Motionless Mixers in Bulk Solids Treatments – A Review†

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Abstract

In this paper the general features, behavior and application possibilities of motionless mixers in mixing and treatments of bulk solids are overviewed, summarizing the results published during the last three decades. Working principles, mechanisms, performance, modeling and applications of these devices are described. Related topics, such as use in particle coating, pneumatic conveying, contacting, flow improvement, bulk volume reduction, and dust separation are also summarized.

1. Introduction

Motionless or static mixers are widely known and applied in process technologies for the mixing of liquids, especially for highly viscous materials, and to contact different phases to enhance heat and mass transfer. Producing dispersions in two- and multiphase systems such as emulsions, suspensions, foams, etc., is also the common aim of using motionless mixers. Far less information is known on their behavior, capabilities and applications in bulk solids treatments. Although investigations started more than thirty years ago in this field, research and development is still under way even now. Recent studies and applications gave evidence on the beneficial features of such devices in powder technology for mixing and other treatments of bulk solids.

Motionless or static mixers are flow-modifying inserts, built into a tube, duct or vessel. These tools do not move themselves, but using the pressure difference or the kinetic and potential energy of the treated materials, create predetermined flow patterns and/or random movements, causing velocity differences and thus relative displacements of various parts of the moving material. In this way, motionless mixers can considerably improve the process to be carried out. In fluids, motionless mixers work efficiently both in turbulent and laminar regions. Splitting, shifting, shearing, rotating, accelerating, decelerating and recombining of different parts of materials are common mechanisms in this respect, both in fluids and bulk solids.

Motionless mixers eliminate the need for mechanical stirrers and therefore have a number of benefits: No direct motive power, driving motor and electrical connections are necessary. The flow of materials (even particulate flow) through them may be induced either by gravity, pressure difference or by utilizing the existing potential or kinetic energy. The space requirement is small, allowing a compact design of equipment in bulk solids treatments. Installation is easy and quick, e.g. by simple replacement of a section of tube or by fixing inserts into a tube or vessel. Set-up and operating costs are much lower than those of mechanical mixers, while maintenance is practically superfluous. Motionless mixers are available in a number of different types, shapes and geometries, made from a great variety of materials. The mixer can therefore easily be matched to process requirements and to the features of the processed materials. Physical properties, e.g. flow behavior, particle size, mechanical strength, abrasive effects, safe prescriptions, e.g. for food and pharmaceutical industries, can be taken into account by the proper design of mixers. Applications in powder technology are equally feasible in gravity and pneumatic conveying tubes, in chutes, hoppers and silos, or even in rotating, vibrated or shaken containers.

The greatest advantages of motionless mixers in bulk solids treatment are: high performance, continuous operation, energy and manpower savings, minimum space requirement, low maintenance costs,
trouble-free operation, easy measurement and control, and improvement of product quality.

There are a number of different types of motionless mixers available from a number of manufacturers, most of them are applicable for bulk solids, too. The most widely known types are, e.g. Sulzer SMX and SMF mixers, Ross ISG and LPD mixers, Komax mixer, Kenics and FixMix mixers, etc. Fig. 1 shows some examples of these devices.

The Sulzer SMX mixer (Fig. 1a) is a typical form of lamellar mixer, composed of narrow strips or lamellas placed side by side within a tube section. These strips decline from axial direction alternately by positive and negative angles, crossing the planes of each other, and thus constituting a 3-D series of X forms. During flow, the material is split into several streams or layers corresponding to the number of strips, shifted to opposite directions relative to each other. Flow cross-sections contract along its up-flow sides and expand at the down-flow sides. Thus, the material is forced laterally from the contracting to the neighboring expanding channels. One SMX element, i.e. one series of crossing strips, mixes principally in two dimensions along the plane of the X forms. Therefore, the next series of X forms is aligned at 90° to ensure three-dimensional mixing. Sulzer SMX is thus characterized by excellent cross-sectional (transversal) mixing and a high dispersing effect with a small space requirement and a narrow residence time distribution. In multiphase flows no deposits and blockages occur, due to the high turbulence caused by the sharp edges and crossings. But, a drawback of this mixer also comes from this, because sharp edges and the sudden changes in flow directions increases pressure drop. In bulk solids flow, troubles can arise, especially for cohesive materials, for larger particles or broad size distributions.

Fig. 1b shows the Ross LPD mixer which consists of a series of slanted semi-elliptical plates positioned in a discriminatory manner in a tubular housing. When the material flows through this mixer, the input stream is split and diverted repeatedly in different directions along the cross-section of the tube, until a homogeneous mixture is achieved. This type of motionless mixer is generally used for the turbulent flow of low-viscosity liquids to enhance macro- and micro-mixing and/or to improve the heat transfer coefficient in heat exchangers. It is also feasible for particulate flows. But, since the flow at a given tube section is divided into two streams only, shear and material exchange takes place in one plane only between the two half-tube cross-sections, thus the mixing effect along a given length is weaker than in SMX mixers, especially for viscous materials or bulk solids. Naturally, the pressure drop is also less. For bulk solids, the maximal throughput in a Ross LPD mixer...
mixers is higher than in SMX, and the risk of plugging for cohesive powders or large particle sizes is considerably reduced. Another difference is that, due to the non-uniform axial velocity profile, the longitudinal mixing effect of the LPD mixer may be higher than that of the SMX mixer.

