Survey of Recent Advances in Research on Powder Mixing in Japan

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1. Introduction

Mixing or blending of solid particles is one of the most important unit operations widely used in many industries to control the raw materials or to homogenize the final products. According to various requirements in many processes, various kinds of mixing equipments have been developed and a lot of technical devices have been applied to solve the practical problems. Numerous studies on the mixing of solid particles have been done by means of theoretical and experimental methods. Research on the solid mixing involves very comprehensive subjects such as the expressing method of the mixing state and the mixing process on the basis of mathematical model, mechanisms of mixing and segregation caused by the difference in the physical properties of solid particles, effect of the physical properties of powders and operating conditions on the performance of the mixers, design and scale up of mixers, power requirement of mixers, computer simulation of mixing processes and so on.

In this review, recent works on the mixing of solid particles published in academic journals from the last review in 1975 to today are introduced.

2. Fundamental studies on the mixing processes

2. 1 Degree of mixing

Various kinds of index to express the mixing state of solid particles have been proposed and used by many researchers. Most of the available definitions of the mixing index, which specifies homogeneity or distribution of the composition in a solids mixture, are based on the variance of the concentration of a certain component among spot samples. This statistical definition cannot provide a sufficiently deep insight into the microscopic and geometric nature of a mixture. A new definition of the degree of mixing was proposed based on the mean contact number from a microscopic and geometric viewpoint. Usually, it is difficult to measure the contact number around the key particles in a mixture. The determination of the concentration of particles by spot sampling, instead of direct counting of the contact number, as a practical method of estimating the mean contact number was examined for the regular packing of binary component system. It was shown that the concepts of the coordination number and contact number could be applied to the expression of the mixing state for the regular packing arrangements with irregular patterns and for the multicomponent solids mixture in the completely mixed state. The knowledge of the structure of a mixture which is the final product of the mixing operation is essential in understanding sintering and packing characteristics, and reactivity of the mixture. From this viewpoint, clarifying the microscopic arrangement of particles comes to be of great importance.

2. 2 Mechanisms of mixing

The solids mixing process has been regarded as a probabilistic phenomenon which involves basic three mechanisms: convective, diffusive and shearing mixing. The mixers have been classified into the various types according to the ways to work the mechanical forces which promote the mixing of solid particles. Rotary vessel type mixers have been adopted in many researches for the observation of flow patterns.
and the application of mathematical models. Steady state Markov chain model was applied for describing the main flow patterns of particles in the V-shaped type mixer and circulation time distribution along the flow was obtained by the transition probability. Furthermore, as the application of this model, the segregation of solid particles in the mixer was simulated with the aid of a digital computer.

In the actual mixers, it is difficult to distinguish or separate basic three mechanisms. A new approach called "the synthesis of a mixing system" was proposed to describe the complicated mixing processes. It was assumed that the mixing process consisted of two basic mechanisms, diffusive and convective mixing. The diffusive mixing is described by a probabilistic branching model where the particles flow down between hexagonal obstacles which are located in zigzag lines on a plane as shown in Fig. 1(a). On the other hand, for the convective mixing, the mixing process is attempted to describe using the models by stacking and folding operation as shown in Fig. 1(b). The optimum feeding strata to achieve the completely mixed state in the shortest time was discussed by the combination of these two elemental models.

2.3 Segregation of de-mixing models

It is well known that solid particles tend to segregate when the particles in the mixture have different physical properties such as size, density, internal friction coefficient, shape, surface conditions and so on. A number of mechanisms have been proposed as responsible ones for the segregation effect, including vibrational segregation in which larger particles tend to rise to the surface, percolating segregation in which the top layer of particles acts as a screen through which all except the larger particles are able to pass and reach the stationary region below, puring segregation in which larger particles tumble further down the free surface of a growing pile, free flight segregation which results from particles having different trajectories and so on. The axial segregation profile of binary solid mixtures during the mixing and segregation processes in a horizontal rotary conical vessel was studied by using several kinds of combination of particles. The segregation characteristics profiles based on the concentration distribution of concerned particles with time were measured as shown in Fig. 2(a) and (b) and it was confirmed that the de-mixing potential, proposed in the Rose's equation, related to the axial arrangement of the particles in the vessel. Furthermore, the radial and axial segregation in a rotary vessel type mixers were closely related to the permeation effect measured in a moving bed. The cascading angle difference between particles of the mixture was found to be one of the important factors for the segregation in the mixer. The rotary conical vessel can be used as a continuous separator of the mixture applying the characteristics of segregation of which larger particles tend to move toward the narrower end of the vessel and smaller particles toward the wider end. The segregation of particles with different density in both the axial and radial direction was measured by counting the tracer particles according to the mixing time.
3. Mixing operations

