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Recent Developments in Solids Mixing

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SUMMARY

This review covers the major development in solids mixing since 1976. The publications on the subject have been divided into three major categories: characterization of states of solids mixtures, rates and mechanisms of solids mixing processes, and design and scale-up of mixers or blenders. Possible future work has been proposed.

INTRODUCTION

Solids mixing is a common processing operation widely used in industry. It is extensively employed in the manufacture of ceramics, plastics, fertilizers, detergents, glass, pharmaceuticals, processed food and animal feeds, and in the powder metallurgy industry. In fact, this operation is almost always practised wherever particulate matter is processed. We resort to solids mixing to obtain a product of an acceptable quality or to control rates of heat transfer, mass transfer and chemical reaction. It is a common occurrence to read about, or to view on television, researchers and technicians blending particulate ingredients for producing superconducting materials.

The present comprehensive review of solids mixing focuses on the published works since 1976; nevertheless, significant papers not identified in our previous reviews are also included. The works prior to 1976 have been extensively reviewed in a number of expositional articles and literature surveys, including those by Lacey [1], Scott [2], Weidenbaum [3], Valentin [4], Venkateswarlu [5], Clump [6], Gren [7], Fan *et al.* [8], Chen *et al.* [9], Fan *et al.* [10], Fan *et al.* [11], Fan and Wang [12], Cooke *et al.* [13], Hersey [14], Kristensen [15], Rowe and Nienow [16] and Williams [17]. Some of the works in the last ten years have also been included in more recent reviews [18 - 27].

In blending or mixing different kinds of particulate matter, we need to be concerned with three broad aspects. The first is the type of mixer selected or designed and the mode of its operation. The second is the characterization of state of the resultant mixture, and the third is the rate and mechanism of the mixing process giving rise to this state. The mixing process is influenced profoundly by the flow characteristics of the particulate matter to be mixed. Recognition of the existence of the two types of particulate matter, free flowing and cohesive, forms the basis for classifying and characterizing mixtures and mixing processes. The present review covers the classification of mixing equipment, the characterization of mixtures and the rates and mechanisms of mixing processes, and the design and scale-up of mixers.

CLASSIFICATION OF MIXING EQUIPMENT

Mixing equipment can be categorized relatively simply according to the mixing mechanisms prevailing in them. The four major types are tumbler, convective, hopper (gravity flow) and fluidized mixers [28]. Their main characteristics are given in Table 1.

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TABLE 1

Summary of mixer characteristics [165]

Type of mixer	Batch or continuous	Main mixing mechanism	Segregation (suitability for ingredients of different properties)	Axial mixing	Ease of emptying	Tendency to segregate on emptying	Ease of cleaning
Horizontal drum	B	Diffusive	Bad	Bad	Bad	Bad	Good
Lödige mixer	B	Convective	Good	Good	Good	Good	Bad
Slightly inclined drum	C	Diffusive	Fair	Bad	Good	Good	Good
Steeply inclined drum	B	Diffusive	Bad	Good	Bad	Bad	Good
Stirred vertical cylinder	B	Shear	Bad	Good	Good	Bad	Good
V mixer	B	Diffusive	Bad	Bad	Good	Bad	Good
Y mixer	B	Diffusive	Bad	Bad	Good	Bad	Good
Double cone	B	Diffusive	Bad	Bad	Good	Bad	Good
Cube	B	Diffusive	Poor	Good	Good	Bad	Good
Ribbon blender	B	Convective	Good	Slow	Good	Fair	Fair
Ribbon blender	C	Convective	Good	Fair	Good	Good	Fair
Air jet mixer	B	Convective	Fair	Good	Good	Good	Fair
Nauta mixer	B	Convective	Good	Good	Good	Good	Bad

Tumbler mixers

A tumbler mixer, a totally enclosed vessel rotating about an axis, causes the particles within the mixer to tumble over each other on the mixture surface. In the case of the horizontal cylinder, rotation can be effected by placing the cylinder on driving rollers. In most other cases, the vessel is attached to a drive shaft and supported on one or two bearings. Common vessel shapes include the cube, double-cone, drum, and V and Y (see Fig. 1).

