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Current Status and Development of Production Technologies of Multicomponent Mixtures of Bulk Materials in Large Volumes

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Abstract

Currently, the problem of producing multicomponent mixtures of bulk materials in large volumes with a stable composition and quality is topical in the chemical industry of Russia. Mixing devices of different design are used to solve this problem. The organization of the mixing process in mixing devices is one of the main factors affecting the quality of the products obtained. The article analyzes the current state of mixing of bulk materials in chemical and related industries. The paper considers the most widespread and advanced methods of mixing bulk materials and designs of mixing devices for granular materials. The main problems of mixing bulk materials in the chemical industry, as well as the ways of improving the mixing equipment are discussed. The most promising are the methods and designs that allow increasing the turbulence and circulation of the flows of mixed bulk materials in the mixing vessel. We propose a design of a mixing device, consisting of a cascade of mixing funnels and disintegrators installed between them. In the mixer, mutual penetration of bulk material particles intensifies and ensures a homogeneous volumetric distribution of the particles of the components to be mixed.

Keywords

Process, mixture, bulk material, homogenization, mixing vessel.

Introduction

In various industries, it often becomes necessary to obtain a uniform mixture of large volumes (up to 500 m^3). Such a problem occurs in cases of producing bulk materials in batch devices in relatively small volumes and with different properties. At the same time, in manufacturing conditions, it is necessary to feed a uniform mixture of bulk materials for a long time or feed a large amount of material at a time. The process of mixing bulk materials is widely used in the ore and coal industries. However, the mixing methods and devices used are quite specific and far from being suitable for chemical and related industries. In this connection, this paper explores the methods and devices for mixing of bulk materials in chemical and related industries. At the same time, the equipment used in the ore and coal industries is also reviewed.

The homogenization process is widely used in various industries, for example, in the food industry it is used for preparation of emulsions and suspensions, homogeneous mixtures of bulk materials and other media, and for the intensification of heat and mass transfer processes. In the chemical industry, it is used to prepare various chemical additives, in the agricultural industry it is used to manufacture mixed fodders and fertilizers, in the pharmaceutical industry it is used to produce bone cements, drugs, premixes, and in the construction industry it is used to manufacture dry construction mixtures and composite materials.

Traditional designs of batch mixers (drum, centrifugal, conveyor belt, etc.) with a working volume of more than 5 m^3 have low economic indicators, as well as complexity of manufacture and operation. Therefore, their use as a mixing equipment for bulk materials is not suitable for effective solution to the indicated problem.

In domestic and foreign practices, mixtures of bulk components in large volumes are prepared in special mixers consisting of large volume tanks and transporting devices. Such mixers are often used for homogenization of finished batches of bulk materials, differing from each other in composition.

The equipment for the homogenization process of bulk material batches is called a homogenizer. Depending on the operating mode, the homogenization devices can be periodic or continuous.

Methods of homogenization of bulk materials

Homogenization of bulk materials is understood as a technological process aimed to stabilize the composition and quality of bulk materials [1].

A significant contribution to the theoretical and experimental studies of the process of mixing bulk materials in large volumes has been made by such scientists as Yu.I. Makarov, A.I. Zaitsev, V.V. Kafarov, V.N. Ivanets et al. [1–10]. However, up to the present time, it remains relevant to increase the efficiency and intensity of homogenization of bulk materials to prepare a mixture of high and stable quality of the final product. Consequently, this paper aims to analyze the exisitng methods and designs of mixing equipment and the possibility of their application for effective homogenization of bulk materials in large volumes in chemical and related industries.

The mixing of bulk materials in the chemical and related industries occurs in the following ways:

– gravitational mixing in stationary silos, in which the source material moves under the action of gravitational forces, repeatedly circulates in the silo and is redistributed in the volume of the batch;

– gravitational-inertial mixing in rotating drum-type devices (drum mixers);

– vibrational mixing using various vibrating devices (trays, pipes, etc.);

– mixing by different moving mechanisms (blades, augers, screws, etc.);

– pneumatic mixing by fluidizing the material under the effect of gas (air).