There are a number of problems to be solved in the actual mixing operations such as selection of the mixing equipment, determination of the optimum operating conditions, improvement of the physical properties of solid particles and so on. Segregation caused by the difference of particles size is remarkable when the particles have spherical shape and good flowability. The degree of segregation based on the standard deviation of tracer concentration was measured using radioactive tracer method, after mixing of atomized powder metal mixture having widely dispersed size distribution. Two different types of mixers, a ball mill and a static (or motionless) mixer, were examined in the mixing performance. It was shown that using the static mixer as a secondary mixer after mixing with the ball mill was rather effective than using each mixer respectively. It was also noticed, however, that some segregation took place at the declining part of the mixer where the free flowing layer was observed at the same time. To obtain homogeneous mixture of fine and irregular shape powders, the static mixer was attempted to apply to the mixing system.

It was pointed out that the internal friction coefficient was one of the important factors to affect mixing characteristics. Internal friction coefficients have been measured by a direct shear tester for a number of powders having different particle diameters and densities, and for their binary mixtures. The mixing performances of the mixers have been correlated much better with the internal friction coefficient than with the change in particle diameter or density. Fig. 3 shows the relationship between the final degree of mixing \( M_s(1 - \sigma/\sigma_0) \) and difference of the internal friction coefficient \( \Delta \mu_s \) of each powder component before mixing. While the final degree of mixing in the rotary vessel type mixers decreases as \( \Delta \mu_s \) increases, those in the fixed type ones are hardly influenced by the
Fine powders under 10μm in diameter are difficult to achieve the complete mixing state because of their high adhesiveness, tendency to agglomeration and poor flowability. Mixing of these materials requires some mechanisms to homogenize them disintegrating their agglomerates by strong shearing force and some additional device to prevent adhesion of the materials on to the mixing equipment and coagulation each other.

Experimental studies on the continuous mixing of fine particles have been done by using a vertical cylindrical mixer with a variety of impellers. It has been found that the principle of designing an effective impeller for continuous mixing is to give intensive radial mixing without increasing axial mixing. On the basis of this principle, the new types of impellers suitable for continuous mixing of fine and cohesive powders have been developed and their performance has been evaluated by means of the tracer response technique. It has also been shown that a properly designed vibratory feeder with a suitable feedback control system can be used to keep the feed rate of fine and cohesive powders into a continuous mixer at a constant value. Another report gave experimental results that in case of mixing fine and coarse materials, sufficient agitation of the coarser one is essential for effective mixing of the finer at the beginning of mixing and that adhesion of the finer particles on the surface of the dispersed coarser ones has a great effect on the final mixing state. In this case, the cohesive fine powder decreases the tendency of segregation by means of coagulation by itself and agglomeration with the coarser particles.

These results suggest the possibility of controlling the physical properties of solid particles according to the mixing purposes.

Fluidized bed or pneumatic type mixers are suitable for mixing of solid particles having almost equal physical properties and good flowability. On the other hand, injection of gas into the particle bed tends to segregate the component having different physical properties. Mixing and/or segregation processes of particles by succeeded single bubble were observed in a two dimensional fluidized bed, containing particles of different size and density. It was found that the local convective mixing of particles was influenced by the bubble diameter and the frequency of bubble formation. Even if there exists difference of physical properties between the component in a binary mixture, the motion of the particles of less amount of component was restrained by the motion of bulk component, i.e. segregation of different particles.
from the mixture bed was controlled by the mass flow\(^{14}\).

