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Modeling of Mixing Nanopowder Materials when Designing Process Equipment

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Abstract

A study of the process of gravitational mixing of nanodispersed materials in the oncoming flows of coalescing fans is presented. Based on a number of assumptions, the analysis of the three-stage process of pouring material from an inclined plane and the formation of a falling fan is given. Introducing the concept of a cell in the form of an elementary volume containing particles of material, it is shown that the size of the elementary area of the fan is determined by the height of its opening and the rate of fall of the material.

Based on the proposed physical model, the optimum condition is formulated under which the overlapping particles of fan flows capable of mutual penetration occur. The proposed model allows with high reliability to determine the probability of the introduction of cells from stream to stream (i.e., ultimately, to determine the quality of the mixture), received experimental confirmation.

The main factors affecting the quality of mixing and design parameters of the designed equipment for processing nanodispersed materials are established.

Keywords

Nanodispersed material; processing; modeling; gravitational mixing; mixer; process equipment.

Introduction

The creation of new composite materials (dispersion-hardened and superhard materials, cermets, structural ceramics, and modified alloys) with unique properties, or the improvement of characteristics already known, is one of the priority areas for the development of the scientific and technological complex of Russia. Process schemes for producing composite materials in all cases involve the use of powders, and their dispersed composition has a significant effect on the properties of the materials obtained. The transition from powders with characteristic particle sizes of ~ 1–10 μm, traditionally used in composite materials science, to nanodispersed powders with characteristic particle sizes of 10–100 nm, allows one to achieve both a significant improvement in the properties of existing composite materials and the production of composite materials with fundamentally new properties due to a change in the physicochemical properties of the powders upon reaching the nanometer particle size. The specific surface area and chemical activity of the powders significantly increase, which is of fundamental importance for the creation of new composite materials. Therefore, nanodispersed powders are increasingly used in composite materials science technologies, making it important to study nanoparticle mixing processes and study the dynamics of their motion in order to develop new highly efficient equipment for processing nanodispersed powders on an industrial scale. The problem of obtaining nanopowders of substances and their compounds is solved in world practice in a variety of ways.

One of the main processes used in processing is the mixing process. Being sometimes auxiliary, this process is widely used in many industries, and, ultimately, determines the quality of the finished product. It consists in the random redistribution of components in the volume of the mixture and intended for the preparation of the mixture.

At the same time, an insignificant number of publications are devoted to directly modeling the process of mixing dispersed materials and preparing compositions containing a solid phase. Among them can be distinguished, for example, the works [1–3], which are devoted to the study of mixing various bulk materials. Their authors indicated that the study of the process is at the level of accumulation of experimental data and understanding of its basic laws. As a result, neither single view of the essence of the process, non-unified terminology or sound methodology for the experiment and no common criteria for assessing the quality of mixtures have been developed. These circumstances have led to the fact that even the results of experiments of various authors are difficult to compare [4–6].

Moreover, modeling the behavior of bulk media is purely applied in nature. In [7], simulation modeling of the movement of dispersed bulk material in a drum set to determine the segregation and volume of the dust fraction was considered. In [8–10], the definition of the general laws of behavior of bulk material depending on its properties in drum and circulation mixers was determined. The analysis of the possibility of using various models to describe the mixing process was carried out in [11–16]. Also, in a number of the same works, the authors tested the models used as applied to the calculation and design of both individual units and mixers in general [17–21].

Recently, the widespread introduction of carbon nanomaterials, for modification and functionalization, makes it necessary to take into account their properties when designing technological equipment [22–24]. Moreover, these materials – nanodispersed materials (**NDMs**) – include, for example, carbon nanotubes (**CNTs**) and graphene. A significant number of works have been devoted to the study of the properties of NDMs, the authors of which note a complete analogy in its properties and the properties of dispersed bulk materials (including powders and industrial dusts) [25–30]. For example, in [31] the influence of the electrostatic properties of NDMs on the processing process was considered. The general physicmechanical characteristics of individual nanoparticles and the laws of their motion were considered in [32], and in [33] the hygroscopicity and density of nanomaterials was applied to transistors and microelectronics. It should be noted that in all the works only certain characteristics of NDMs were considered in relation to laboratory research and all their parameters, as well as the conditions of use and calculation of equipment, were not taken into account, i.e. there are no works devoted to their practical application [34–36].

The analysis of the studies showed that the effect of gravitational mixing is widely used in industry for the preparation of mixtures of dispersed materials. When mixing in a gravitational field, mutually intersecting or overlapping flows of dispersed materials have good permeability for component particles, which allows avoiding uncertainty when considering the dynamics of flows of mixed materials, achieving a good degree of uniformity of the mixture at relatively low energy costs.