The Komax mixer (see Fig. 1c) consists of flat plates arranged essentially in axial direction in a tube, but at both ends of these plates they are hatched, rounded and bent in opposite directions. The neighboring mixer plates are arranged at 90 degrees in radial direction, touching each other with the tips of the bent flaps. This mixer is also called a "Triple-Action Mixer", because it provides (i) two-by-two division, (ii) cross-current mixing and (iii) back mixing of counter-rotating vortices. Each mixing element set in combination sweeps approximately two-thirds of the circumference of the pipe and directs the flow to the opposite side, providing very strong wall-to-wall radial transfer. Between the sets of generally four mixer elements, inter-set cavities provide space for intensive contacting of the sub-streams of material by strong momentum reversal and flow impingement. For multiphase flow, this mixer is resistant to fouling or clogging, because the tips of the mixer elements are smoothly contoured with a large radius. Intersections between the element ends with the wall are all oblique angles, eliminating corners that can trap solid or fibrous materials and promote material accumulation. Momentum reversal and flow impingement provide a self-cleaning environment.

The Kenics static mixer shown in Fig. 1d possesses almost all the advantages of the Komax mixer. It consists of a long cylindrical pipe containing a number of helical elements twisted by 180 degrees alternately in left-hand and right-hand directions, perpendicular to flow direction. The adjacent elements are set by 90 degrees in radial direction, therefore the outlet edge of a given element and the inlet edge of the next one are perpendicular to each other. The smooth helical surface directs the flow of material towards the pipe wall and back to the center, due to secondary vortices induced by the spiral-form twist of the flow channels. Additional velocity reversal and flow division results from shearing of the material along the tube cross-section between the adjacent elements. The systematic division of streams and their recombination in another way enhance the mixing effect proportionally to 2^n, where n is the number of the applied mixer elements. For fluids or in multiphase flows, a relatively narrow residence time is ensured, in addition to excellent radial mixing. Due to the smooth and mildly bending surfaces of the helices, the pressure drop along a Kenics mixer is very low, while it provides continuous and complete mixing and eliminates radial gradients in temperature, velocity and composition. For bulk solids, because of the non-uniform axial velocity profile, a certain degree of longitudinal mixing also takes place. Due to the smooth surfaces and relatively wide flow channels, the risk of plugging or blockage is very limited.

The FixMix motionless mixer shown in Fig. 1e is very similar to the Kenics static mixer, with the essential difference that the individual elements are slanted relative to the tube axis and are tapered along their length. It results in several benefits: the slightly increasing gap between the mixer element and the tube wall eliminates the corners or contact points between them. Therefore, there are no dead zones, and deposition or blockage cannot occur. On the other hand, the cross-section of the flow channels on the two sides of a mixer element changes continuously along its length: the cross-sectional area on one side expands while on the other side it contracts. Due to the tangential flow at the wall and the pressure difference between the two sides, an intensive cross-flow takes place between the neighboring flow channels. These features provide improved mixing efficiency, lower pressure drop with suitable cross-sectional turbulence, and more uniform radial and tangential velocity fields. The higher velocity and the turbulence close to the tube wall results in higher heat transfer coefficients and a cleaner surface. In addition to this self-cleaning effect, the lack of corners makes the cleaning easier for difficult materials. This mixer provides higher mixing efficiency per unit mixer length and reduces the risk of blockage in bulk solids treatment.

During the past three decades, quite a number of papers were published on the application of motionless mixers in this latter field, and it is worth surveying these results to initialize further studies and practical applications.

2. Motionless Mixers in Bulk Solids Mixing

The mixing of bulk solids is an important operation in many industries, such as in the chemical and pharmaceutical industries, mineral processing, food industry and for treatments of agricultural materials. Uniform composition in these processes is of primary importance, as well as to eliminate segregation. Besides mechanical mixers and silo blenders, motionless mixers represent a viable solution for this task,
especially if continuous operation is possible or necessary. The application to homogenize solids was already envisaged as early as in 1969 by Pattison [1].

A crucial condition of such an application is the trouble-free flow of the bulk solids to be treated. Therefore, motionless mixers can only be used for free-flowing particles, but cohesiveness to some extent is tolerable even in gravity flow of such materials.

In addition to the devices conventionally known as motionless mixers, any other tools inserted into a tube or vessel or the intentional changes of tube or chute cross-sections can modify the flow pattern of solids. Therefore, they may also be considered as some kind of motionless mixer. Various inserts in silos or hoppers, or cascade chute assemblies causing the multiple division and recombination or modification of bulk solids flows can also be ranked here.