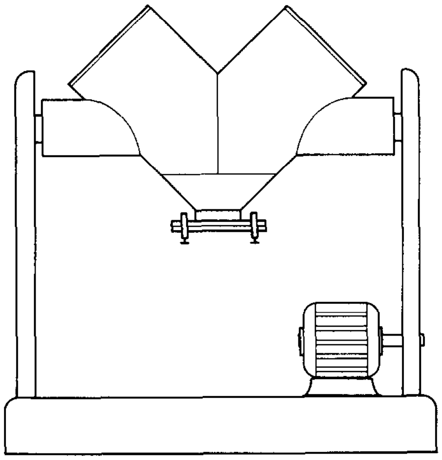

Fig. 1. V-shaped tumbler mixer [28].

In a tumbler mixer, radial mixing is relatively fast while axial mixing is slow and is the rate-controlling step. Appreciable segregation can occur in this type of mixer. If an internal impeller is added, its impaction action is likely to minimize segregation.

Convective mixers

In the majority of convective mixer designs, an impeller operates within a static shell and groups of particles are moved from one location to another within the bulk of the mixture [28]. The ribbon blender is probably the most widely used convective mixer (see Fig. 2). A ribbon rotates within a static trough or open cylinder and the particles are relocated by the moving ribbon. If the powder is cohesive in nature, mechanical

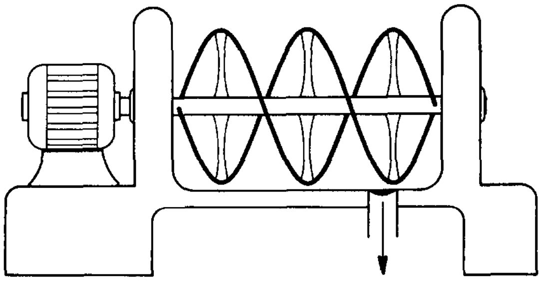

Fig. 2. Ribbon mixer [28].

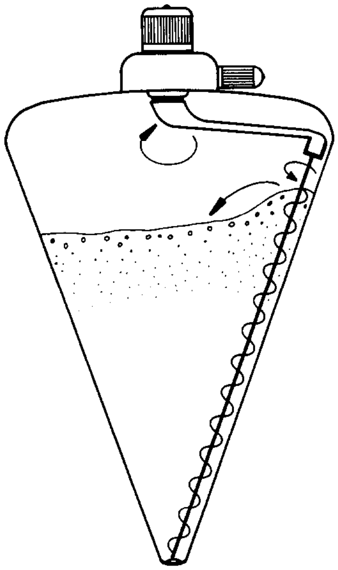

Fig. 3. Orbiting-type vertical screw mixer [30].

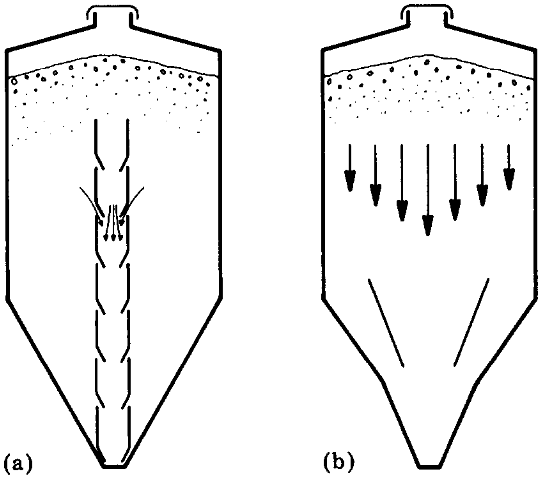

Fig. 4. Gravity flow blender [30]: (a), With multiple inner hoppers; (b) with single inner cone.

mixing devices, such as rotating screws (see Fig. 3), are normally required. Convective mixers are likely to be less segregative than mixers having a predominant mechanism of diffusion or shear mixing.

Hopper (gravity flow) mixers

In a hopper mixer, particles flow under the influence of gravity and mixing is totally energized by gravity flow [28]. A central cone is usually installed so that a pronounced velocity gradient in the vertical direction is produced without causing dead zones (see Fig. 4). Depending on the required degree of homogeneity, the particles may need to be recycled externally, thus causing considerable axial mixing. The recycle can be effected by either pneumatic or mechanical means. Due to percolation, segregation is likely to occur in this type of mixer, both on the free surface of the hopper and within the bulk of the material.