The purpose of the research is the development of new approaches to modeling, calculation and optimization of mixing processes of nanodispersed bulk materials for their use in design and technological measures to improve the quality of mixtures and the performance of mixers.

The movement of material on an inclined plane, modeling the mixing process

Analyzing the behavior of NDMs on an inclined plane, its movement can be divided into stages. In the first stage, the material comes from the hopper to the guide plane; in the second stage, the material acquires speed and initial layered location before pouring; and in the third stage, the material is poured under the influence of gravitational forces with the formation of a fan of falling particles.

For further consideration, we make a number of assumptions:

– particles are poured with a guide stream, consisting of a series of parallel sublayers;

– speeds of particles located in one sublayer are equal;

– the trajectory of the fall of particles depends on their velocities at the moment of separation from the guide plane;

– when falling, particles of one stream practically do not collide with each other;

– the flow of particles of material when falling loosens.

So to determine the number of sublayers on the guide plane (Fig. 1) we use the expression

$$n = \frac{h}{d_{av}} \qquad (1)$$

where h is thickness of the rolling layer; d_{av} is the average particle size of components.

We divide the flow of the fan, the pouring flow of NDMs into cells (Fig. 2).

In our case, each cell represents an elementary volume V_e, containing the particle material. the trajectory of the particle's fall. Moreover, from what was said above, despite the increase in the area of the flow fan, the quantitative content of the material in it, in any cross section, will remain constant. Then, for the size of the elementary volume (and therefore the cell as

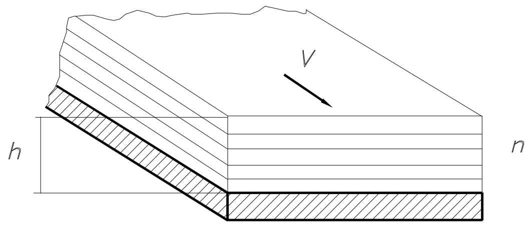


Fig. 1. A layer of material on the guide before pouring (1 stage):
(V is flow rate; n is the number of sublayers of the material; h is thickness of the rolling layer)

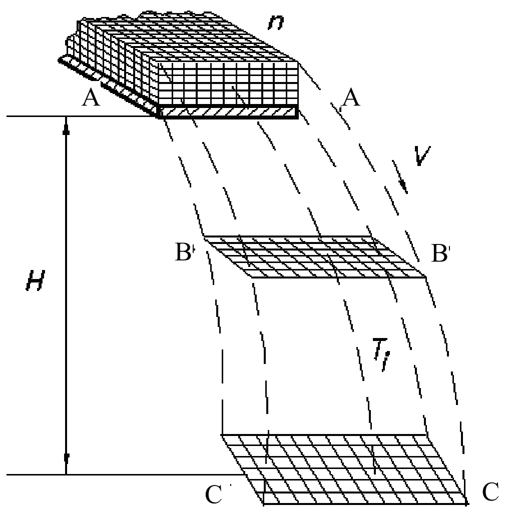


Fig. 2. Breakdown of the fan flow path into cells (stages 2 and 3)
(H is fan height; A–A is cross section of material flow before pouring; B–B is fan section; C–C is material flow cross-section at the time of complete fan opening; V is material speed; n is the number of cells; T_i is trajectory of the fall of the i-th cell)

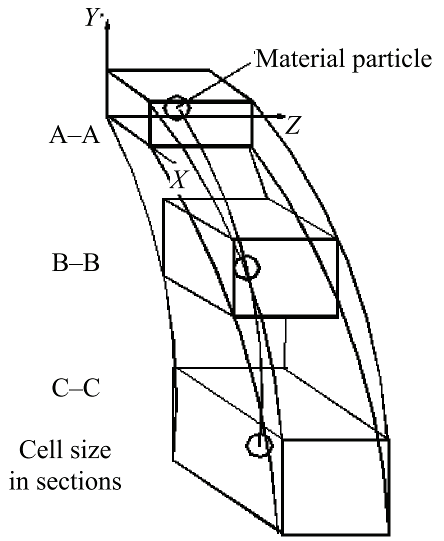


Fig. 3. Changing the cell size in different sections of the material flow in the fan

a whole, with a constant amount of material) for the cross sections along the height of the layer (Fig. 3), the following expression is fair

$$V_e\,(\text{A–A}) < V_e\,(\text{B–B}) < V_e\,(\text{C–C}). \quad (2)$$

From this it can be argued that the size of V_e is determined by the height of the fan opening and the rate of fall of the material

$$V_e = f(H, \nu). \quad (3)$$

Bearing in mind that after the flow reaches the height of the fan H_{min} the boundaries of the fan practically do not change

Next, we consider the mechanism of interaction of the cells of the flow of materials with each other in the process of mixing two oncoming fans. In our case, mixing occurs when the flows of materials are superimposed on each other with the mutual penetration of the cells (elementary volumes V_e of components A and B from the flow to the flow).

