




Directed Fluidized Bed in Vortex Granulators: Optimization Calculation of Hydrodynamic Characteristics

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Abstract. The article deals with the study of main hydrodynamic characteristics of the directed fluidized bed in vortex granulators. The algorithm to calculate hydrodynamic characteristics of the directed vortex fluidized bed in the granulator's workspace is described. Every block of algorithm has theoretical model of calculation. Principles of granules' motion in various areas in the vortex granulator with variable heightwise workspace area are established. The software realization of author's mathematic model to calculate granules' motion trajectory in free and constrained regime, granule's residence time in the granulator's workspace, poly-disperse systems classification is proposed in the study. Calculations of granule's motion hydrodynamic characteristics using the software product ANSYS CFX, based on the author's mathematic model, are presented in the article. The software product enables to automatize calculation simultaneously by several optimization criteria and to visualize calculation results in the form of 3D images. The fields of the granules' vortex flows velocity are obtained, principles of wide fraction granules' distribution in the workspace of the vortex granulator are fixed. The way to define granule's residence time in the workspace of the vortex granulator in free (without consideration of cooperation with other granules and granulator's elements) and constrained motion regimes is proposed in the research. The calculation results make a base for optimal choice of the granulator's working chamber sizes.

Keywords: Vortex granulator · Directed fluidized bed · Software · Hydrodynamics · Motion trajectory · Residence time · Free and constrained motion

1 Introduction

Creation of the fluidized bed directed motion thanks to the selection of workspace optimal configuration in the device and implementation of the gas flow accelerating elements (swirlers) enable to form disperse phase motion, controlled in time. The workspace rational construction, optimum flow of heat transfer agent and its temperature-humidity characteristics in every block of the granulation module are searched due to the optimization criterion “minimum “hydrodynamic” residence time of the disperse phase in the device's

workspace". "Hydrodynamic" time has not to exceed "thermodynamic" time – that is time, by which temperature-humidity characteristics of the disperse phase must have normative value. The directed vortex fluidized bed enables to control "hydrodynamic" residence time of the disperse phase in the device's workspace.

The urgent scientific and practical tasks are to define principles of the twisted flows in the axysymmetrical channels when they are used in the granulation technology [1]. Ways to solve these tasks are to investigate new mathematic models, which will describe hydrodynamic characteristics of the flows motion, to create software computer modeling of the flows motion hydrodynamics, and to implement author's mathematic models in hydrodynamic processes modeling in the modern software products.

Today scientists from Sumy State University continue to work on theoretical description and experimental investigation of the vortex flows motion hydrodynamics and granulation process kinetics in the devices with disperse phase twisting [2–6]. Therefore, the main attention in further studies is paid to creation of the vortex granulators' automated optimization calculation, based on the theoretical base, developed earlier [7–9].

Aim of the work is to create mathematic tool, which will describe two-phase flow hydrodynamics in the vortex granulator's workspace, and software implementation of the created mathematic model.

Methodology. The demonstrated results are obtained through computer modeling on the model, formed in accordance with an experimental-industrial sample of the vortex granulator, based on the analytical model of the two-phase flows motion hydrodynamics.

Results. The hydrodynamic characteristics of two-phase flows, based on the software implementation of the hydrodynamics analytical model are obtained. The model is implemented in the software product ANSYS via author's mathematic model for calculations.

Scientific novelty. It is demonstrated that analytical models implementation to calculate hydrodynamics of two-phase flows in the software products, enables to perform optimization constructive calculation of the vortex granulator with heightwise variable cross sectional area.

Practical significance. The presented results of computer modeling together with theoretical investigations, carried out earlier, regarding flows motion hydrodynamics and experimental data give base to develop the vortex granulator's engineering calculation technique.

This article continues the work [10], where fundamentals of two-phase vortex flow modeling are observed. In this research a new approach to study hydrodynamics of the granules' constrained vortex motion is proposed and the author's approach to define granule's residence time in the device under conditions of their cooperation with other particles and vortex granulator's elements is developed.

2 Theoretical Bases of Modeling

In order to model two-phase flows, in which granules compose a disperse phase, Lagrange approach is used. Based on this approach, disperse phase motion, influenced by continuous phase is observed. Unlike the gas flow description models (in this case one may disregard mass force as a result of phase's small density), it is obligatory to

analyze active forces, which influence the disperse phase, in granule's motion description [3]. Besides, under conditions of the granules' constrained motion, it is necessary to take into account changing of the disperse phase trajectory and its residence time in the vortex granulator's workspace, depending on relative ratio of granules in the device [6].