Fluidized mixers

Mixing in a fluidized bed is energized by both convective and gravity effects. In the fluidized bed, the powder is subject to a gas stream flowing upward against the direction of gravity [31]. The weight of the particles is counterbalanced by the buoyancy. The individual particle mobility, therefore, is greatly increased. If the gas flow rate is sufficiently large, the turbulence within the bed

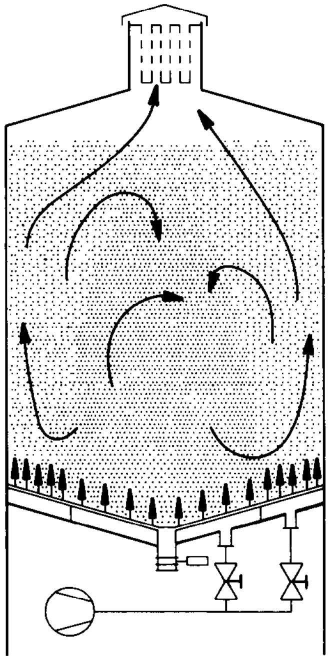

Fig. 5. Fluidized-bed blender [30].

will be considerable, and the combination of turbulence and particle mobility can produce excellent mixing. Figure 5 illustrates a fluidized-bed blender.

CHARACTERIZATION OF STATES OF MIXTURES

This section reviews publications dealing with the characteristics of mixtures. Mixtures can be classified into two major groups, one only involves free-flowing particles and the other contains cohesive or interactive constituent(s). A free-flowing mixture will generally permit individual particulates in it freedom to move independently, while a cohesive mixture generally has some interparticulate bonding mechanism, permitting particles to move only with an associated cluster of particles. Yet, the boundary between a free-flowing and a cohesive particle is not distinct; instead, it is "fuzzy" [28, 32].

Free-flowing mixtures

The formation of a mixture involving only free-flowing particles is a statistical or stochastic process in which the rules of probability apply. If the free-flowing particles are identical in all aspects except color, then a completely random mixture can be obtained. If they are not identical, a partially randomized final mixture will be generated due to incomplete mixing or segregation present in the mixing process. A mixture in this group exhibits a skewed distribution of the individual particles, thus featuring a relatively low degree of homogeneity.

The homogeneity of a solids mixture or the distribution of its composition is usually quantified by a mixing index. Over thirty different mixing indexes have been reviewed and summarized [8]. The diversity of the definitions is indicative of the difficulty involved in describing the complex nature of the mixing process and that of the resultant mixture. Most of the available definitions are based on the variance of the concentration of a certain component among spot samples [15, 33 - 41]. Nevertheless, it is difficult to discern the significance of these definitions.

For processes involving contact between different solid phases, the mixing rate is proportional to the contact points or area among particles of the different phases. Thus, a definition of a geometric mixing index based on the number of contact points appears to be of practical significance. Two approaches exist for determining the mixing index based on the contact number. One involves the co-ordination number sampling, and the other, the spot sampling [42]. The former is effected by selecting a number of non-key particles in contact with a randomly sampled key particle. The latter is accomplished by obtaining concentrations of a certain or key component in spot samples.

When a single particle is taken randomly from a mixture, the number of all particles in contact with this particular particle is called the total co-ordination number denoted by n^*, and the particle is called the key particle. Let A_0 particles be key particles in a binary mixture containing two kinds of particles of the same size A_0 and A_1. The number of particles of component A_1 in contact with a key particle is defined as the contact number contributed by component A_1 and is denoted by $C_{1(0)}$ (see Fig. 6).

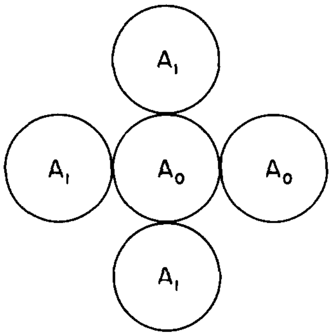

Fig. 6. Illustration of the contact number and the co-ordination number: $C_{1(0)} = 3$, $n^* = 4$.