We consider the process of mixing the flows of materials A and B in more detail. To obtain a high-quality mixture, mutual penetration of particles from the flow into the flow is necessary. The determining parameter will be the volumetric coefficient of flow loosening K_v and

$$K_v = K_x K_y K_z,$$

i.e. penetration of the flow will be characterized, ultimately, by the distance between the particles

$$K_{vi} \geq K_v,$$

where K_{vi} is volumetric coefficient of loosening the i-th ematerial flow; K_v is required volumetric coefficient of loosening of the material flow.

The immutability of the flow along K_z was experimentally found; therefore, we can take K_z = const for the entire flow.

We consider the factors affecting the penetration of particles from a stream into a stream. If the distance between the mixer and the receiving hopper is incorrectly selected (insufficient height), fans of materials do not open and, as a result, they are superimposed on each other; mixture formation is observed only in a small section of intersecting fans, i.e. $K_{vi} \geq K_v$, but the flow width $A - B_A \neq B_B$ and $H < H_{min}$ (Fig. 4*a*)

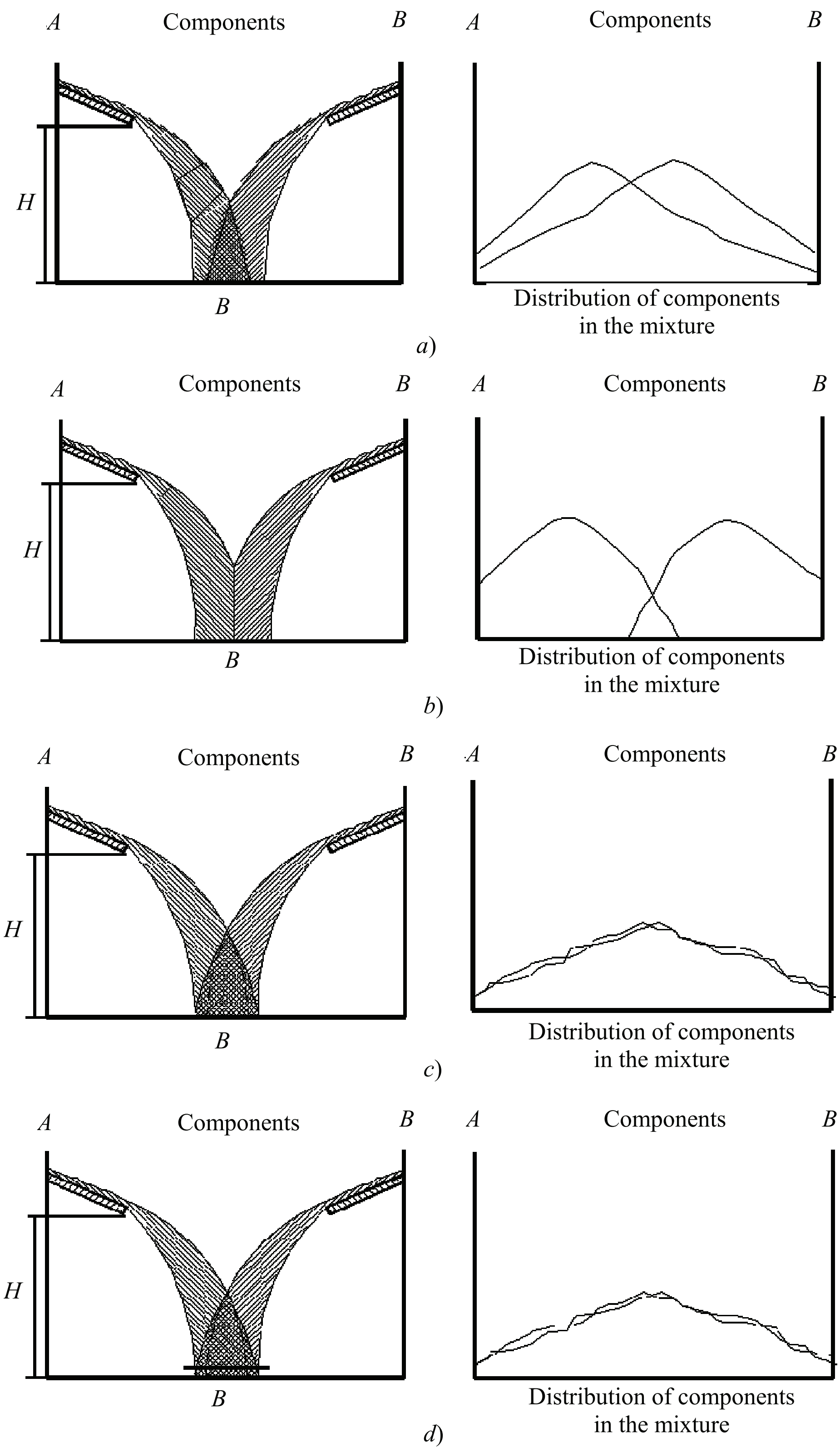
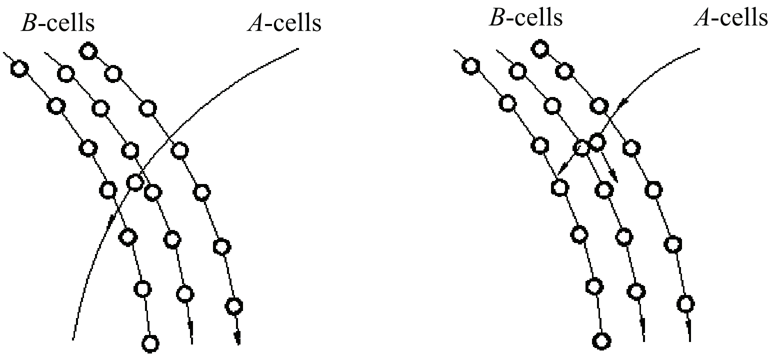