### 2.1 Mixing Mechanisms of Motionless Mixers

Several workers investigated the mixing mechanisms of particulate solids in motionless mixers acting in transversal [2] and longitudinal directions [3]. Observing the interactions between the particles and mixer elements, four kinds of mixing actions were distinguished [3, 4]. Namely: (a) multiple division and recombination of the particle flow, (b) interaction of particles with other particles, with the surface of mixer elements and the tube wall, (c) changes in flow direction, and (d) differences in velocity profile. Three main mechanisms, namely diffusive, convective and shear mixing were attributed to these actions. Shear: certain particle regions are sheared during particle flow, creating velocity differences between the adjacent layers. Convection: multiple division and recombination of the particle flow, as it is split into sub-streams and diverted to different ducts or directions, and then unified with other sub-streams. Dispersive or diffusive-type mixing: stochastic movements with interchanges of different particles. A great deal of experience accumulated in the last decades indicates that these mixing mechanisms act more or less together in any type of motionless mixer, and therefore they are hardly separable from each other.

The majority of experimental studies carried out until now used helical mixer elements such as Kenics or FixMix lx-type devices. In a few works, other types of motionless mixers such as Sulzer (Koch) mixers and mixer grids composed of helices, rods or lamellas, were investigated.

For certain types of mixers, the mixing mechanisms influence the characteristic direction of mixing. There is a general belief that motionless mixers perform mainly radial (transversal) mixing, and that axial (longitudinal) mixing is negligible. But, according to our experience, also seen from the results of other workers, this is not entirely valid even for viscous liquids or plastic materials, due to non-uniform axial velocity profiles. Depending on their shape, arrangement and operational conditions, and in addition to a high radial dispersion [2], motionless mixers may cause effective axial mixing [3, 4], too. This latter feature is of crucial importance in equalizing concentration variations in time and space in continuous particle flows caused either by segregation or by non-uniform feeding.

### 2.2 Mixing Kinetics and Performance

The performance of a bulk solids mixer is characterized by its throughput, i.e. the treatable mass per unit volume and time, and by the degree of homogeneity achieved. These features are in close relation with the mixing kinetics, i.e. with the rate of homogeneity improvement, characterizing how fast the concentration uniformity is getting better as a function of time or mixer length. The mixing kinetics determines the number of motionless mixers necessary to achieve a given degree of homogeneity or its equilibrium. The latter may be the result of two competing processes: mixing and segregation. In other words: whilst the mixing mechanism tells us in what manner, the mixing kinetics characterizes by which rate and how far the process is going on.

From a practical point of view, the performance of a mixer is the most important feature, if we disregard the actual mechanism of mixing. However, the mechanism gives an explanation of the mixing kinetics experienced, thus also serving as a starting point for further improvements. Therefore, almost all studies carried out in this field aimed at determining the rate of process [5-14], and only a few works dealt with the mechanism. The kinetics of the mixing and segregation processes competing with each other can be characterized by the equation [14]:

\[
\frac{dM}{dt} = K_m(1-M) \pm K_s \Phi
\]

where \( M \) denotes the actual degree of mixedness, \( K_m \) and \( K_s \) are the kinetic constants of mixing and segregation, respectively, while \( \Phi \) is the so-called segregation potential [14]. Although there are a number of various definitions for the degree of mixedness [15], the most simple and well applicable one was defined by Rose [16] as
2.3 Modeling and Simulations

To describe a process or equipment theoretically, or to predict the characteristic features and results of their applications under different conditions, mathematical modeling and simulation proved to be widely applied and useful tools. To investigate motionless mixers in solids mixing, various modeling principles and simulation methods were used till now. Chen et al. [4] adapted the concepts of an axially dispersed plug-flow model, commonly used at that time to describe the mixing of fluids in various unit operations. In their work, a quasi-continuous deterministic model was applied to describe the axial dispersion of particles in a gravity mixer tube containing motionless mixer elements. Residence time distributions were measured by the stimulus-response technique, and apparent Peclet numbers and axial dispersion coefficients were determined for three different kinds of solid particles, after different number of passes through the mixer tube.