All methods of mixing, except for the gravitational one, are energy consuming and involve crushing of material particles and dust formation. A common shortcoming of the above-mentioned methods is the need for independent mixing equipment and storage equipment, which allows producing large batches of material but requires a complex system of transporting devices.

In addition to the methods mentioned above, the ones aimed at overcoming the shortcomings of the existing methods have been proposed. The Kazan joint-stock company “Organic Synthesis” developed and patented a method for homogenization of granular bulk materials, consisting of pre-mixing, layer-by-layer collection, subsequent emptying and additional mixing [11]. The advantages of the proposed method of homogenization include the reduction in the process cycle and an increase in the degree of homogeneity of the batch mixture.

According to this method, the material to be homogenized is premixed, then it is collected in the vessel and only then it all layers are emptied simultaneously over the collection coordinate (i.e., over the entire height of the collected material layers). However, with this technology, the production cycle becomes much more complicated, and additional transport and handling operations as well as extra containers for pre-collection of the material are required.

Another shortcoming of this method is the uneven emptying of the material over the entire height of the layers due to the uneven compression of the lower layers of the material by the upper layers, i.e. varying degrees of compression from layer to layer. This affects the quality of mixing and, consequently, the quality of the prepared mixture.

Some shortcomings of the method mentioned above are eliminated in the method of bulk material homogenization [12], which comprises a layerwise collection of material in a vessel and a simultaneous emptying of all layers along the collection coordinate. During the movement of the material through the tank, it is maintained at a constant upper predetermined level and provides for the even distribution of the incoming and outgoing material. The homogenized material is emptied by cyclic fluidization of the layers in the discharge zone. The implementation of this method ensures the continuity of the mixing process and the improvement of the quality of the bulk material mixtures in large volumes.

Homogenization equipment

In the chemical industry, the so-called mechanical mixers are most common; the homogenization process is implemented by the mechanical action of working bodies of the device, different in design and shape, on the particles of bulk material. Typically, the homogenization devices are tanks for storing raw material, in which a more homogeneous composition of the output material is achieved by mixing as compared to the raw material.

The known designs of continuously operating homogenizers, in analogy with continuous mixers, can be conditionally divided into three groups depending on the nature of the flow of bulk material in them, namely:

1) the homogenization devices, in which the piston movement of the material along the axis occurs without the longitudinal mixing of particles;

2) the homogenization devices, in which the particles of the bulk material are further mixed in longitudinal motion;

3) the homogenization devices with a chaotic movement of particles throughout the internal volume of the device.

An example of the homogenization device with piston movement of the material along the axis of the housing and negligible longitudinal mixing of the particles in the conical part of the hopper is a filling-type mixer (Fig. 1) developed at Moscow Institute of Chemical Engineering in the last century [1].

The hopper *1* and the screws *3, 4* and *6* form a closed loop for circulating the homogenized bulk material. Filling of raw materials into the silo is performed through the nozzle *7*, and he homogenized material is emptied through the branch pipe *5*. Mixing of bulk material occurs mainly in a relatively small volume of the conical part of the silo, in which the particles are redistributed. To prevent the material from chocking-up, a slow-moving stirrer *2* is installed. The required quality of the mixture can be achieve by repeated passage of the material filled into the hopper through its conical part. As a result, the efficiency of the filling-type mixer depends largely on the multiplicity of circulation (pouring) of the material inside the housing.

Since the intensity of the homogenization process in the hopper is low, it is possible to achieve an acceptable quality of the mixture only if the mixture circulates at least thirty times.

In order to intensify the mixing process in the homogenization hoppers, an additional mixing element of different design is used. Such designs are called circulating-type mixers (Fig. 2).

In circulating-type mixers, under the action of a rotating working body, the material circulates along a closed contour, with the additional longitudinal movement of the material occurs.

The Gerbrudiger Lödige Mashinenbau (Germany) developed the design of a “Vertamix” type circulating-type mixer, which makes it possible to intensify the mixing process significantly in comparison with the filling-type design. The principle of the mixer is as follows. The raw material is fed into the central pipe *4* in two vortexes using fixed cones *3* (Fig. 2). In the pipe, the material is partially mixed by means of radial blades *2*. At the top of the hopper of the mixer, the distribution grid *1* is mounted.