The continuous phase flow, streaming of which is modeled by Navier-Stokes equations and by continuity equation (as it is shown in [2]), gives the disperse flow part of the motion quantity moment. When the disperse phase appears in the working volume of the device, it is drawn into the circular motion thanks to the gas flow energy. Therefore, input of the disperse phase into the continuous phase flow will cause great changes in the circumferential component of the gas flow velocity V_φ .

Thus, author proposes the following algorithm of the calculation, block-scheme of which is demonstrated in Fig. 1.

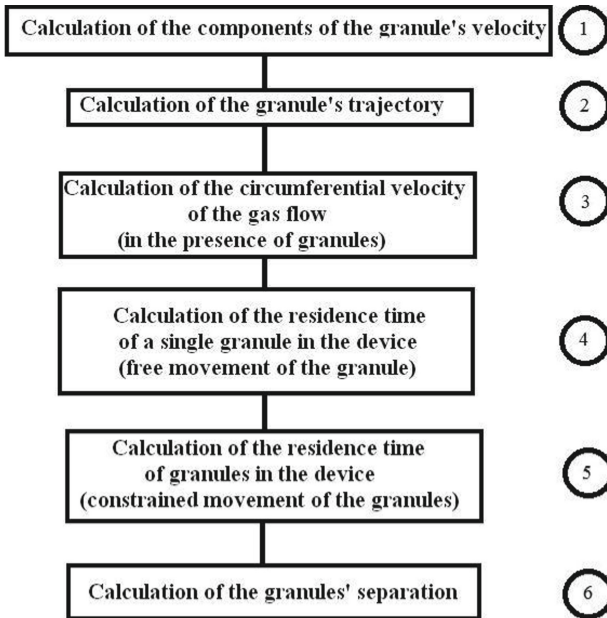


Fig. 1. Block-scheme of the algorithm of vortex granulator's hydrodynamic characteristics calculation.

Blocks 1

Equations system of the granule's motion:

$$\left. \begin{aligned} \frac{dW_r}{d\tau} &= \frac{W_\varphi^2}{r} + \psi \cdot \frac{\pi \cdot \mu_g \cdot d_{gr}}{8 \cdot m} (V_r - W_r), \\ \frac{dW_\varphi}{d\tau} &= -\frac{W_r W_\varphi}{r} + \psi \cdot \frac{\pi \cdot \mu_g \cdot d_{gr}}{8 \cdot m} (V_\varphi - W_\varphi), \\ \frac{dW_z}{d\tau} &= -g + \psi \cdot \frac{\pi \cdot \mu_g \cdot d_{gr}}{8 \cdot m} (V_z - W_z), \end{aligned} \right\} \quad (1)$$

where W_r, W_φ, W_z – radial, circumferential and axial (vertical, rate) components of the granule's motion; m – mass of the granule; τ – time; r – current radius of the vortex granulator's workspace; g – gravity acceleration; ψ – linear coefficient of the granule's resistance to the gas flow; μ_g – gas flow viscosity; d_{gr} – diameter of the granule.

Blocks 2

In order to find the granule's motion trajectory, we will write the equations system (1) taking into account the fact that granule during time τ passes some way in the radial S_r , circumferential S_φ and vertical S_z directions:

$$\left. \begin{aligned} m \frac{d^2 S_r}{d\tau^2} &= \frac{W_\varphi^2}{r} + \psi \cdot \frac{\pi \cdot \mu_g \cdot d_{gr}}{8 \cdot m} (V_r - W_r), \\ m \frac{d^2 S_\varphi}{d\tau^2} &= -\frac{W_r W_\varphi}{r} + \psi \cdot \frac{\pi \cdot \mu_g \cdot d_{gr}}{8 \cdot m} (V_\varphi - W_\varphi), \\ m \frac{d^2 S_z}{d\tau^2} &= -g + \psi \cdot \frac{\pi \cdot \mu_g \cdot d_{gr}}{8 \cdot m} (V_z - W_z), \end{aligned} \right\} \quad (2)$$

The equations system solving (2) towards variable S in each direction is carried out for definite time of the granule's motion inside the granulator's case.

Blocks 3

Moment of the gas phase motion quantity with absence of disperse phase in the working volume

$$M_g = 2 \cdot \pi \cdot \rho_g \cdot V_\varphi \cdot r_{gr}^2 drdz, \quad (3)$$

where ρ_g – gas flow density, r_{gr} – radius of the granule.

Moment of the gas phase motion quantity after cooperation with disperse phase in the working volume

$$M'_g = 2 \cdot \pi \cdot \rho_g \cdot V'_\varphi \cdot r_{gr}^2 drdz, \quad (4)$$

where V'_φ – circumferential velocity of the gas flow after cooperation with disperse phase.