Apparent Peclet numbers (Pe') and axial dispersion coefficients (K_{\text{ax}}') have similar definitions here to those used in fluids to characterize the intensity of longitudinal mixing. Their values can be determined from the residence time distribution of tracer particles in the mixer tube determined by discrete sampling at the outlet at different times after they are introduced at the inlet in the form of a plug [17]. The second central moment \( \mu_2 \) of the residence time distribution is as follows:

\[
\mu_2 = \sum_{i} (t_i - \bar{t})^2 \cdot x_i
\]  
(3)

where \( t_i \) is the residence time of tracer particles in the mixer tube taken off by the i-th sample, and \( x_i \) is the mass fraction of tracer particles in the i-th sample. The mean residence time of all tracer particles along the mixer tube corresponds to the first moment of the residence time distribution as:

\[
\bar{t} = \sum_{i} t_i \cdot x_i
\]  
(4)

The apparent Peclet number is determined from the mean residence time \( \bar{t} \) and the second central moment \( \mu_2 \) of the residence time distribution, corrected by \( \mu_{2,0} \), which is the second central moment obtained in a plain tube, i.e. without motionless mixer elements:

\[
Pe' = \frac{2\bar{t}^2}{\mu_2 - \mu_{2,0}}
\]  
(5)

and the axial dispersion coefficient:
where $L_{mix}$ is the length of the studied mixer section. The intensity of mixing, i.e. the achievable mixing effect of motionless mixer elements per unit length is the higher the lower $P_e'$ is or the higher $K'_ax$ is.

Chen et al. [4] pointed out that smaller particles had a higher apparent axial dispersion coefficient than the bigger ones. By increasing the linear velocity of solids through the motionless mixers, an almost exponential improvement was obtained in the axial dispersion coefficient. A similar technique and model was used by Gyenis et al. [17] to investigate the influence of different flow regimes, particle properties and length-to-diameter ratios of helical motionless mixers on the resultant axial dispersion coefficient.

In mixing processes, especially in particulate systems, stochastic behavior is a common feature which causes random variations both in flow characteristics and in the local concentrations of components. Such behavior in gravity mixer tubes containing motionless mixers was already recognized by the team of L. T. Fan [3, 7]. To interpret the experimental findings, a discrete stochastic model was applied [3, 7, 9, 18]. For this, prior knowledge of the one-step transition probabilities of the particles was necessary, which were determined experimentally. This model seemed to be suitable to predict concentration distributions after different passes through the mixers. However, on examining the results of experiments and those obtained by the stochastic model, two kinds of discrepancies can be recognized. One is that, in spite of identical particle properties, segregation and a spatially non-uniform mixing rate could be recognized [3]. Gyenis and Blickle proposed a possible theoretical explanation of this behavior [19]. It was assumed that spatially non-uniform transitions of particles between the adjacent layers were caused by the changing conditions during the non-steady-state flow. A correlation was proposed between the mixing rate and the energy dissipation caused by the interactions of the particles and the mixer elements.

The other discrepancy came from the fact that earlier stochastic models used only expected values to characterize the one-step transition probabilities, totally ignoring their possible random variation. This can be quite high if large-scale flow instabilities occur, especially in larger mixer volumes. Gyenis and Katai proposed [20] a new type of stochastic model to explain and describe the high random variations experienced in repeated experiments in an alternatively revolving tumbler mixer, with and without motionless mixer grids. Some years later, this model was simplified for simulation purposes [21], and was then made more exact by Mihalyko and his co-worker [22], introducing the concept of a so-called double stochastic model.

DEM simulations based on a Lagrangian approach also helped to understand the features and working mechanisms of motionless mixers in particulate systems [23].

### 2.4 Application Studies for Bulk Solids Mixing

The mixing of free-flowing particle systems in gravity flow through motionless mixers was investigated by several workers [2-12]. Most of these studies resulted in suitable homogeneity after a few passes, but in some cases, depending on the physical properties of the components, considerable segregation also emerged. Herbig and Gottschalk [24] applied horizontal bars serving as motionless mixers built into a gravity mixer. It was found that assuring the smallest possible shear action is essential to suppress segregation.

A special, alternatively revolving bulk solids mixer equipped with motionless mixer elements shown in Fig. 2 was studied by Gyenis and Arva [13, 14, 25, 26] and provides practically segregation-free mixing. This device consists of two cylindrical containers (1) and a mixer section between them containing horizontal mixer grids (2) composed of a number of...
ordered FixMix elements. The material to be mixed is filled into the lower container, then the mixer is rotated intermittently. In other words, the mixer body is turned through 180° in one direction, then stopped to allow the bulk solids that are meanwhile at the top enough time to flow down through the mixer elements. After this, the mixer is turned again through 180° but in the opposite direction. The whole procedure is then repeated till the required homogeneity is obtained. Because of the periodically reversing directions of particle flow and the changing direction of acceleration and deceleration of the particles, segregation can be almost totally avoided.

By this method, a considerable improvement of the mixing rate was achieved, resulting in a short mixing time and a high homogeneity at a reasonably low power consumption [27]. This was evidenced by examining the mixing kinetics of particle systems composed of materials with extremely different physical properties, listed in Table 1. The density ratios of the component particles were varied from 1.2 : 1 to 2.9 : 1, while the particle size ratios were changed from 1 : 2.7 to 1 : 110 as seen from Table 2. Kinetic curves, i.e. the variation of the degree of mixedness as a function of mixer turns are plotted in Fig. 3. It shows that this mixer provides rapid and segregation-free mixing. The degrees of mixedness were determined from the concentration variations of 65 spot samples taken after different numbers of mixer turns or mixing times by metal templates according to a regular pattern. A detailed description of this sampling method was given by Gyenis and Arva [13]. The mass of each sample was 20 g, and the compositions of samples were determined from 3×2.5 g material taken off from each sample, by dissolving the sodium chloride tracer particles and measuring the conductivity of the solution, or in other cases, by weighing the polypropylene tracer particles after mechanical separation of the samples.