The mixing characteristics of positive and negative air mixers were investigated under the unsteady fluidizing conditions. Using both methods of injecting gas into the powder bed by compression and suction, the degree of mixing, mixing time and the power requirement were measured and these results were compared with the results of a V-shaped mixer. It was shown that the mixing performance of the air mixer was better than that of the other types when the particles to be mixed had little difference in the physical properties, and that the power requirement in suction fluidized mixer was less than pressurized one\(^{4}\).

4. Power requirement of mixer

For design or selection of suitable mixing equipments of solid particles and for decision of optimal operational conditions, the mixing performances should be evaluated taking account of the power requirement of mixers as well as the rate of mixing and the final degree of mixing. Power requirement of mixers is markedly influenced in a complicated manner by various factors, such as the structure and dimension of mixing equipment, the physical properties of solid particles, the operational conditions and so on.

4. 1 Rotary vessel type mixers

Power requirement of horizontal cylindrical mixers has been measured with a variety of solid particles\(^{20}\). The total force exerted on the mixer shaft by the charged solid particles was assumed to be the sum of \(i\) the gravitational force by the powder bed, \(ii\) the inertia force for accelerating the powder mass, and \(iii\) the frictional force acting between the powder bed and the inside wall of the mixer. A dimensional analysis of the basic force balance equations has been made to obtain useful correlation of the power data in terms of the operating conditions, the dimensions of the mixers and the physical properties of the solid particles, specifically the bulk density and the friction factor between the vessel wall and the powder bed.

The Newton number, \(Ne\), and the Froude number, \(Fr\), both non-dimensional terms have been found important for the estimation of power requirement for this type of mixer. They can be correlated by the following equation\(^{21}\):

\[
\frac{T \cdot g \cdot c}{R^3 \cdot L \cdot \rho g} = A + B \cdot \frac{N^2 \cdot R}{g} \quad (1)
\]

where \(T\): torque (kg-m), \(R\): radius of cylinder (m), \(L\): length of cylinder (m), and \(N\): rotary speed (rps), respectively. The left hand of the
equation (1) represents Newton number and the second term on the right hand side corresponds to Froude number. The value of $A$ and $B$ are function of the charge ratio $f(-)$, angle of repose $\phi$ (deg) and the friction coefficient of vessel wall $\mu_w(-)$. Fig. 4(a) and (b) show the calculated values of $A$ and $B$ as the function of the charge ratio. Using these figures, the power requirement of horizontal cylindrical mixers can be estimated. For the V-shaped and double cone type mixers, equation (1) is still admitted fundamentally, though the torque varies periodically with the revolution of the mixer's vessel.

4.2 Fixed type mixers

The fixed type mixers consist of various shapes of vessel and agitator (mixing paddle, screw, pin or rod, ribbon, scraper etc.). It is very difficult to obtain the general relationship among the power requirement, the shape and dimension of mixer, the physical properties of solid particles and the operating conditions, because the flow pattern and mixing mechanism are more complicated than those in the rotary vessel type mixers. This situation is probably related with the fact that still very little is known about the rheological behaviour of solid particles.

The relationship among the mixing torque for the horizontal ribbon mixers and various factors has been studied. The torque increases with the charge ratio $f$, the bulk density $\rho_a$, the internal friction coefficient $\mu_i$, and the dimension of the ribbon blade. On the other hand, the torque is not influenced by the rotary speed $N$ in the range of $30 \leq N \leq 200$ (rpm). The shear force has been found to be a dominant factor in the total power requirement of the mixer. The power data $P$ were well correlated with the experimental conditions by the relation\(^\text{17}\):

$$P \cdot g_c = K \mu_i \cdot \rho_a \cdot g \cdot f(\pi D_o^2 L) d_c N$$  \hspace{1cm} (2)

where, $D_o$: diameter, $L$: length, $d_c$: characteristic length of ribbon and $K$: experimental constant.