Moment of the gas phase motion quantity, which is gained after cooperation with gas flow

$$M_d = m \cdot W_\varphi \cdot r_{gr}. \quad (5)$$

Due to the ratio between disperse phase and gas flows rates Q_{gr}/Q_g , Eq. (5) will be

$$M_d = 2 \cdot \pi \cdot \rho_{gr} \cdot \left(\frac{Q_{gr}}{Q_g} \right) W_\varphi \cdot r_{gr}^2 \cdot drdz, \quad (6)$$

where ρ_{gr} – the granule's density.

According to [3] we write down equality

$$M_g = M'_g + M_d, \quad (7)$$

or

$$\rho_g \cdot V_\varphi = \rho_g \cdot V'_\varphi + \rho_{gr} \cdot \left(\frac{Q_{gr}}{Q_g} \right) W_\varphi. \quad (8)$$

In this case the circumferential velocity of the gas flow after cooperation with disperse phase is

$$V'_\varphi = V_\varphi - \frac{\rho_{gr}}{\rho_g} \cdot \left(\frac{Q_{gr}}{Q_g} \right) W_\varphi. \quad (9)$$

Blocks 4, 5

In case of the granule's free motion its residence time in the granulator's working area is determined by solving of the third differential equation of the system (1) regarding granule's motion in the vertical direction.

The free motion of granule is observed only with small volume content of the disperse phase in two-phase system ($\phi < 0.1$). In this case distance between granules enables to avoid crashes and mutual impact on each other. If $\phi > 0.1$ distance between surfaces of granules (size of pass) become smaller than their diameter, granule cannot easy jump between two others. In this case it is necessary to consider granules' crash effect between each other. The granules' crash in two-phase system can appear when disperse phase consists of polydisperse granules (that relates to the observed process). Besides, the granule's motion in the surrounding gas environment forms velocity and pressure fields. Other granules, which compose the so called assembly, and granulator's walls, have hydrodynamic impact on the granule.

Consideration of such hydrodynamic situation and calculation of the granule's motion velocity (or its residence time in the device) in the constrained motion regime is an important factor in description of two-phase vortex flow hydrodynamics.

This study proposes to take into account terms of the constrained motion in calculation of the granules' residence time in the workspace of the device in the following way

$$\tau_{st} = \tau_{fet}(\phi), \quad (10)$$

where τ_{st} – the granule's residence time in the workspace of the device under conditions of granule's constrained motion; τ – residence time of the single granule in the workspace

of the device; $f_{et}(\phi)$ – empiric function of the constraint impact on the granule’s residence time in the workspace of the device.

Function $f_{et}(\phi)$ is:

$$f_{et}(\phi) = (1 - \phi)^{-m}, \tag{11}$$

where m – empiric index (constraint coefficient for time calculation).

Results of investigations [7] show that it is necessary to distinguish three zones of the gas flow motion and of granules heightwise of the device in the vortex granulator’s workspace (Fig. 2). In every zone intensity of gas flow and granules’ motion is determined by the velocity’s components and preferential direction of the total velocity.

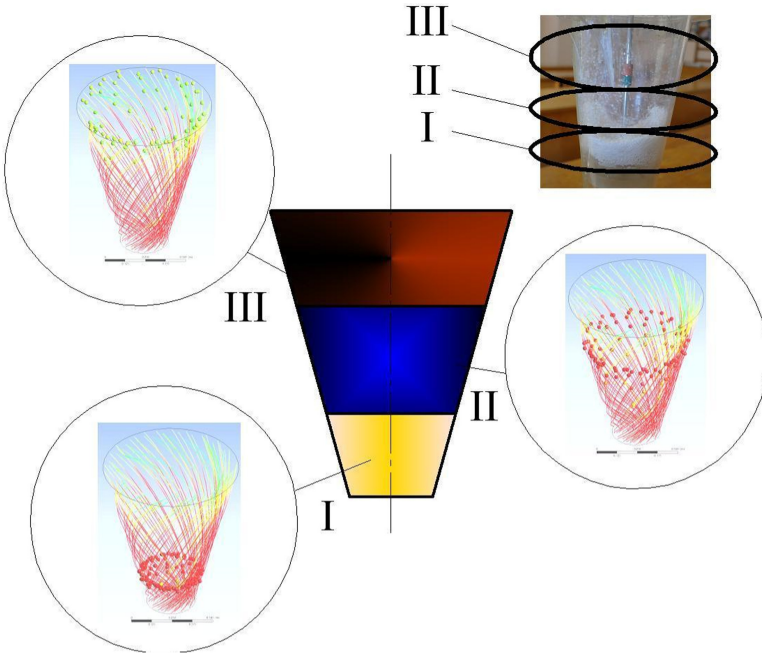


Fig. 2. Main zones of granules’ motion in the vortex granulator [7]: I – zone of the granules’ preferential vortex motion; II – zone of the granules’ combined vortex and ascendant motion; III – zone of the granules’ preferential ascendant motion.

