characteristics of powder only the characteristics correlating with the target operation result can be called "characteristics".

In another viewpoint, three categories of characteristic values, "Descriptor", "Index", and "Factor" were introduced in the discussions of the shape factor of the particle [4]. The descriptor means the characteristics of particles and powder which is a numerical value expressing the "difference" of each particle and powder. In the descriptor, the numerical value correlated with the behaviour of particles or powder during the operation is an indicator of the behaviour. In other words, the descriptor is a menu for searching for an index, and if the index is found, a correlation line or equation may be obtained by plotting the graph with the index on the horizontal axis and the target operational result on the vertical axis. The factor corresponds to the coefficient in the correlation line or equation. The factor and the index are the powder operational characteristics in [3].

"Micro-scale", "Meso-scale" and "Macro-scale" are often used as terms to classify the characteristics of particles and powder. In this classification, the scale of phenomena and/or event reflecting on the characteristics is focused and the correlation with the result of powder unit operation is not considered for the classification. In other words, the focus points of the classification are different from "Descriptor", "Index" and "Factor".

3.1. Case study – pneumatic conveying and dry dispersion

The powder operational characteristics must reflect the behaviour of the particles or powder in the operation. One method for obtaining such characteristics is, therefore, to apply a standardised operation in which the same factor as the target powder operation is included to the powder to be manipulated in the operation. Here, we consider a deposition of particles on a pipe in a pneumatic conveyor, as an example. In the pneumatic conveyor, air velocity is an important operating condition. In the air velocity decision making process, the resuspension test using the apparatus shown in Fig. 2 can be utilised. By using the apparatus, the minimum air velocity (=critical air velocity) u_c at which particles start to resuspend steadily from a powder layer can be obtained [5]. From the critical air velocity u_c, the airflow shear stress τ_c working on the surface of the powder layer can be calculated.

$$\begin{aligned} \tau_c &= C_f \frac{\rho_a u_c^2}{2} \\ C_f &= 16/\mathrm{Re} \qquad (\mathrm{Re} < 2300) \\ C_f &= 0.0791\mathrm{Re}^{-1/4} \qquad (\mathrm{Re} \geq 2300) \end{aligned} \tag{1}$$

Here, ρ_a is the density of the gas, Re is the Reynolds number ($=\rho_a u_c D/\mu$, μ: viscosity of the gas, D: hydrodynamic equivalent diameter of the flow path). There is a proportional relationship between this airflow shear stress τ_c and the tensile strength of powder layer σ [6]. Therefore, Eq. (2) can be obtained.

$$\tau_c = k\sigma = k\frac{\phi k_n F}{\pi x^2} \tag{2}$$

By re-arranging Eq. (2), following equation can be obtained [6].

$$\frac{kF}{\pi x^2} = \frac{\tau_c}{\phi k_n} (\equiv F_p) \tag{3}$$

In this equation, k is a proportional constant, x is the particle diameter and F is the adhesion force between particles. Coefficient k_n is the coordination number of the particles depending on the packing fraction ϕ which is the experimental condition for the resuspension test. To estimate coordination number k_n, we can use Ridgway–Tarbuck's empirical equation [7].

$$k_n = 13.8 - \sqrt{175 - 232\phi} \tag{4}$$

The left side of Eq. (3) is a value reflecting the particle property of inter-particle adhesion and particle size which can be recognise as a characteristic value independent of experimental conditions (packing fraction ϕ). Here, the term expressed by Eq. (3) was designated as F_p. Fig. 3 shows experimental results. Although F_p changes with the packing fraction in low packing fraction region, F_p gradually approaches a constant value as the packing rate increases. Here, the asymptotic value is defined as the "Adhesion

Please cite this article as: K. Gotoh, Powder characteristics for index of powder unit operation, Journal of the Taiwan Institute of Chemical Engineers (2018), https://doi.org/10.1016/j.jtice.2018.01.033