Fig. 4. The distribution of the material components in the mixture:
$a - K_{Vi} \geq K_V$, $B_A \neq B_B$, $H < H_{min}$; $b - K_{Vi} < K_V$, $B_A = B_B$, $H \geq H_{min}$;
$c - K_{Vi} \geq K_V$, $B_A = B_B$, $H \geq H_{min}$; $d - K_{Vi} \geq K_V$, $B_A = B_B$, $H >> H_{min}$
(*H* is the fan height (from the edge of the guide plane to the hopper); *B* is the fan opening width)



Cell paths   Cell paths

a)   *b*)

Fig. 5. The interpenetration of cells from flow to flow:
a – the first method; *b* – the second method

If the distance between the bins is not optimally selected, i.e. when the requirement $K_{vi} \geq K_v$ is not met, the loosening of the flows is too small and they cannot miss the particles of another. In this case, materials *A* and *B* after collision fall in parallel flows without the formation of a mixture (Fig. 4*b*).

Optimum is subject to conditions $K_{vi} \geq K_v$, $B_A = B_B$ and $H \geq H_{min}$ superposition of particles of streams *A* and *B* capable of mutual penetration occurs on top of each other (Fig. 4*c*).

With increasing height ($H >> H_{min}$) the qualitative picture of the formation of the mixture does not change. Thus, in order to reduce the dimensions of the installation, the recommended height to the level of the receiving tank must satisfy the condition $H = H_{min}$ (Fig. 4*d*)

We consider the physical model of the process. In the general case, the cell of component A can penetrate the particle flow of component *B* in two ways. Moreover, we assume that the mutual nonpenetration of cells is impossible in principle. Let us denote the probability of penetration of the cell of component *A* (*A*-cell) into the flow consisting of the cells of component *B* (*B*-cell) as *P*1. Moreover, in the first method, the *A*-cell passed through the boundary layer of *B*-cells – probability *P*11 (failed – *P*21). In the second method, the *A*-cell collided with the *B*-cell in the boundary layer, and after m-collisions, it deepened into the flow – probability *P*31, remained in the boundary layer – *P*41. The penetration of particles from flow to flow after collision is possible according to the law of classical mechanics (on the equality of action and reaction), therefore, particles will continue to move under the action of gravitational forces, but with a change in vectors (directions), i.e. cells will change their paths. In addition, the porosity of the flow (loosening in the fan) increases. Cell penetration methods are shown in Fig. 5.

Then the probability of penetration of the cells when applying fans is determined by the expressions

$$P1 = P01\left(1 - C_{i,j+1}\right); \quad (4)$$

$$P2 = P02\left(1 - C_{i,j-1}\right); \quad (5)$$

$$P3 = P03\left(1 - C_{i+1,j}\right); \quad (6)$$

$$P4 = P04\left(1 - C_{i-1,j}\right), \quad (7)$$

where *P*01, *P*02, *P*03, *P*04 are penetration probabilities of a key component (e.g., *A*-cells into the flow of *B*-cells); $C_{i,j}$ is the penetration depth.

Thus, if at the moment of time the *i*-th cell passes through the boundary layer (a certain distance between the particles, determined as $S'_e = S_{ei} + S_{ei+1}$), then the penetration of the second particle in this place is possible only through $\Delta\tau_i$. Therefore, we will assume that the probability of penetration of the key component depends on the distance between the particles – the size of S'_e in the neighboring elementary volumes V_{ti} and V_{ti+1}.