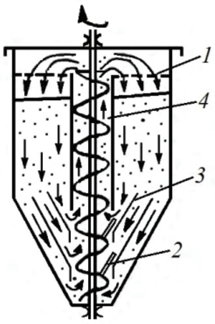

Fig. 2. A circulating-type mixer

The use of these mixing devices makes it possible to intensify the mixing process significantly, so that the homogenization time according to the company data is 15–20 min. The company supplies two-vortex circulating-type homogenizers with a volume of 5–100 m^3.

In both mixing and homogenizing techniques, the devices with a planetary drive auger are widely used.

The Dutch firm Nautamix, now included in the company HOSOKAWA MICRON B.V. (the Netherlands), produces Nauta circulating-type homogenization devices, in which the auger conveyer mounted inside a conical hopper performs planetary rotation around its inner surface.

In the upper drive adjuster (Fig. 3), the screw *4* is rotated about its axis from the actuator *1* mounted on the top cover of the hopper [1]. In addition, the auger makes a planetary rotation around the axis of the body *5*.

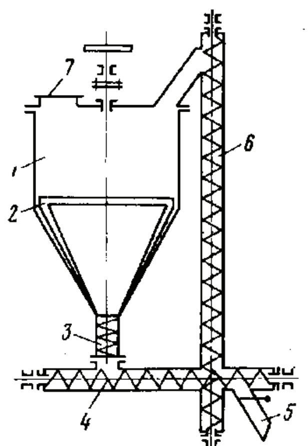

Fig. 1. A design of filling-type mixer

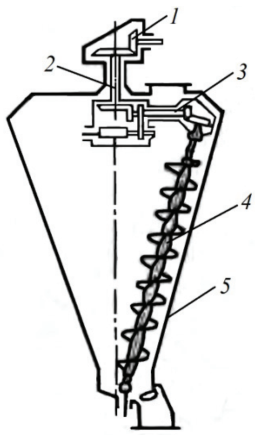

Fig. 3. Design of homogenization device with a planetary drive auger:
1 – drive; *2* – shaft; *3* – secondary shaft;
4 – auger conveyor; *5* – housing

The rotating auger conveys the material from the lower section of the mixer to the surface. With planetary rotation, the auger moves the material along the wall of the housing, providing convective mixing of the particles and the necessary shear action. As a result, rapid and intensive mixing of the material particles occurs, resulting in a sufficiently high homogeneity of the mixing.

A shortcoming of planetary auger drive mixers is the possibility of formation of stagnant zones in the near-wall areas of the device's housing, as well as a low efficiency of horizontal movement of the material particles.

In the production of granular polymer materials (in particular, polypropylene), homogenizers with a fluidized bed of material are used; this technology involves blowing an inert gas through the devices. The design of the pneumatic homogenizer is shown in Fig. 4.

In the lower part of the welded cylindrical body *1* of the homogenizer (Fig. 4), a gas distribution grid is mounted from sectoral ceramic plates with a thickness of 20 mm. The fluidized bed of the material is created by means of gas supplied through the nozzles into the welded box *2*, divided into two chambers. The finished product leaves the homogenizer through the connection *3*. The powder material from different batches is loaded into the homogenizer through the fittings located in the lid *4*. The exhaust gas leaving the housing is sent to the baghouse filter *5*. The homogenization cycle of polymer materials ranges from 1 to 2. 5 hours.

The major shortcoming of this design is its low efficiency when mixing large volumes of bulk materials, the possibility of abrasion of particles and, as a consequence, a significant dust burden.