Under conditions of the granule’s constrained motion, constrain coefficient and granule’s residence time is defined individually for zones I, II, III.

Results of investigations [8] let to determine values of the parameter m in every granulator’s zone by formula (11): zone I – $m = 1.7-1.74$; zone II – $m = 1.46-1.49$; zone III – $m = 1.1-1.13$.

Thus, total residence time of granules in the constrained motion regime is calculated by formula

$$\sum \tau_{cm} = \tau_{cm}^I + \tau_{cm}^{II} + \tau_{cm}^{III} = \tau^I (1 - \phi^I)^{-m^I} + \tau^{II} (1 - \phi^{II})^{-m^{II}} + \tau^{III} (1 - \phi^{III})^{-m^{III}}, \tag{12}$$

where an average value of ϕ in every zone depends on average porosity of the weighted layer ε [9] and is calculated by the formula

$$\phi_i = 1 - \varepsilon_i. \tag{13}$$

According to data of experimental studies to determine the optimal construction of the gas distributor device and its impact on the vortex weighted layer stability [10] one proposes the following diapasons of average values ϕ in every zone of vortex granulator, which will be implemented in computer modeling and in further engineering calculation of the medium-powered device: zone I – $\phi = 0.48-0.53$; zone II – $\phi = 0.35-0.4$; zone III – $\phi = 0.2-0.24$.

Blocks 6

Based on the force analysis (Fig. 3), formulas to find conditions of granules' classification in the granulator's workspace with heightwise variable cross sectional area of the workspace are received [6]:

- Velocity of the gas flow, which confirms the condition of granule's (with size r_{gr}) balance

$$V_{op} = 1,63 \cdot \sqrt{\frac{\rho_{gr} \cdot g \cdot r_{gr}}{\psi \cdot \rho_g}}. \tag{14}$$

- height of the current location of the granule in size r_{gr}

$$Z = 1,584 \sqrt{\frac{Q_g}{tg\varphi^2 \cdot \sqrt{\frac{\rho_{gr} \cdot g \cdot r_{gr}}{\psi \cdot \rho_g}}}}. \tag{15}$$

- radius of the granulator's lower cross section, if granules with maximum size r_{max} are located in the polydisperse system

$$R_0 = 0,442 \sqrt{\frac{Q_g}{\sqrt{\frac{\rho_{gr} \cdot g \cdot r_{max}}{\psi \cdot \rho_g}}}}. \tag{16}$$

- height in accordance with Fig. 3

$$Z_1 = Z - Z_0, \tag{17}$$

$$Z_0 = R_0/tg\varphi. \tag{18}$$

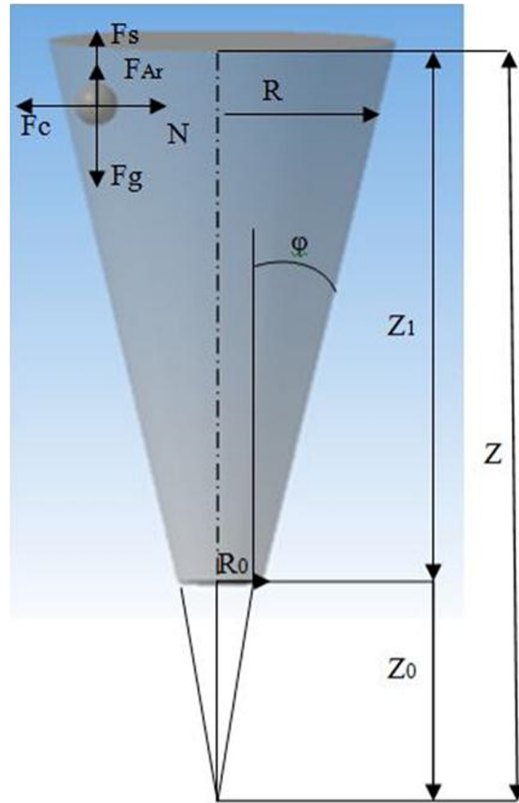


Fig. 3. Calculation model of the vortex granulator's workspace [6]: Z – total height of the cone; Z_0 – height of the gas distributor unit; Z_1 – height of the granulator's workspace; ϕ – half of the cone angle; R_0 – radius of the gas distributor; R – present radius of the workspace; F_g – gravity force; F_s – drag force; F_{Ar} – Archimedes force; F_c – centrifugal force; N – response of the wall.