Theoretical considerations gave an explanation of this segregation-free operation and of the high achievable equilibrium homogeneity [14].

Bauman [29] studied three different types of motionless mixers (Kenics, Komacs and Sulzer SMX) to mix particulate materials differing in mean particle size and size distribution, in bulk density and in mass ratio. It was concluded that the mass ratio of the components, as well as the shape and number of motionless mixers played a significant role in the achievable homogeneity. Kenics-type mixers proved to be the best when mass ratios were equal. But, when these differed significantly, Komacs and Sulzer SMX mixers gave much better results.

Motionless mixers are now increasingly applied in various process technologies to mix particulate solids. An interesting example for this is, e.g. the industrial standard of Tennessee [30], which mandates the use of Komax, Ross, Koch (Sulzer) or similar commonly accepted motionless mixers to manufacture hydraulic cement.

3. Bulk Solids Flow through Motionless Mixers

3.1 Gravity Flow Studies

The continuous flow of bulk solids in vertical tubes through Kenics-type motionless mixers was studied
by Gyenis and his co-workers [12, 31, 32] under different conditions. These mixer tubes consisted of three sections: (1) a plain feeding tube at the top, (2) motionless mixers in the middle, and (3) another plain tube below the motionless mixers. The mass flow rate of solids was controlled by two means: (a) by adjusting the feeding rate at the inlet, or (b) by controlling the particle discharge at the bottom. Local particle velocities were measured by fiber-optical probes that captured light reflection signals. Average and local solids hold-ups were determined by weighing the material remaining in the tube after closing both ends, and by gamma-ray absorption during operation at different cross-sections, respectively. The axial mixing intensity was characterized by apparent Peclet numbers and dispersion coefficients calculated from residence time distributions of tracer particles. The details of experiments and the applied experimental devices were described in several papers of Gyenis and his co-workers [12, 31, 32].

Experiments [12, 31, 32] and DEM simulations [23] equally revealed that, depending on the feeding and discharging conditions, three characteristic flow regimes could be distinguished in such gravity mixer tubes, shown schematically by visualized simulation results in Fig. 4.

A first type of flow regime takes place, shown in Fig. 4a, if a solids flow withdrawn from the bottom, e.g. by a belt or screw conveyor, is less than the maximal possible throughput of the gravity mixer tube, determined by its diameter and the configuration of motionless mixers. Naturally, the inflow of particles at the tube inlet must be unlimited in this case, e.g. directly from a hopper. This 1st flow regime is characterized by dense flow, i.e. high solids hold-up in all the three tube sections.

By increasing the discharged flow rate in this 1st flow regime, the solids hold-up in the mixer tube decreases slightly, mainly due to the growing “gas bubbles” just below the lower surface of the motionless mixer elements. After reaching the maximal throughput, which is achieved by unlimited outflow, the solids hold-up suddenly drops to a well-determined value, resulting in a second flow regime shown in Fig. 4b. It is characterized by a dense sliding particle bed in the upper tube, accelerating particle flow along the mixer elements and almost free-falling particles in the lower plain tube section below the mixer section. The transition between the 1st and 2nd flow regimes can be well recognized from the snap-shots in Fig. 4d, obtained by DEM simulation, showing the actual situations at successive moments in time.

Another flow regime evolves when the solids flow rate is controlled at the inlet of the tube, with free outflow at the bottom. In this case, the flow rate of bulk solids fed into the tube must be lower than the maximal attainable throughput of the motionless mixers. This 3rd flow regime, shown in Fig. 4c, is characterized by almost free-falling particles in the upper and bottom plain tube sections with very low and progressively decreasing solids concentration. In the mixer section, however, a rapid sliding particle flow takes place along the surface of the mixer elements with a much higher solids hold-up compared to the upper and lower tube sections. When the solids flow rate in this flow regime is increased from zero to the maximal attainable capacity, the average solids volume fraction in the tube also increases from zero to a maximal value. Reaching this latter stage, the upper tube
Section above the motionless mixers suddenly becomes choked with this sliding particle bed. This causes a rapid transformation from the 3\textsuperscript{rd} to the 2\textsuperscript{nd} flow regime.

Visual observations and experimental data revealed that in these flow regimes, a different and well-defined correlation exists between the solids hold-up in the mixer tube and the mass flow rate of particles taken off at the bottom or fed into the tube.

