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ТЕОРЕТИЧЕСКИЙ ПОИСК ОПТИМАЛЬНОЙ ЗАГРУЗКИ ПЕРИОДИЧЕСКОГО СМЕСИТЕЛЯ ДИСПЕРСНЫХ МАТЕРИАЛОВ

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Цель настоящего исследования – выявить, как загрузка предназначенных для смешивания в периодическом смесителе дисперсных материалов влияет на качество смеси и производительность смесителя. Известно, что небольшие количества компонентов (то есть малая загрузка) позволяют обеспечить лучшее качество смеси, но приводят к меньшей производительности смесителя. Особенно это проявляется, когда необходимо смешать компоненты, склонные к значительной сегрегации друг в друге. В этом случае полностью однородная смесь вообще недостижима, и существует оптимальное время смешивания, при котором качество смеси достигает максимума. Это оптимальное время возрастает с ростом загрузки. Таким образом, с точки зрения собственно смешивания, предпочтительно смешивать компоненты не один раз большими порциями, а несколько раз малыми порциями. Однако, полное время процесса смешивания состоит из времени загрузки смесителя, времени собственно перемешивания и времени разгрузки. Таким образом, производительность смесителя определяется не только временем собственно перемешивания, но также, по меньшей мере, и временем загрузки. Для того, чтобы оценить производительность смесителя при заданном качестве смеси, использована ячеечная модель, основанная на теории цепей Маркова. Показано, что существует оптимальная загрузка, которая обеспечивает максимальную производительность смесителя, и эта оптимальная загрузка существенно зависит от времени загрузки компонентов.

Ключевые слова: дисперсный материал, смешивание, сегрегация, загрузка смесителя, производительность смесителя, цепь Маркова, качество смеси, время смешивания, оптимизация

THEORETICAL SEARCH FOR OPTIMUM HOLD-UP IN A BATCH MIXER OF PARTICULATE SOLIDS

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The objective of the study is to investigate how the hold-up of particulate solids to be mixed in a batch mixer influences the mixture quality and mixer capacity. It is known that a small amount of components (i.e., a small hold-up) allows reaching better quality of a mixer but leads to small capacity of a mixer. It is particularly appreciably when it is necessary to mix the components, which have a strong tendency to segregate into each other. In this case the perfect mixture cannot be reached, and there exists the optimum mixing time, at which the mixture homogeneity reaches maximum. This optimum time increases with the hold-up increase. Thus, from the mixing as such viewpoint, it is better to mix components not in big portions one time but in small portions several times. However, the total time of a mixing process consists of the loading time, mixing time and discharge time. The loading time depends on many factors such as a dosage device design, feeders design, and others, while the discharge time is usually much smaller. Thus, the mixer capacity is determined not only by the mixing time but also by the loading time at least. In order to estimate the mixer capacity at a required mixture quality, a cell model based on the theory of Markov chains is used. It is shown that the optimum hold-up exists that provides the maximum mixer capacity, and this optimum hold-up strongly depends on the loading time.

Key words: particulate solids, mixing, segregation, mixer hold-up, mixer capacity, Markov chain, mixing quality, mixing time, optimization

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INTRODUCTION

Mixing of powders and granular materials is of central importance for the quality and performance of a wide range of products. It is emphasized in [1,2] that the design and operation of the mixing process are very difficult, being largely based on judgments rather than science. The next stage of development is to build on the emerging knowledge and methods so that the basics for such design can be laid down. Then this design can become predictable with operation giving effective control of performance. One of the key problems in mixing of dissimilar granular materials is their segregation into each other. The segregation occurs due to differences in physical properties of the components, such as particle size, density, shape, etc. Action of gravity that is always present in mixing is different on different sorts of particles and also leads to their segregation. At no segregation the achievement of homogeneous mixture is the problem of mixing time alone. Very often it is virtually impossible to achieve the state of homogeneous mixture if segregation occurs. First, the homogeneity of a mixture increases, then passes its maximum and then decreases again. There are a lot of studies, mostly experimental, on influence of the segregation effect on mixture quality (for instance, the papers [3-9] and others). Various attempt of theoretical study of segregation can be found in [10-15]. A promising mathematical tool to model the process is DEM-simulation, in which the position-time history of each individual particle is calculated [16-18]. However, this method is very time consuming, and needs precise identification of parameters of a model. The effect of segregation on mixing kinetics is studied much less.