3 Results of Studies, Analysis and Comparison of Theoretical and Experimental Data

Some results after calculation of granule velocity's components in the vortex granulator's workspace are shown in Fig. 4. Fields of the granule's velocities enable to find resultant velocity of the disperse phase. This velocity and its direction vector compose the base to calculate granules' motion trajectory and their "hydrodynamic" residence time in granulator.

Analysis of the previous works in the two-phase flows modeling sphere, consisting of gas (disperse phase) and disperse particles, shows that one of the most perspective ways to calculate particles' motion is the trajectory method [11]. Authors [12, 13] conclude that Lagrangian model of the particles' motion force analysis via motion differential equations, which was implemented to describe hydrodynamic conditions of the disperse phase motion in the vortex granulator's workspace can be the basis in the constrained motion modeling of particles with large diameter (0.5–5 mm) [14]. At the same time,

implementation of the trajectory method for granules' motion in the vortex granulator's workspace is complicated by the following factors:

- polydispersity of the system;
- constrained motion of granules in the vortex granulator.

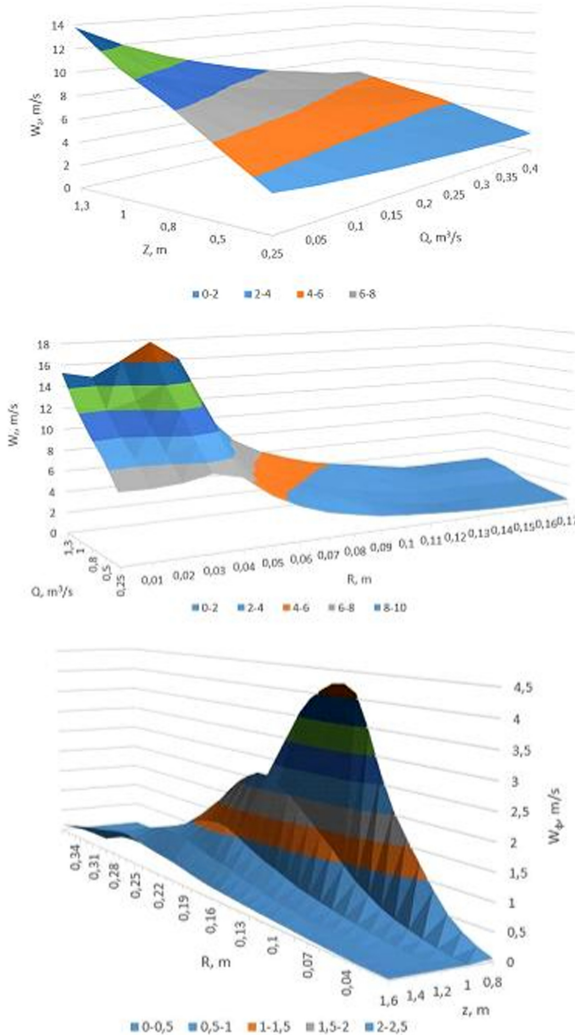


Fig. 4. Components of the granule's velocity in the vortex granulator's workspace.

Nevertheless, the trajectory method with accurate obtained results can be implemented only if there is the software, which enables to export theoretical model of singular particle's motion and to consider degree of the flow constraint.

In this research the software product ANSYS FLUENT is used to export an author's mathematic model, to calculate granules' motion trajectory and polydisperse system distribution law in the granulator's workspace considering granules concentration (degree of the flow constraint) [15].

The Fig. 5 demonstrates motion trajectory of the granules' polydisperse composition in the vortex granulator with different configuration of the workspace. Based on the computer modeling results, it is possible to observe division of granules into separate zones by fractions - large (or heavy) granules are concentrated in the lower cross section, small non-commodity fraction enters the separation zone. Besides, height of every fraction zone is changed in inverse proportion to the cone angle given steady parameters of the heat transfer agent.

The granulator's working regime starting process is demonstrated in this figure. The granules' separation and classification processes are clearly expressed – tiny particle get to the vortex granulator's separation zone, and large fraction is classified by size, is thrown away to walls and moves along the spiral trajectory.