As seen from Figs. 4a-d, the particle concentration and thus solids volume fraction changes from place to place along the length of the tube. However, since the usual mixer tubes are composed of several sections (e.g. feeding, mixing and post-mixing sections) and, very frequently, free tube sections (inter-element distances) can be present between the individual mixer elements, it is reasonable to characterize operation conditions by the mean solids volume fraction averaged within the whole tube.

Plotting this mean solids volume fraction vs. the mass flow rate, important characteristics of the above-described flow regimes can be recognized, also indicating the conditions of transitions between them, as is shown in a general status diagram in Fig. 5.

The upper, slightly slanted curves of this diagram correspond to the changes in the 1\textsuperscript{st} flow regime. Namely: by increasing the discharged mass flow rate at the tube bottom, the solids volume fraction averaged within the whole mixer tube also decreases slightly, mainly due to the increasing void fraction within the section containing motionless mixers. Decreasing the \( l/d \) ratio of the mixer elements also decreases the mean solids volume fraction, making these curves steeper.

Achieving the maximum throughput of the given mixer tube, the average solids volume fraction suddenly drops to a distinct point shown in Fig. 5, which characterizes the 2\textsuperscript{nd} flow regime in the given system. It should be emphasized in this respect that local solids volume fractions in this flow regime changes from place to place, generally decreasing in downwards direction from the inlet of the mixer section, and especially in the plain tube below the mixer elements. However, the average solids volume fraction is a well-determined distinct value, belonging to the maximal possible mass flow rate of particles under this condition. This mass flow rate and average solids volume fraction depend on the diameter of tube, on the physical properties of material, e.g. particle size, density, shape, surface properties, particle-particle and particle-wall frictions, as well as on the geometrical and other properties of the motionless mixer elements, on the length ratios of feeding, mixing and post-mixing sections, on the distance between the mixer elements, etc. From Fig. 5, it is clearly seen that by decreasing the \( l/d \) ratio of the helical mixer elements, the maximal throughput of the tube belonging to the 2\textsuperscript{nd} flow regime also decreases. The gap between the solids volume fraction at the end point of the 1\textsuperscript{st} flow regime curves and at the 2\textsuperscript{nd} flow regime mainly depends on the length of the plain tube below the mixing section and on the distances between the mixer elements: the gap diminishes if these plain tube sections are shorter.

In the 3\textsuperscript{rd} flow regime, shown by the lower curves in Fig. 5, the mean solids volume fraction increases as the mass flow rate of solids fed into the tube inlet is increased. The higher the retaining effect of the mixer elements against the particulate flow, i.e. the lower their \( l/d \) ratio, the higher the mean solids volume fraction in the tube will be: i.e. the slope of the corresponding curves becomes steeper. After achieving the maximum throughput of the mixer tube from this side, the feeding section becomes choked and the mean solids volume fraction in the tube increases: i.e. the 3\textsuperscript{rd} flow regime transforms to the 2\textsuperscript{nd} flow regime. This transformation is reversible, but some hysteresis loop was experienced here. The gaps between the ends of the 3\textsuperscript{rd} flow regime curves and the data point of the 2\textsuperscript{nd} flow regime mainly depend on the length of the feeding section.

It should be noted that Fig. 5 is a general diagram only and therefore does not give precise quantitative data on given particle systems or mixer tube configurations. It is a summary of our experiences and mea-
smeasurements carried out with different particle systems and mixer tubes under different conditions [12, 31, 32]. However, this is a quite realistic diagram regarding the scales of its axes and tendencies of its curves, since they are close to the results obtained for the gravity flow of quartz sand of 0.17 mm mean particle size in a gravity mixer tube of 1.6 m length and 0.05 m inner diameter, with about 0.6 m total length of helical mixer elements. Very similar curves were obtained by recent DEM simulations for polymer particles with 3 mm diameter and 1190 kg/m³ density [23], with the difference that the corresponding mass flow rates with similar mean solids fractions are somewhat lower compared to those of quartz sand.

Measurements [12] and DEM simulations [23] revealed a periodic variation of the local solids volume fractions along the motionless mixers in the middle tube section. As typical examples, Figs. 6a, b, c show the results obtained by the DEM simulation of particulate flow in a mixer tube of 0.05 m ID and 0.80 m length, composed of a feeding, a mixing and a post-mixing section of 0.20, 0.30 and 0.30 m length, respectively. The number of spherical model particles in the tube used for the DEM simulation was changed from 10,000 to 65,000, with 3.0 mm diameter and 1190 kg/m³ density. Other parameters such as stiffness, restitution coefficients, particle-particle and particle-wall frictions, and inlet velocity were described in detail by Szepvolgyi [23]. The mass flow rate controlled at the inlet or at the outlet of the tube to generate different flow regimes was varied between 300 and 1500 kg/h. From this diagram, it is seen that periodicity of local solids volume fractions took place in all the three flow regimes, due to the multiple interaction with the motionless mixers, which caused periodic deceleration and acceleration of the flow along the mixer lengths. These diagrams also show significant differences between the three flow regimes regarding the change of local solids volume fraction along the various sections of the mixer tube.