One of the ways to reduce the negative influence of segregation is mixing of thin layers of the components to be mixed. However, if one and the same batch mixer is used, such mixing leads to the decrease of mixing line capacity because it becomes necessary to load and discharge the mixer several times that take time, which is sometimes compatible to the mixing time as such. Thus, on the one hand, transition from mixing of thick layers of components (high hold-up in the mixer) to mixing in thin layers (small hold-up) allows improving the mixture quality but, at the same time, leads to reducing of the mixer capacity.

In order to estimate how the hold-up of particulate solids to be mixed in a batch mixer influences the mixture quality and mixer capacity a mathematical model of the mixing kinetics can be used. A comprehensive review on various approaches to model mixing kinetics is presented in our previous papers [19,20]. According to the authors' viewpoint the most appropriate tool for this purpose is the theory of Markov chains, which is rather native to the process of mixing because both are related to the evolution of the state of a stochastic system. It was successfully used by many researches not only for the process description but also for searching for the ways how to improve it (see, for instance, our papers [19-21]). However, in all these papers, the models were built for a fixed total volume of the components to be mixed, and its influence on the process parameters was omitted from objectives of their study. An attempt to investigate this influence is presented below.

Theory

The model to describe the mixing kinetics of dissimilar particulate solids is borrowed from [21]. The brief description of it is presented below. A batch mixing zone is presented as a one-dimensional array of m perfectly mixed cells. The model deals with a binary mixture of dissimilar particulate solids. The key segregating component distribution over the cells can be described by the column state vector $S = \{S_j\}$ of the size $m\times1$. The state of the process is observed at discrete moments of time $t_k = (k - 1)\Delta t$ where Δt is the transition duration, and k is the transition number that can be interpreted as the discrete analogue of time. In this case, the evolution of the key component state (i.e., mixing kinetics) can be described by the recurrent matrix equation:

$$\mathbf{S}^{k+1} = \mathbf{P}\mathbf{S}^{k} \qquad (1)$$

where **P** is the matrix of transition probabilities that distributes S_j over the cells at each time step, or transition. This is a tridiagonal matrix, the entries of which can be calculated as follows:

- downward transition probability during Δt

$$P^k_{j,j+1} = v_0(1 - S^k_{j+1}) + d\,,\ j=1,\dots,m-1; \qquad (2)$$

- upward transition probability during Δt

$$P^k_{j+1,j} = d\,,\ j=1,\dots,m-1 \qquad (3)$$

- probability to stay within the cell j during Δt

$$P^k_{j,j} = 1 - \sum_{i=1,i\neq j}^{m} P^k_{i,j}\,,\ i=1,\dots,m. \qquad (4)$$

These probabilities have the symmetrical part d that is related to the pure quasi-diffusion mixing, which always leads to flattening of the component distribution, and the non-symmetrical part v that is related to segregation, which leads to non-homogeneity. The values of d and v can be calculated as: $d = D\Delta t/\Delta x^2$, $v = V\Delta t/\Delta x$ where D is the dispersion coefficient, V is the rate of segregation, Δx is the cell height.

In order to run the recurrent calculations given by Eq.1 the initial state vector, i.e., the initial components distribution S^0 is to be given. Let the segregating component after loading into a mixer occupies ms upper cells and a cell volume is equal to the conditional unit. In this case the conditional hold-up in the mixer is equal to m, the mixture composition is $m_l:(m - m_l)$, and the initial state vector has m_l upper entries equal to 1.

This known model allows describing mixing kinetics but also allows setting up the new question to it: how the hold-up m influences the process characteristics.

RESULTS AND DISCUSSION

The numerical experiments with the described above model were carried out for the 50/50% composition of components with v = 0.3 and d = 0.12 for the segregating component, which was loaded to the upper part of the mixer. The mixing kinetics for four hold-ups characterized by the total number of cells was compared: m = 8, 16, 32 and 64. It was supposed that the increase of the hold-up had no influence on the level of particles agitation, i.e., the values of v and d could be kept identical for any hold-up. The non-homogeneity of a mixture was characterized by the standard deviation σ. The mixing kinetics for different value of m is shown in Fig. 1.