The expression of the probability of penetration of the key component in depth to *k*+1 the path of the main component will be

$$C_{i,j}^{k+1} = C_{i,j}^{k} - C_{i,j}^{k}\, P1_{i,j+1}^{k} - C_{i,j}^{k}\, P2_{i,j-1}^{k} + C_{i,j-1}^{k}\, P1_{i,j}^{k} + C_{i,j+1}^{k}\, P2_{i,j}^{k} - C_{i,j}^{k}\, P3_{i+1,j}^{k} - C_{i,j}^{k}\, P4_{i-1,j}^{k} + C_{i-1,j}^{k}\, P3_{i,j}^{k} + C_{i+1,j}^{k}\, P4_{i,j}^{k}. \quad (8)$$

In the last expression, the indices of the penetration probabilities determine the cell that penetrates, and the sign in front of each of the members determines the direction of movement.

Depending on the depth of mutual penetration of the cells in the flow of bulk material, three types of cells can be distinguished. Cell types are shown in Fig. 6. We consider these types of cells:

– type *1* – cells of this type will penetrate through the entire flow according to its path;

– type2 – these cells will penetrate into the depths, and having collided,will form local mixing zones;

– type *3* – these cells will create mixing zones in the boundary layers.

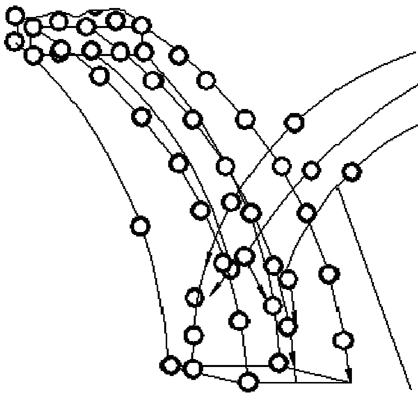


Fig. 6. Cell types

Thus, the expression of the probability of penetration of the key component for each type of cell is obtained from the general, taking into account the above features.

Identification of model parameters

The presented model of the process of mixing materials in a gravitational mixer received experimental confirmation during the experiments, and it fully corresponds to the empirical data. Identifications are subject to *P*01, *P*02, *P*03, *P*04 probabilities of penetration of the cells of the key component into the cell flow of the main component.

For the experimental determination of penetration probabilities, the following method was used. A monodisperse bulk material and a key component (differing only in color) were poured into the

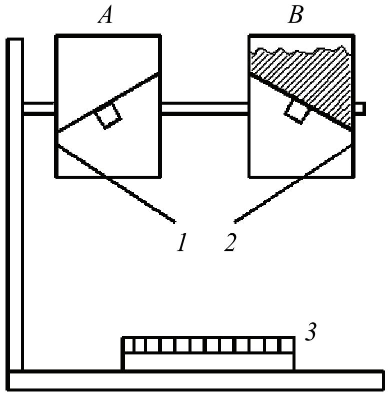


Fig. 7. Experimental setup:
A and *B* – silos; *1*, *2* – inclined planes; *3* – sampler

experimental setup (Fig. 7). After the installation was turned on, the moment of filling the sectional sampler was recorded and the experimental setup was turned off. Further, the ratio of the main and key components in the sections of the sampler was analyzed (Table 1), the penetration probabilities were determined for given geometric parameters of the setup. After that, the relative position of the elements of the experimental setup was subjected to correction and the experiment was repeated.

Despite its duration, this method allows one to determine with high reliability the probabilities of introducing cells from a stream into a stream (i.e., ultimately, to determine the quality of the mixture).

However, it should be borne in mind that for materials with other physical and mechanical properties it is necessary to repeat experiments on adjusting the mixer parameters.

Table 1

Experimental data

Sampler cells	1	2	3	4	5	6	7	8	9	10	11	12
Component *A*	0.53	1.57	2.60	3.44	7.19	5.12	2.71	1.68	1.09	0.50	0.64	0.49
Component *B*	0.45	1.51	2.52	3.31	6.87	5.37	3.08	1.55	0.84	0.52	0.48	0.54
$(A+B)^{v}$	0.98	3.08	3.12	6.75	14.1	10.5	5.79	3.23	1.93	1.02	1.12	1.03
$(A+B)^{e}$	0.92	2.79	3.24	6.21	14.0	11.0	5.67	3.25	2.21	0.96	1.07	0.79
$(A+B)^{e}$	0.87	2.64	3.25	6.15	13.2	10.9	5.36	2.11	2.09	0.74	0.81	0.62

Note: $(A+B)^{v}$ is design value; $(A+B)^{e}$ is experimental content of the components of the mixture in the cells of the sampler.