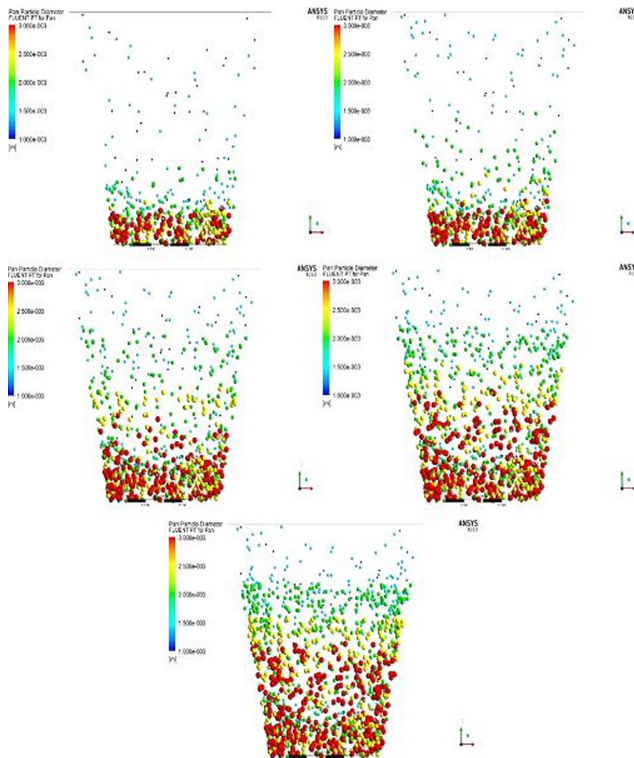


Fig. 5. The granulator's working regime starting process (demonstration of data on calculation by the theoretical model).

Theoretical calculations and computer modeling results are confirmed by experimental studies of the granulator's working regime starting process. Evolution of this process is shown in Fig. 6.

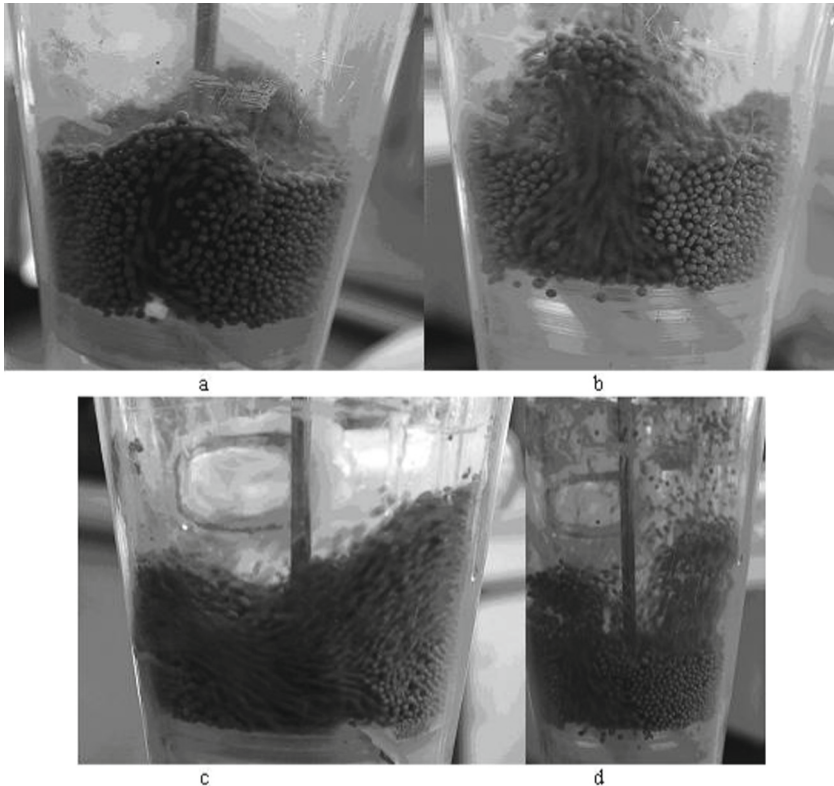


Fig. 6. Development of the vortex fluidized bed (evolution of the granules' motion trajectory): a - starting of the layer horizontal movement; b - combined motion of granules; c - vortex motion of granules; d - vortex motion of granules with partial separation of tiny granules.

Such trajectories analysis shows that:

- increase of the gas flow rate and cone angle of the vortex granulator's workspace leads to reduction of the spiral turns amount, growth of their pitch and decrease of granule's residence time in the vortex granulator's workspace;
- increase of the gas flow initial twisting degree (it is defined by the angle of tilt of swirler's vanes and by their number) and granule's diameter change its motion trajectory thanks to spiral turns number increase, reduction of their pitch, upper spiral turn diameter increase and increase of the granule's residence time in the vortex granulator's workspace.

Granules are moving along the wall of the vortex granulator and are not practically hold in its central zone. It is explained by the direction of total velocity vector action of their motion from center to periphery owing to the domination of granule's motion radial component up to two thirds of the device's radius. The radial component influence decreases close to the granulator's walls, granules are drawn into the rotating movement with vertical transfer.