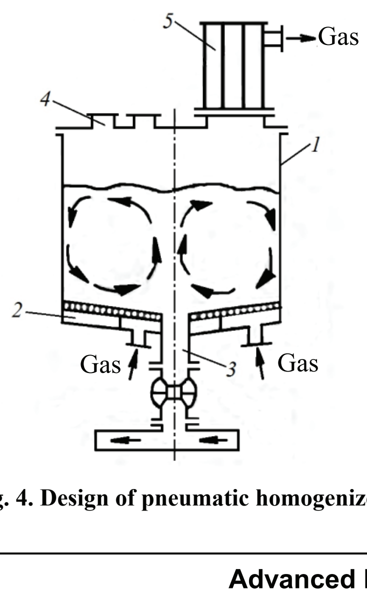

Fig. 4. Design of pneumatic homogenizer

Drum mixers of continuous operation have simple and versatile design. Fig. 5 shows the design of a drum mixer with a working volume of 1 to 3 m^3.

In the steel drum *1* there is a rotating shaft *2* with working spirals *3* and *4*. The rotation of the blades directs the homogenized material is from the side walls to the center, and here it is intensively mixed when two vortexes meet [1]. The material is loaded from above through the hatch *5*, and emptied after homogenization through the lower hatch *6*. The major shortcoming of this type of mixer is the presence of dead zones. The homogenization time ranges from 15 to 30 min. If homogenization takes longer, it can cause increased abrasion of the particles and their grinding.

For homogenization of materials prone to sticking on working surfaces, it is advisable to use a mixing device for bulk materials shown in Fig. 6 [13].

The device works as follows. The bulk material is fed into the cylindrical housing *1* through the cone part *2*, in which the sleeve *3* with the dispensing spout *4* rotates. Consequently, the bulk material from the conveyor *5* is uniformly distributed over the cross section of the housing *1*. In this case, it is sequentially filled through the dividing grids *6* and *7* set alternately along the entire height of the housing *1*. Due to their mutual arrangement and the fact that the grid elements have the form of triangular prisms, they divide the flow of material and mix it. The multiple separation and mixing of the flow on the dividing grids leads to homogenization of the material. In the lower part of the body *1*, the homogenized material flows through the pipe *8* to the receiving conveyor *9*.

In this type of homogenizer, a long and stable operation of the entire device is maintained, and, consequently, its operational reliability significantly increases.

In our opinion, this device does not ensure the even distribution of bulk materials along the cross section of the housing. In addition, there is practically no control over the homogenization process.

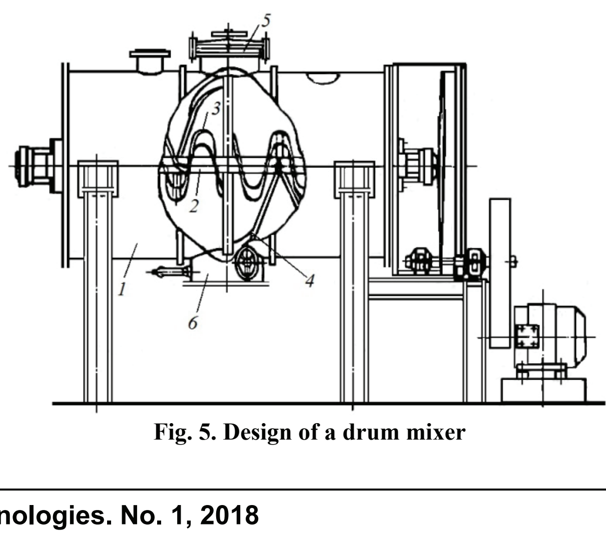

Fig. 5. Design of a drum mixer

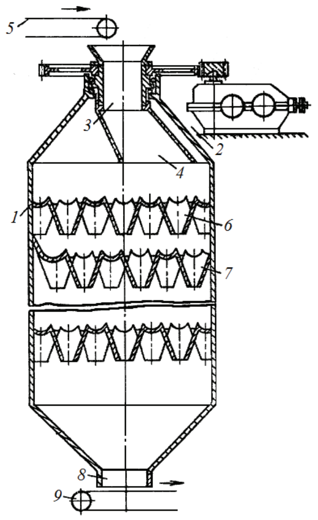

Fig. 6. Design of a mixing device for bulk materials

As noted above, at present the process of homogenization of bulk materials is widely used at metallurgical plants. This is due to the need to obtain a homogeneous physical-chemical composition of raw materials in large quantities. Due to the high efficiency of the homogenization process, the mixing equipment in the ore and coal industries is currently being developed and improved.