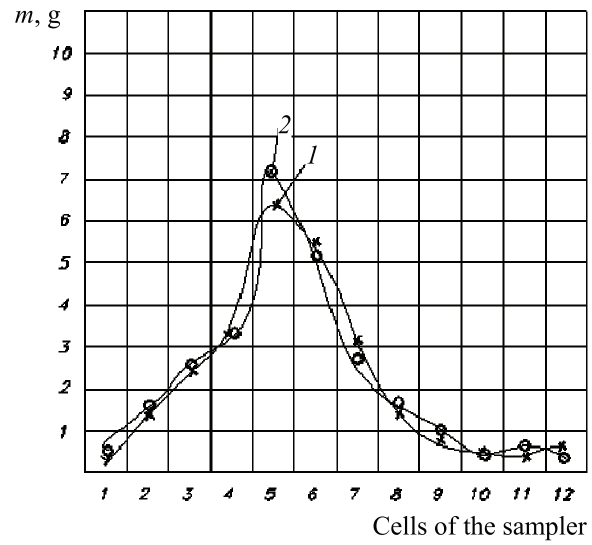


Fig. 8. The distribution of the components of the mixture *A* and *B* in the cells of the sampler:
1 –*A* component; *2* – *B* component

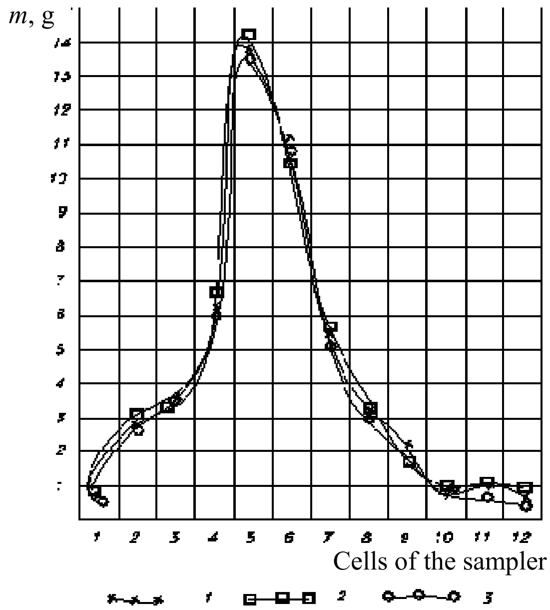


Fig. 9. The distribution of the mixture in the cells of the sampler:
1 – design curve; *2*, *3* – experimental curves

Conclusion

The analysis of literary sources and experimental studies made it possible to propose a model for the mixture preparation of dispersed materials (including NDMs), as well as to verify its adequacy. The main factors affecting the quality of mixing and the design parameters of the developed technological equipment for the functionalization of CNTs as applied to gravity-type mixers are established. The results were tested and showed high convergence in practical implementation.

References

1. Aleksandrovskij A.A. Issledovanie processa smeshenija i razrabotka apparatury dlja prigotovlenija kompozicij, soderzhashhih tverduju fazu. Dokt. diss. [Study of the mixing process and the development of equipment for the preparation of compositions containing a solid phase. Doct. Diss.]. Kazan, 1976. 48 p. (Rus)

2. Makarov Yu.I. Apparaty dlya smesheniya sypuchikh materialov [Devices for mixing bulk material]. Moscow: Mashinostroyeniye, 1973, 216 p. (Rus)

3. Shubin I.N., Sviridov M.M., Tarov V.P. *Tehnologicheskie mashiny i oborudovanie. Sypuchie materialy i ih svojstva* [Technological machines and equipment. Bulk materials and their properties]. Tambov: Izd-vo Tamb. gos. tehn. un-ta, 2005. 76 p. (Rus)

4. Bytev D.O., Zajcev A.I., Makarov Ju.I., Severcev V.A. Dvizhenie tonkih sloev sypuchego materiala po nepodvizhnym poverhnostjam gravitacionnyh smesitelej i rashodomerov [The movement of thin layers of bulk material on the fixed surfaces of gravity mixers and flow meters]. *Izd. vuzov SSSR. Himija i himicheskaja tehnologija*, 1980, *23*(11), 1437-1441. (Rus)

5. Vajberg L.V., Pisarenko G.S. *Mehanicheskie kolebanija i ih rol' v tehnike* [Mechanical vibrations and their role in technology]. Moscow: Gos. izd. fiz.- mat. lit., 1958. 232 p. (Rus)

6. Burakova E.A., D'jachkova T.P., Ruhov A.V., Tugolukov E.N., Popov A.I. *Nanomaterialy: sposoby poluchenija, metody diagnostiki, oblasti primenenija* [Nanomaterials: production methods, diagnostic methods, application]. Tambov, 2018. (Rus)

7. Wangchai S., Hastie D., Wypych P. Particle Size Segregation of Bulk Material in Dustiness Testers via DEM Simulation. *Particulate Science and Technology*, 2016, p. 298. doi: 10.1080/02726351.2016.1205688