In general, spiral trajectories of the granules' motion depending on its properties and vortex granulator's construction differ by number of turns and pitch between them, and also by the diameter of lower and upper spiral turn. It causes the fact that granule gets over different way in length in the vortex granulator's workspace that has an impact on its contact time with gas flow.

Analysis of the calculation results shows that as the granule moves from center to the wall, total velocity vector is changed in the direction depending on this or that component predominance. At the initial moment of time granule is moving from the axis of the device perpendicular to it owing to its velocity's radial component predominance. Granules are drawn into the vortex motion when they get closer to the vortex granulator's half radius, owing to its velocity's circumferential component predominance. At the granulator's wall granules move along spiral trajectories with gradual movement in vertical direction thanks to the impact increase of its velocity's rate component; motion trajectory is not changed till reaching of the vortex granulator's upper cross section.

The clearly demonstrated granules' motion trajectory in the developed vortex layer regime (Fig. 6c) and clear division of the polydisperse system into fractions (Fig. 7) give ground to confirm the appropriateness of the modeling results.

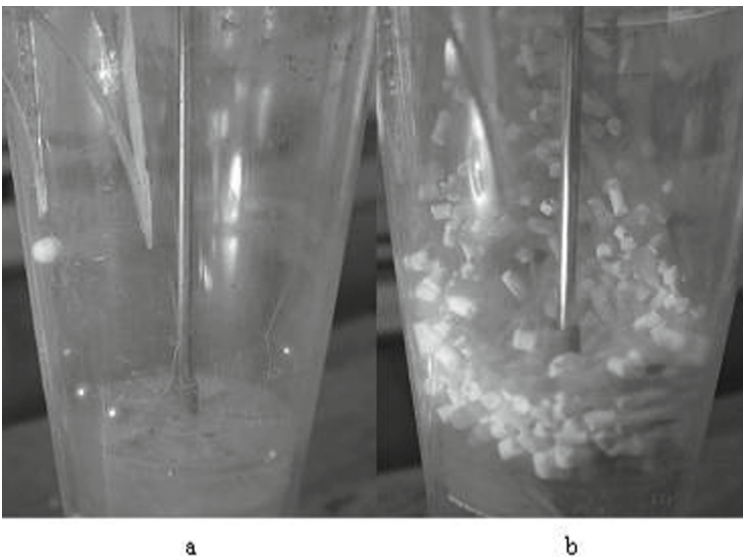


Fig. 7. Distribution of granules in the vortex granulator's workspace [6]: a – wide fraction composition of the polydisperse system; b – narrow fraction composition of the polydisperse system.

4 Conclusion and Recommendations

The algorithm to calculate hydrodynamic characteristics of two-phase flow in the vortex granulator's workspace, proposed in the article, enables to perform optimization projecting by the criterion of minimum required time of granules' contact with high-temperature heat transfer agent. The received results of the computer modeling based on the proposed algorithm let to predict granule's behavior with various physical and chemical properties in the working volume of the device. Therefore, it is important to observe conditions, under which the granule's "hydrodynamic" residence time in the workspace of the device must not be less than "thermodynamic" time (this parameter is defined by kinetics of the granule's dehydration process) [16–20]. The optimal construction of the vortex granulator, which satisfies optimization criterion requirements, is achieved by the regulation of hydrodynamic characteristics of the flows motion.

The aim of further studies is to model the vortex granulator's work under conditions of different constraint flow degree and to create "hybrid" calculation model, which will include both author's software products and present tools for calculation of thermodynamics and heat and mass transfer in devices with active hydrodynamic regimes.

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References

1. Artyukhova, N.A., Shandyba, A.B., Artyukhov, A.E.: Energy efficiency assessment of multi-stage convective drying of concentrates and mineral raw materials. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*. (1), 92–98 (2014). <http://nv.nmu.org.ua/index.php/en/archive/on-the-issues/887-2014/contents-no-1-2014/power-supply-technologies/2472-energy-efficiency-assessment-of-multi-stage-convective-drying-of-concentrates-and-mineral-raw-materials>. (in Russian)
2. Artyukhov, A., Sklabinskyi, V.: Theoretical analysis of granules movement hydrodynamics in the vortex granulators of ammonium nitrate and carbamide production. *Chem. Chem. Technol.* **9**(2), 175–180 (2015). <https://doi.org/10.23939/chcht09.02.175>
3. Artyukhov, A., Sklabinskyi, V.: Hydrodynamics of gas flow in small-sized vortex granulators in the production of nitrogen fertilizers. *Chem. Chem. Technol.* **9**(3), 337–342 (2015). <https://doi.org/10.23939/chcht09.03.337>
4. Artyukhov, A.E.: Optimization of mass transfer separation elements of columnar equipment for natural gas preparation. *Chem. Pet. Eng.* **49**(11–12), 736–741 (2014). <https://doi.org/10.1007/s10556-014-9827-8>
5. Prokopov, M.G., Levchenko, D.A., Artyukhov, A.E.: Investigation of liquid-steam stream compressor. *Appl. Mech. Mater.* **630**, 109–116 (2014). <https://doi.org/10.4028/www.scientific.net/AMM.630.109>