At the metallurgical companies, homogenization of raw materials involves accumulation of a certain quantity of raw materials and their consecutive emptying [14]. In the process of emptying, the raw material is additionally mixed, which leads to an increase in its homogeneity.

Homogenization of the quality of minerals is understood as a set of technological and organizational measures to ensure the required consistency of the quality of solid minerals in the process of their extraction and primary processing.

In the metallurgical industry, three methods of homogenization of raw materials are used [14]: in stacks using clamshell loaders and excavators; in silos; in stacks using intake machines. The homogenization methods in the mining industry are classified as follows: 1) ore quality control in extraction; 2) graded homogenization; 3) mixing.

Homogenization of extracted minerals is performed by the following methods: stacking in open and closed warehouses; hopper or semi-hopper storage [14–19]. The most promising homogenization method is the bunker storage method, which ensures high quality of raw materials and maximum economic efficiency.

The homogenization devices include blast-furnace plants, various mixers, homogenizers, hoppers, pulp tanks and silos for crushed material [20–23].

Hopper mixing assumes a linear arrangement of bunkers in the form of a trestle [14, 15]. The mixed material is loaded into the hoppers using a belt conveyor with a dump truck, which reciprocates along the trestle. The homogenized material is emptied from the hoppers by means of feeders into the wagons or to the conveyor under the hoppers. As different batches of the homogenized material are arranged in horizontal layers, when the hopper is emptied into the car or on the conveyor, the material from the various layers is mixed and comes onto the conveyor.

A modification of the structure described above is a long-length hopper having a slot-like opening. The homogenized material is emptied from the hopper by means of a movable feeder and then transported to the longitudinal conveyor. The layers of material in such a hopper are located at the angle of a natural slope, and the material is emptied opposite to the loaded layers.

The process of hopper homogenization involves separation of the material, and has the low efficiency of its mixing, which leads to a poor quality of the mixture. In addition, the manufacture of homogenization hoppers is associated with higher costs.

Homogenization in stacks is a widely used method of homogenization of materials in blast-furnaces. The shape of the stacks can be different: rectangular or rounded at the ends of the rectangle of the base, have triangular or trapezoidal section, as well as circular in the form of a cone or truncated cone, and ring stacks of various shapes [17].

The quality of the homogenized material is determined mainly by the way the material is stacked and taken from the stack. When forming the stack, the raw material is laid in a longitudinal or transverse direction relative to the rectangular base. Other ways of stacking are applied: chevron layering, combined layering etc.

Due to the great prospects of practical use of the silo homogenization method, we will consider the most typical design solutions applied in the mining industry.

In the mining industry, homogenization of ores of different grades and coals of different ash content is done by the following homogenization device (Fig.7).

The device [24] comprises a housing *1* consisting of a receiving hopper *2* and a loading unit *3*, and a mixer. Structurally, the mixer is a set of inverted truncated pyramids *4* and double-spaced dividers *5* arranged successively in height. The lower truncated pyramid is connected to a transporting device *6.*

Solid bulk materials of different quality (for example, coal, ore) are fed to the receiving hopper *2* through the loading unit *3*. After filling the hopper and