8. Selivanov Yu.T. Movement of Bulk Material in the Longitudinal and Cross Sections of the Classifying Drum. *Vestnik TGTU*, 2016, *22*(4), 615-623. doi: 10.17277/vestnik.2016.04.pp.615-623. (Rus)

9. Selivanov Yu.T., Pershin V.F. *Raschet i proektirovanie tsirkulyatsionnykh smesitelei sypuchikh materialov bez vnutrennikh peremeshivayushchikh*

ustroistv [Calculation and design of circulation mixers of loose materials without any internal mixing devices], Moscow: Mashinostroenie-1, 2004, 120 p. (Rus)

10. Pershin V.F. Modelirovanie processa smeshenija sypuchego materiala v poperechnom sechenii vrashhajushhegosja barabana [Modeling the process of mixing bulk material in the cross section of a rotating drum]. *Teoret. osnovy him. tehnologii*, 1986, *20*(4), 508-513. (Rus)

11. Moshanskii A.I. Some questions of the theory of cell model. *Teoreticheskie osnovy khimicheskoi tekhnologii*.,1990, *24*(6), 743-754. (Rus)

12. Pershin V.F. *Mashiny barabannogo tipa: osnovy teorii, rascheta i konstruirovanija* [Drum type machines: the fundamentals of theory, calculation and design]. Voronezh: Izd-vo Voronezh. universiteta, 1990. 166 p. (Rus)

13. Pershin V.F., Selivanov Ju.T. Modelirovanie processa smeshivanija sypuchih materialov v cirkuljacionnyh smesiteljah nepreryvnogo dejstvija [Modeling the process of mixing bulk materials in continuous circulating mixers]. *Teoret. osnovy him. tehnologii*, 2003, *37*(6), 629-635. (Rus)

14. Ponomarev D.A. *Modelirovanie processov smeshivanija sypuchih materialov v staticheskih povorotnyh smesiteljah*. Diss. kandidat tehn. nauk. [Modeling the processes of mixing bulk materials in static rotary mixers. Diss. Cand. Tech. Sci]. Ivanovo, 2006, 155 p. (Rus)

15. Smolina I.O., Smolin D.O., Djomin O.V. K voprosu o modelirovanii processa smeshivanija sypuchih materialov v lopastnyh smesiteljah [On the issue of modeling the process of mixing bulk materials in paddle mixers]. *Sovremennye naukoemkie tehnologii*, 2013, *8-1*, 93-94. (Rus)

16. Volkov M.V., Korolev L.V., Tarshis M.Ju. Matematicheskaja model' processa smeshivanija sypuchih materialov v novom ustrojstve gravitacionno-peresypnogo dejstvija [A mathematical model of the process of mixing bulk materials in a new gravity-pounding device]. *Fundamental'nye issledovanija*, 2014, *9(5)*, 960-964. (Rus)

17. Baranceva E.A., Mizonov V.E., Hohlova Ju.V. *Processy smeshivanija sypuchih materialov: modelirovanie, optimizacija, raschet* [Bulk materials mixing processes: modeling, optimization, calculation]. Ivanovo: GOU VPO "Ivanovskij gosudarstvennyj jenergeticheskij universitet im. V.I. Lenina", 2008, 116 p. (Rus)

18. Demin O.V. *Sovershenstvovanie metodov raschjota i konstrukcij lopastnyh smesitelej: dis. ... kand. tehn. nauk*. [Improvement of calculation methods and designs of paddle mixers: dis. ... cand. tech. of sci.]. Tambov, 2003. 210 p. (Rus)

19. Berthiaux H., Mizonov V., Zhukov V. Application of the theory of Markov chains to model different processes in particle technology. *Powder Technology*, 2005, *157*(1–3), 128-137.

20. Dewicki G. Bulk Material Handling and Processing – Numerical Techniques and Simulation of Granular Material, *Bulk Solids Handling*, 2003, *23*(2), 1-4.

21. Makarov A.S., Popova A.A., Shubin I.N. Jenergojeffektivnoe universal'noe oborudovanie dlja pererabotki dispersnyh sred [Energy-efficient universal equipment for the processing of dispersed media]. *Materialy I Vseros. konf. s mezhdunar. uchastiem "Importozameshhajushhie tehnologii i oborudovanie dlja glubokoj kompleksnoj pererabotki sel'skohozjajstvennogo syr'ja"*. Tambov, 2019, 179-183. (Rus)

22. Tarov D.V., Gurova T.V., Shubin I.N. Apparaturnoe oformlenie funkcionalizacii nanotrubok stearatom titana [Hardware design of functionalization of nanotubes with titanium stearate]. *Vestnik Tambovskogo gosudarstvennogo tehnicheskogo universiteta*, 2015, *2*(2), 360-366. (Rus)