For the vertical ribbon mixer, the effects of various operating condition on the mixing torque have been studied experimentally\(^\text{18}\) and the power requirement for agitation of the powder bed has been analyzed by introducing a simplified model\(^\text{19}\). The total force exerted on the ribbon blades by the powder bed was assumed to be the sum of: (i) the pressure force by the powder bed in the passive Rankin state, (ii) the shear force acting on the circumscribing cylindrical surfaces around the ribbon blades, and (iii) the inertia force for accelerating the powder mass surrounded by the cylindrical surfaces. The ratio of the total force to the inertia force and the ratio of the inertia force to the shear force were calculated. Further experimental correction would be necessary for this kind of power equation and besides it becomes important to evaluate the dynamic physical properties of solid particles and flow patterns.

The tensiling process curves for powders with various moisture contents have been obtained experimentally in order to correlate the mixing torque with the tensile strength. From the trend between the breakup displacement and the moisture content, the powders were able to be classified into three stages according to the region of moisture content. Characteristics curves of torque were discussed based on the stage of powders and the tensile strength. The mixing torque for moist powders was excellently correlated with the tensile strength obtained by the tensile tests for the powders with the void fraction identical to that for the torque measurement\(^\text{32}\).

4.3 Fluidized bed and moving bed type mixers

In the fluidized or moving bed with mixing devices, the fluidization of solid particles is promoted by the injection of air or gas into the powder bed and the mechanical agitation. It is well known that the packing state of powder bed becomes looser and both the bulk density and the internal friction coefficient decrease, once the powder bed is set to motion in the mixing equipments.

Relationship between the optimum condition of mixing and the total power requirement was investigated using a model of fluidized bed with plate paddles\(^\text{15}\). The total energy (defined as the sum of power requirement for mechanical agitation and aeration) taking account of the time required to reach the final degree of mixing became minimum in the region where the air velocity was about 1.4 to 2 times as high as the minimum fluidization velocity. The resistance force for agitating the powder bed depends much upon the pressure drop when
the air velocity is under the minimum fluidization velocity. The pressure drop in a moving bed with a double herical ribbon was measured changing the shape of ribbon blades, operating conditions and physical properties of solid particles. The relationship among the dimensionless pressure drop $\Delta p^*$ and various parameters was expressed in the following equation\(^{22}\),

$$\Delta p^* = K_{gas} R_p^{0.5} R_b^{-1} \exp\left(-N/S\right) u^*$$

where, $\Delta p^* = \Delta p/\Delta p_{mf}$, $\Delta p$: pressure drop, $\Delta p_{mf}$: pressure drop at the minimum fluidizing point, $R_p$: ratio of ribbon pitch to ribbon diameter, $R_b$: ratio of width of ribbon blade to ribbon diameter, $N$: rotary speed, $U^* = U/U_{mf}$, $U$: air velocity, $U_{mf}$: minimum fluidization velocity and $K_{gas}$: experimental constant.

On the other hand, the amount of decrease in torque due to the blowing air into the powder bed has been well interpreted in terms of a dimensionless pressure drop $\Delta p^*$ as shown in Fig. 5. The general correlation equation for agitating torque with aeration has been provided as follow\(^{23}\),

$$T_G = T_0 \left(1 - 0.93\Delta p^*\right)$$

where $T_G$ and $T_0$ are mixing torque with and without aeration. The power requirement for the moving bed with mechanical agitation has been well correlated by the various experimental parameters within an accuracy of $\pm 30\%$. Additionally, the starting torque for moving bed type mixer was measured under the various operating conditions and the relation between the initial void fraction of the powder bed and starting torque was discussed. The starting torque decreases almost exponentially with increasing initial void fraction. The reduction of the torque due to increase in void fraction has been correlated by an experimental equation\(^{24}\).

5. Conclusion

The recent advances in research on the mixing of solid particles were introduced in this review. For modeling of mixing mechanisms and mixing processes in the actual mixing equipments, effects of the physical properties of solid particles both in the state of static and dynamic on the behaviour of powder bed should be considered in the basic models. Research on the mixing processes under the condition of gravity free state or under different force field such as magnetic, electric, sonic etc, becomes more important item for designing mixers based on new mixing mechanisms. Furthermore, controlling the characteristics of powders for each purpose or designing the physical properties of solid particles (diameter, shape, density, void fraction, pore size, surface conditions, activity, flowability, etc.) using chemical and physical treatment is another interesting future subject of research.

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