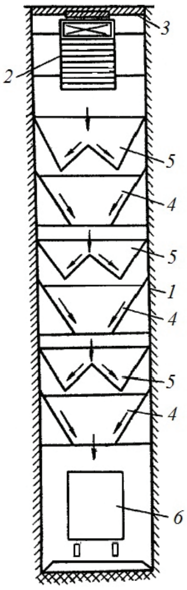

Fig. 7. Homogenization device for solid bulk materials

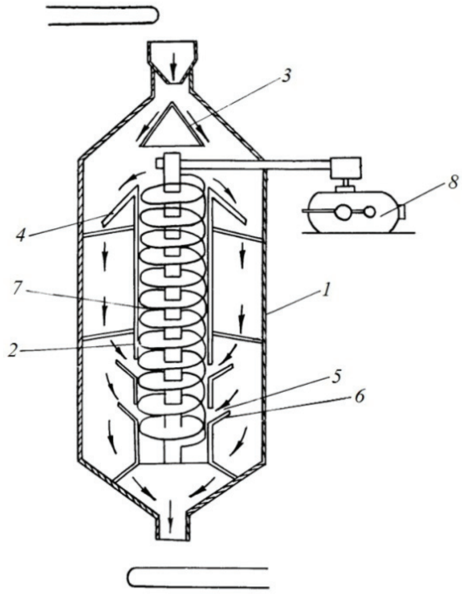

Fig. 8. Device for homogenization of bulk materials

achieving the average grade of bulk material, it is sent to the mixer. In the process of gravitational motion along a two-slope dissector, and then along the walls of an inverted pyramid, the solid bulk material is mixed. The process of mixing the material is repeated many times by a cascade of dividers and inverted pyramids. After this, the resulting mixture is collected in the lower inverted truncated pyramid until it is emptied into the transporting device *6*.

After the hopper *2* is fully emptied, its bottom is closed and the homogenization process is repeated.

In this device, a sufficiently strong segregation takes place, leading to the separation of large and small pieces of ore, which is the cause of the decrease in the quality of homogenization.

A homogenization device for solid bulk materials can also be used at coal and ore deposits [25].

The efficiency of homogenization in this device is improved by ensuring the stabilization of the bulk material quality. For this purpose, a cylindrical pipe *2* is mounted in the center of the housing *1* (Fig. 8) of the device. In the upper part of the pipe, there are a cone dissector *3* and guide grooves *4*. In the lower part of the pipe, along the periphery there are niches *5*, under which there are cutters *6*. In the cylindrical pipe, screw auger *7* is mounted, its upper end is connected to the actuator *8*.

Niches and slots relative to the guide grooves are installed so that they coincide with the gap between the grooves. Trough-shaped guide rails protrude beyond the intake zone of the cutters. The cutters mounted underneath the niches cut off part of the flow, thereby causing a longitudinal shift in the phase of the dispersed flow. The cut off flows fall into the return body through the niches. As they rise, they mix with each other, thereby ensuring uniformity of the returned flow. The trough-shaped guide rails mounted at the upper end of the return body divide the return flow into several more flows and are combined with the incoming flow of other content, while they are ejected from the area of the cutter grippers. The incoming flow, falling into the tops of the cone dissector, conically aligns. At the same time, the part is mixed with the returned flow, and the other part, passing between the troughs, gets into the cutters.

The advantage of this device is that it implements all functional operations (material storage, phase shift due to multiple flow separation and mixing, mixing and combining) in one vessel. The disadvantage of this design is that it is difficult to control the flow of various materials in their separation and mixing.

"Vibrotechcenter-KT" LLC is currently manufacturing a device for multi-component mixing (homogenization) of bulk materials UMKS-1.0 (Fig. 9).

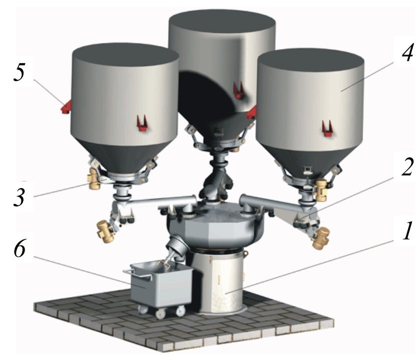

Fig. 9. UMKS-1.0 technological system for multi-component mixing of bulk materials

The UMKS-1.0 technological system is designed for high-quality mixing of bulk materials that are not prone to sticking in the automatic mode. The particle size of the mixed materials can vary from tens of micrometers to tens of millimeters.

Using the vibrating feeder *2*, the components to be mixed are fed from the supply hoppers *4* to the vibrating mixer *1*. For uniform feeding, in the case of the filling of fine materials susceptible to hanging and arcing, a vibratory feeder-activator *3* is mounted in the lower part of the hopper. If the material has a sufficiently large size and good bulk properties, the feeder-activator can be excluded from the process.