An expression has been derived for estimating the contact number by spot sampling of a binary mixture in a completely mixed state [43]. Under the assumption that the completely mixed state exists in each of the spot samples, the population contact number can be directly estimated from its concentrations in spot samples; it is

$$\hat{C}_{1(0)} = \frac{\text{total contact no. contributed by component } A_1 \text{ in } k \text{ spot samples}}{\text{total no. of key particles in } k \text{ spot samples}}$$

$$= \frac{\sum_{i=1}^{k} n^* x_i n(1-x_i)}{\sum_{i=1}^{k} n(1-x_i)}$$

$$= \frac{\sum_{i=1}^{k} n^* x_i (1-x_i)}{k(1-\bar{x}_i)} \tag{1}$$

where
x_i = concentration of A_1 particles in the ith spot sample,
$\bar{x}_1$ = sample mean concentration of the particles of component A_1,
k = number of spot samples,
n = number of particles in a spot sample, and
n^* = total co-ordination number, the number of particles in contact with the sample particle.

The unbiased estimator of the population contact number $\hat{C}_{1(0)}'$ can be defined from the biased estimator $\hat{C}_{1(0)}$ obtained in eqn. (1) as follows:

$$\hat{C}_{1(0)}' = \frac{n}{n-1}\hat{C}_{1(0)} \qquad (2)$$

Based on the contact number evaluated in eqn. (1), the mixing index is defined as

$$M = \frac{C_{1(0)}}{n^*\bar{X}} \qquad (3)$$

where $\bar{X}$ denotes the population mean concentration of A_1 particles.

Expressions similar to eqns. (2) and (3) have been derived for a multicomponent solids mixture in the completely mixed state [44]. They are

$$\hat{C}_{j(0)}' = \frac{n}{n-1}\,\frac{\sum_{i=1}^{k}(n^*x_j)_i(x_0)_i}{k\bar{x}_0} \qquad j = 1, 2, \ldots, p \qquad (4)$$

and

$$M = \sum_{j=1}^{p}\frac{\hat{C}_{j(0)}'}{n^*\bar{X}_j}\,\frac{\bar{X}_j}{1-\bar{X}_0} \qquad (5)$$

where
$(x_j)_i$ = concentration of A_j particles in the ith spot sample of size n,
$\bar{x}_0$ = sample mean concentration of the key component,
k = number of spot samples,
$\bar{X}_0$ = population mean concentration of the key component, and
$\bar{X}_j$ = population mean concentration of component A_j.
$\hat{C}_{j(0)}'$ in eqn. (4) can be referred to as the unbiased estimator of mean contact number contributed by component A_j in k spot samples. The precision of the estimator $\hat{C}_{j(0)}'$ in estimating the population mean contact number has also been derived through evaluation of the variance of its distribution. Numerical experiments have resulted in a smaller relative standard error of the mean contact number estimator than that of the variance estimator of spot samples. Thus, the former is considered to be superior to the latter. This new mixing index was employed to investigate the transverse mixing in a Kenics Motionless Mixer [45]. The mixing index has been found to increase exponentially as the number of helices in the motionless mixer increases; it is also more effective in differentiating the quality of a mixture than the conventional ones derived from the variance of some spot samples. Based on this study of the relationship between the co-ordination number and compaction in the mixture through the mixer, it has been concluded that the packings of the mixtures are between cubic and hexagonal.

For a binary mixture in the incompletely mixed state, the total co-ordination number is random and it varies throughout the whole mixture; therefore, the population concentration is a variable. To deal with the distribution of the concentration or inhomogeneity among the spot samples, a beta-binomial distribution has been introduced as a model for an incompletely mixed or semi-random binary mixture [42]. A general expression has been developed to estimate the precision of the estimation of the population contact number from the distribution of the number of non-key particles.

The application of the contact number to estimation of the mixing index in an incompletely mixed state has been extended to a multicomponent mixture [46]. A Dirichlet-multinomial model, a multivariate generalization of the beta-binomial model, has been proposed to describe a multicomponent mixture in an incompletely mixed state. The model gives the distribution of the number of particles of component A_j in a spot sample of size n. By equating the sample mean of each component to its respective expectation, an estimator of the model parameter has been derived. The parameter has been found to define uniquely the mixing index based on the contact number.

In a study of the effect of particle-permeation on the segregation of a solids mixture in

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