Experimental studies revealed that these flow regimes had a great influence on the mixing performance, too. Fig. 7 shows some examples for residence time distributions of tracer particles measured during gravity flows through Kenics-type motionless mixers [12]. The model material for these experiments was quartz sand, the same as used for the solids volume fraction measurements, and a short plug of sodium chloride or polypropylene granules was used as the tracer. It was found that residence time distributions were somewhat broader in the 1st flow regime relative to the 2nd or 3rd flow regimes, especially for smaller length-to-diameter (l/d) ratios. However, due to the higher throughput and lower mean residence time, the apparent Peclet numbers and axial dispersion coefficients were more beneficial in the 2nd and 3rd flow regimes, mainly for higher l/d ratios. The best homogeneity values were obtained in the 2nd flow regime and, at higher mass flow rates in the 3rd flow regime, close to its transition point [12].
3.2 Gas-solids two-phase flows

Experiments were carried out by Gyenis et al. [12] in a concurrent downward gas-solids two-phase flow in a test device where the flow rates of both phases could be controlled more or less independently. By increasing the gas flow rate, the mass flow rate and thus the solids hold-up could be enhanced considerably, which is generally beneficial to the performance of in-line mixers and other operations by effective gas-solids contacting.

Motionless mixers can also be applied in counter-current gas-solids two-phase flow for more effective phase contacting. It is known that fluidized bed processes often use various types of inserts in the particle bed to improve the fluidization behavior [33]. Motionless mixers can replace the usual inserts, favorably influencing the minimum fluidization gas velocity, solids hold-up, and heat and mass transfer between the phases by enhancing the relative velocities and avoiding fluidization abnormalities.

4. Other Applications in Bulk Solids Handling

4.1 Improvement of Bulk Solids Flow and Reduction of Bulk Volumes

In handling bulk solids, motionless mixers are well suited to eliminate problems in the bulk solids flow, and to decrease the bulk density in storage and transport.

In silos, inserts are frequently used to enhance flow uniformity in space and/or time [34], avoiding pulsation and bridging, which may totally stop the flow. Concentric, inverted or double cones, slanted plates or rods are frequently used for this purpose. In this way, funnel flow can be transformed to mass flow, avoiding segregation during discharge. For this purpose, various forms of motionless mixers can also be used, but before their application, careful design work is necessary with preliminary investigation of material properties and its flow behavior through the motionless mixers to avoid potential troubles.

According to our experiences, motionless mixers in gravity tubes make the flow of fine powders more stable, even if they are cohesive to some extent, such as flour or ground coffee. It should be noticed, however, that this is true only for continuous or non-interupted flows. If continuous discharge is stopped, troubles can arise in re-starting the flow. This difficulty can be avoided by applying quasi-motionless mixers, connected to each other elastically, joining them by springs, thus making the individual mixer elements mobile to a certain extent [35]. Stresses inside the bulk solids column cause some passive movements of the mixer elements, which is enough to start or to stabilize the flow, therefore avoiding choking.

In loading a container, silo, truck or railroad boxcar from a spout or hopper, the bulk volume of solids may expand. Therefore, during storage or transportation, a considerable part of the available space is occupied by air. However, if particulate materials are passed...
through motionless mixers, the expansion of bulk volume can be reduced by 20-40 percent compared to loading via plain tube, as was proven by experiments with wheat grains [36]. When bulk solids, which were expanded already, are passed through motionless mixers, absolute reduction can also be achieved. By this method, as much as 4-10 percent more bulk solids can be stored or transported in a given volume of a container or ship. To this end, motionless mixer elements should be well designed to avoid attrition or breakage of the grains or particles.

4.2 Coating, Size Enlargement, Size Reduction

Motionless mixers are applicable not only to blend particulate solids, but also to contact different particles effectively with each other. In a suitably designed gravity mixer tube supplied continuously with two particulate solids differing in size, a coating of the bigger particles with the smaller ones can be realized if suitable binding material is also supplied. Gyenis et al. [37, 38] reported on a coating process of jelly bon-bons with crystalline sugar, applying motionless mixers. Similar equipment was used for coating ammonium nitrate fertilizer granules with limestone powder to avoid sticking during storage. Granulation or controlled agglomeration of particulate solids is also conceivable by this method, but a crucial point is to ensure proper conditions to avoid sticking of solids or deposition of the binding material onto the surface of the mixers. Disintegration or size reduction, as well as controlled attrition [39], can also take place during interaction between the particles and motionless mixers, especially at higher velocities ensured by gas-solids two-phase flows.