After the required amount of components is filled, the feeders are switched off and the vibrating mixer starts working at the same time. Mixing occurs under the effect of vibration. Due to the toroidal oscillations, the material performs complex spatial oscillations, and as a result, a finished product with a high degree of homogeneity is obtained.

Homogenization lasts approximately for 5–20 min (depending on the properties of the components to be mixed and the desired degree of uniformity of the mixture). At the end of the mixing process, the mixer is switched off. The valve is manually opened and by using a repeated switch-on of the mixer the material is emptied into trolley the *6*. After emptying, the mixer switches off, the valve closes, and the described cycle is repeated again.

Methods for assessing the quality of homogenization of bulk materials batches

In domestic research practice, methods for assessing the quality of mixing of bulk materials, as a rule, are based on methods of statistical analysis [1]. Most researchers take the standard deviation of the content of the main component in the samples taken from the mixture as the criterion for assessing the quality of the mixture from its average content. The value of the standard deviation S from the experimental data is calculated by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(c_i - \bar{c}\right)^2}{n-1}},$$

wheree c_i is concentration of the key component in *i*-th sample; $\bar{c}$ is arithmetic mean of the key component in all samples; *n* is total number of samples taken.

Due to the dependence of the standard deviation S on the value c_i and their identical dimensionality, this value is not used to compare the quality of mixtures that differ in the content of the main component. Therefore, the inhomogeneity of the mixture is assessed using the coefficient of variation [1]:

$$V_i = \frac{100}{\bar{c}} S.$$

It was proposed in [26] to use the relative inhomogeneity coefficient of the main component in the volume of the device at a given time.

The efficiency of mixing of bulk materials having different qualitative composition is assessed using the homogenization coefficient and the homogenization efficiency [27].

The homogenization coefficient is calculated by the formula:

$$K = V_2 / V_1,$$

where V_1, V_2 are coefficients of variation of the qualitative composition index of the mixture before and after mixing. When the concentration of the main component is equal before and after mixing, the homogenization coefficient is determined by the formula:

$$K = S_2 / S_1,$$

where S_1, S_2 are the mean square deviation of the content of the component in the materials before and after mixing.

The homogenization efficiency *h* is calculated by the formula

$$h = 1 - K = 1 - S_2 / S_1.$$

We considered not all known methods for assessing the quality of mixing of bulk materials batches [28]. These methods vary in the degree of accuracy. When choosing a method for assessing the quality of a bulk material mixture, it is important to take into account the importance of the technological process, while its effectiveness should be assessed with regard to the cost, laboriousness and possibility of repeating the results [29].

Conclusion

The analysis shows that some designs of industrial mixers are morally obsolete. In addition, they are characterized by considerable metal and energy intensity, as well as the inability to obtain a stable composition and high quality of the mixture. A significant shortcoming of the existing designs of mixers is the low efficiency of the homogenization process and their low operational reliability. Therefore, to intensify the mixing process, it is advisable to use methods and approach increasing the turbulization and circulation of flows of materials to be mixed, and reducing metal and energy consumption of the mixing equipment.

Thus, the most effective and preferred designs are those with active hydrodynamic modes, in which bulk materials subject to mixing move along the the body of the device [30–36]. The movement of bulk material in the device is maintained by different transporting devices [37–39], in particular screw conveyors, overflow hoppers, and also devices for aerating the bulk material flow.

We developed the design of a bulk material mixer, in which a mixture of a given quality is prepared by the implementation of the active movement of the mixed components along the height of the device body [40]. The use of a cascade of mixing hoppers and disintegrators installed between them makes it possible to have several flows of material batches in the gap between the hoppers and the housing of the mixer. This substantially increases the efficiency of the process of homogenization of the materials. Intensification of the material mixing in parallel flows is also ensured by inclined brackets mounted in a cascade with an opposite inclination angle in the gaps between the hoppers and the housing. As a result, the mutual penetration of the material from individual batches is intensified, and homogeneous distribution of particles at the mixer outlet is ensured.

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