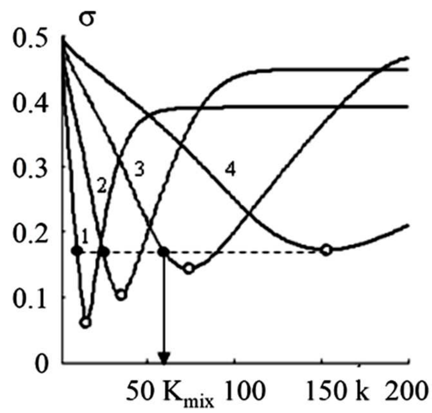

Fig. 1. Mixing kinetics for different value of hold-up: 1 - m=8; 2 - 16: 3 - 32; 4 - 64

Рис. 1. Кинетика смешивания при различной величине загрузки: 1 - m=8; 2 - 16: 3 - 32; 4 - 64

It is seen from the graphs that the optimum mixing time (measured in the number of time transitions k) exists that gives the minimum value to the mixture non-homogeneity σ_{min} (white circles on the graphs). The smaller hold-up, the smaller optimum mixing time and mixture non-homogeneity is, and the influence of m is rather considerable. Let the mixture quality for m = 64 meets the technological requirement. The same mixture quality can be reached for smaller mixing time at smaller hold-up m (black circles on the graphs). However, in order to reach the same mixer capacity as at m = 64, it will be necessary to run the mixing process 64/m times. The total duration of the mixing cycle includes the duration of loading K_{load}, duration of mixing as such K_{mix}, and duration of mixture discharge that can be neglected in comparison to two other durations. Thus, the duration of the total mixing cycle with 64/m repetitions of loading can be estimated as

$$K = K_{mix} + K_{load}(64/m) \qquad (5)$$

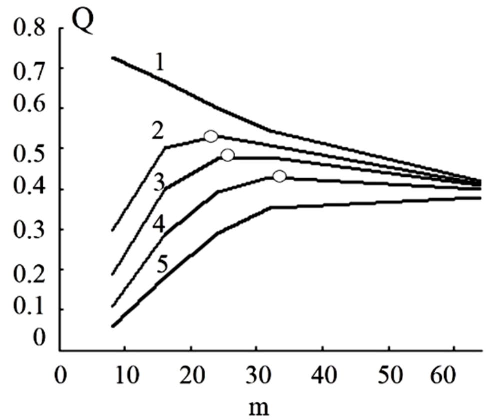

Fig. 2. Influence of the hold-up on the mixer capacity at different value of one-time loading: 1 - K_{load}=0; 2 - 2: 3 - 4; 4 - 8; 5 – 16 (circles correspond to maximum mixer capacity)

Рис. 2. Влияние загрузки на производительность смесителя при различной продолжительности однократной загрузки: 1 - K_{load}=0; 2 - 2: 3 - 4; 4 - 8; 5 – 16 (кружки соответствуют максимальной производительности смесителя)

The duration of one-time loading depends on many factors such as the design and characteristics of a dosage device, feeder device, and so on. In order to compare the capacity of a mixer at different hold-up, let us introduce the conditional capacity of the mixer Q, which is the amount of the mixture treated up to σ_{min} at m = 64 divided by the duration of the total treatment K:

$$Q = m/K. \qquad (6)$$

The graph of Eq.(6) for different value of K_{load} is shown in Fig. 2.

At a very small duration of loading (K_{load} tends to zero) it appears much more profitable to mix the amount of mixture m = 8 eight times than to mix the amount m = 64 one time. However, already at K_{load} = 2 the optimum hold-up m = 22 appears: it is more profitable to mix the amount of mixture m=22 three times than to mix the amount m = 64 one time. At last, at K_{load} = 16 the optimum disappears, and it is better to mix the amount m = 64 one time.

CONCLUSIONS AND PERSPECTIVES

It is obvious that the proposed model and its analysis cannot pretend to be a predictive one. It is just to draw attention of researchers in the field to the fact that the optimum hold-up in a batch mixer of particulate solids exists and its value strongly depends on the ratio between the mixing time and the loading time. Mixing of thin layers of components allows reaching better homogeneity of a mixture and shorter mixing time but reduces the total capacity of a mixer. In order to make the model more close to the predictive one, it is necessary to develop a 2D cell model of the process and to investigate whether the values of v and d can be kept constant at any hold-up, or depend on it. This can be the direction of the process description development, which is planned for future.

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