4.3 Applications in Pneumatic Conveying

As was mentioned above, concurrent gas-solids flow in vertical tubes containing motionless mixers increases the flow rate and solids hold-up, also enhancing the mixing process compared to simple gravity flows of particles [12]. Because of the retaining effect of motionless mixers, the velocity difference between the phases and also the residence time of the particles can be increased considerably, compared to a plain tube. Such conditions are favorable for heat and mass transfer processes or chemical reactions in gas-solids contactors, thus decreasing the necessary dimensions. This makes the realization of various operations during pneumatic conveying [39] conceivable. But for this, carefully planned pilot-scale experiments and caution in design are needed to avoid troubles, e.g. choking or damage of the particles.

Motionless mixers may be useful tools in pneumatic conveying lines, e.g. in horizontal tube sections. DEM simulation studies revealed that particles that tended to settle downwards could be re-dispersed into the gas stream again by suitably designed motionless mixer elements [23, 40]. This may reduce the salting velocity, thus diminishing the required gas flow rate. By using motionless mixers, a given section of pneumatic conveying system can also serve as an effective gas-solids contactor, too, or to realize other types of solids treatments simultaneously with conveying. Caution and preliminary experiments mentioned above are also recommended here.

4.4 Heat Treatment of Particulate Solids

Heat transfer processes in particulate solids can be improved by motionless mixers built in a cooler or heater, due to the multiple transmissions of particles from the bulk material to the heating or cooling surface and back. In some cases, heat-transmitting tubes or lamellas themselves, arranged, e.g. in a hopper, can modify the flow pattern of the solids, similarly to motionless mixers.

Very often, heat treatment is carried out in rotary heater or kiln, as is frequently used in the cement industry or, in smaller dimensions, in food processing. Motionless mixers fixed inside a rotating unit, shown in Fig. 8, enhance the heat transfer between particles and a streaming gas, or between the particles and the heated surface, as was patented by Bucsky et al. [41]. It also ensures uniform temperature distribution throughout the cross-section of the particle bed, which is of crucial importance in the treatment of heat-sensitive materials. Such a device is also applicable for drying particulate solids.
4.5 Drying

Godoi et al. [42] used a vertical tube equipped with helical motionless mixers with perforations on their surface for the continuous drying of agricultural grains. The particulate materials to be dried were fed continuously at the top, and slid or rolled down along the surface of the mixer elements. Heated gas streamed up along the flow channel between the mixer elements and through their perforations. Due to the interactions between the grains, the motionless mixers and the gas, an effective mass and heat transfer was achieved. The rotary equipment in Fig. 8 also can be used for such a purpose.

4.6 Dust Separation

Motionless mixers are applicable for the separation of particles from gases. The dust or volatile solids content of hot industrial gases often causes troubles in pipeline operation due to deposition onto the tube wall, especially at critical sections. Based on laboratory- and pilot-scale experiments, Ujhidy et al. [43] described a new gas purification method and equipment applying helical motionless mixers shown in Fig. 9. Solid particles are captured by a liquid film trickling down along the surface of mixer elements, totally avoiding plugging and thus extra maintenance of the gas pipeline system. Applying proper conditions, i.e. optimal superficial gas velocity and suitable motionless mixer geometry, the dry separation of solids is also feasible, especially above one hundred or several hundred microns particle size. This effect is due to the centrifuging and collision of particles with the motionless mixers.

Concluding Remarks

As was seen from this review, motionless mixers are useful tools for process improvements: not only for fluid treatments, but also in bulk solids technologies. In this latter field, the most detailed knowledge is available in bulk solids mixing, discussed in a great number of papers. Investigations started more than thirty years ago, elucidating the kinetics and mechanisms of this operation, mainly in gravity mixing tubes, but also in a special alternatively rotating bulk solids mixer. Modeling and simulations helped to understand experimental findings and to predict the behavior and results of such equipment.

Particulate flows in motionless mixer tubes show exiting phenomena which greatly influence the processes taking place in these devices. Other applications such as to improve the bulk solids flow in tubes, chutes and silos, or to reduce the bulk volume expansion led to significant results. In gas-solids two-phase flows, namely in pneumatic conveying and simultaneous treatment of bulk solids, their use offers new possibilities for realization and process improvement. Coating, size enlargement, size reduction and attrition, heat treatment, drying, wet dust removal and dry particle separation are also promising fields of applications.

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Nomenclature

- \( d \): diameter or width of motionless mixer element, m
- \( K'_{ax} \): axial dispersion coefficient, Eqn.6, m\(^2\)/s
- \( K_m \): kinetic constant of mixing
- \( K_s \): kinetic constant of segregation
- \( L_{mix} \): total length of the studied mixer section, m
- \( L \): length, measured from the inlet, m
- \( l \): length of one motionless mixer element, m
- \( l/d \): length-to-diameter ratio of a motionless mixer element
- \( M \): degree of mixedness, defined by Eqn.2 [15, 16]
- \( s \): estimated standard deviations of sample concentrations taken from a mixture
- \( S_0 \): estimated standard deviations of sample concentrations taken in a totally segregated
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