23. Pocherevin A.V., Svetlov S.A. Issledovanie vlijanija parametrov processa smeshivanija na odnorodnost' prigotavlivaemyh smesej v planetarnom smesitele [Investigation of the effect of mixing process parameters on the uniformity of prepared mixtures in a planetary mixer]. *Mezhdunarodnyj nauchno-issledovatel'skij zhurnal*, 2016, *4*(46), part 2, 151-155. doi: https://doi.org/10.18454/IRJ.2016.46.093 (Rus)

24. Bakalov V.G., Aleksandrov M.V., Mihalev M.F., Bolkunov O.A Kriterij dlja ocenki kachestva smesi [Criterion for evaluating the quality of the mixture]. *Zhurn. prikl. himii*, 1984, *4*, 1045-1048. (Rus)

25. Sviridov M.M., Chervjakov V.M. Peremeshhenija komponentov v processe smeshivanija sypuchih materialov [Component movements during the mixing of bulk materials]. *Vestnik Tambovskogo gosudarstvennogo tehnicheskogo universiteta*, 2002, *8*(3), 450-454. (Rus)

26. Sviridov M.M., Tarov V.P., Shubin I.N. Tekuchest' sypuchego materiala [Bulk material flow]. *Vestnik Tambovskogo gosudarstvennogo tehnicheskogo universiteta*. 1999, *5*(4), p. 55. (Rus)

27. Ivzhenko V.V., Popov V.A., Sarnavskaja G.F. Issledovanie processa smeshivanija termoplastichnyh mass na osnove poroshkov tugoplavkih soedinenij i parafina [Investigation of the process of mixing thermoplastic masses based on powders of refractory compounds and paraffin]. *Sverhtverdye mater*., 2008, *3*, 56-61. (Rus)

28. Verigin A.N., Panferov A.A., Emel'janov M.V., Nezamaev N.A. Kachestvo smeshivanija mnogokomponentnyh dispersnyh materialov [Mixing quality of multicomponent dispersed materials]. *Izvestija SPbGTI (TU)*, 2015, *31*, 75-83 (Rus)

29. Kosjakov A.V., Kropotov L.M., Kalygin V.G. Ocenka kachestva smeshenija mnogokomponentnyh polidispersnyh poroshkovyh materialov [Evaluation of the quality of mixing multicomponent polydisperse powder materials]. *Tez. dokl. Vsesojuzn. konf. po tehnologii sypuchih materialov.* Jaroslavl, 1989, *2*, 87-88. (Rus)

30. Bytev D.O. Stohasticheskoe modelirovanie processov smeshenija sypuchih materialov [Stochastic modeling of bulk materials mixing processes]. *Tez. dokl. Vsesojuzn. konf. po tehnologii sypuchih materialov.* Jaroslavl, 1989, *2*, 74-77. (Rus)

31. Pershin V.F., Alsajjad T.H.K., Pasko T.V., Pasko A.A. Opredelenie uglov i kojefficientov trenija uglerodnyh nanomaterialov [Determination of angles and friction coefficients of carbon nanomaterials]. *Polzunovskij vestnik*, 2018, *4*, 184-188. (Rus)

32. Simbircev N.A. *Osnovy tehnologii podgotovki dispersnyh materialov pri pererabotke jenergeticheskih kondensirovannyh sistem. V 2 ch. ch.1. Izuchenie svojstv i podgotovka dispersnyh materialov* [Fundamentals of technology for the preparation of dispersed materials in the processing of energy condensed systems. In 2 parts. Part 1. Studying properties and preparing dispersed materials]. Moscow: Evrika, 2006, 191 p. (Rus)

33. Ruhov, A.V., Tarov D.V., Dyachkova T.P., Orlova N.V., Shubin I.N., Tarov V.P. Metodika proektirovanija apparaturnogo oformlenija proizvodstv uglerodnyh nanotrubok i poluproduktov na ih osnove [Technique for designing the hardware design for the production of carbon nanotubes and intermediates based on them]. *Izvestija vysshih uchebnyh zavedenij. Serija Himija i himicheskaja tehnologija*, 2019, *3*, 94-101. (Rus)

34. Guo D., Xie G., Luo J.. Mechanical properties of nanoparticles: Basics and applications. *Journal of Physics D Applied Physics* 2014, *47*(1), 3001, doi: 10.1088/0022-3727/47/1/013001

35. Čitaković N. Physical properties of nanomaterials, *Vojnotehnički glasnik. Military technical courier*, 2019, *67*(1), 159-171. doi: 10.5937/vojtehg67-18251

36. Ghorai Suman. *Chemical, physical and mechanical properties of nanomaterials and its applications*. PhD (Doctor of Philosophy) thesis, University of Iowa, 2013. https://doi.org/10.17077/etd.5r1xf0y8