6. Artyukhov, A.E., Fursa, A.S., Moskalenko, K.V.: Classification and separation of granules in vortex granulators. *Chem. Pet. Eng.* **51**(5–6), 311–318 (2015). <https://doi.org/10.1007/s10556-015-0044-x>
7. Artyukhov, A.: Application software products for calculation trajectories of granules movement in vortex granulator. In: *CEUR Workshop Proceedings, Selected Papers of the XI International Scientific-Practical Conference Modern Information Technologies and IT-Education (SITITO 2016), Moscow, Russia, 25–26 November 2016*, vol. 1761, pp. 363–373 (2016). <http://ceur-ws.org/Vol-1761/paper47.pdf>
8. Artyukhov, A., Sklabinskiy, V., Ivaniia, A., Moskalenko, K.: Software for calculation of vortex type granulation devices. In: *CEUR Workshop Proceedings, Selected Papers of the XI International Scientific-Practical Conference Modern Information Technologies and IT-Education (SITITO 2016), Moscow, Russia, 25–26 November 2016*, vol. 1761, pp. 374–385 (2016). <http://ceur-ws.org/Vol-1761/paper48.pdf>
9. Artyukhov, A.E., Obodiak, V.K., Boiko, P.G., Rossi, P.C.: Computer modeling of hydrodynamic and heat-mass transfer processes in the vortex type granulation devices. In: *CEUR Workshop Proceedings, Proceedings of the 13th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer, Kyiv, Ukraine, 15–18 May 2017*, vol. 1844, pp. 33–47 (2017). <http://ceur-ws.org/Vol-1844/10000033.pdf>
10. Artyukhov, A.E.: Calculation of hydrodynamic indicators of vortex granulators working: program implementation of the mathematical model. *Mod. Inf. Technol. IT-Educ.* **13**(2), 215–222 (2017). <https://doi.org/10.25559/SITITO.2017.2.246>
11. Polyaniin, A.D., Kutopov, A.M., Vyazmin, A.V., Kazenin, D.A.: *Hydrodynamics, Mass and Heat Transfer in Chemical Engineering*. Taylor and Francis, London (2001). <https://doi.org/10.1201/9781420024517>
12. Bowman, K.P., et al.: Input data requirements for Lagrangian trajectory models. *Bull. Am. Meteorol. Soc.* **94**(7), 1051–1058 (2013). <https://doi.org/10.1175/BAMS-D-12-00076.1>
13. Chen, X.Q., Pereira, J.C.F.: Computation of particle dispersion in turbulent liquid flows using an efficient Lagrangian trajectory model. *Int. J. Numer. Methods Fluids* **26**(3), 345–364 (1998). [https://doi.org/10.1002/\(SICI\)1097-0363\(19980215\)26:3%3c345::AID-FLD636%3e3.0.CO;2-G](https://doi.org/10.1002/(SICI)1097-0363(19980215)26:3%3c345::AID-FLD636%3e3.0.CO;2-G)
14. Reynolds, A.M., LoIacono, G.: On the simulation of particle trajectories in turbulent flows. *Phys. Fluids* **16**(12), 4353–4361 (2004). <https://doi.org/10.1063/1.1804551>
15. Rybalko, M., Loth, E., Lankford, D.: A Lagrangian particle random walk model for hybrid RANS/LES turbulent flows. *Pow. Technol.* **221**, 105–113 (2012). <https://doi.org/10.1016/j.powtec.2011.12.042>
16. Artyukhov, A.E., Sklabinskiy, V.I.: Experimental and industrial implementation of porous ammonium nitrate producing process in vortex granulators. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu.* (6), 42–48 (2013). <http://nvngu.in.ua/index.php/en/monographs/862-engcat/archive/2013/contents-no-6-2013/geotechnical-and-mining-mechanical-engineering-machine-building/2398-experimental-and-industrial-implementation-of-porous-ammonium-nitrate-producing-process-in-vortex-granulators>. (in Russian)
17. Artyukhov, A.E., Sklabinskiy, V.I.: 3D nanostructured porous layer of ammonium nitrate: influence of the moisturizing method on the layer's structure. *J. Nano- Electron. Phys.* **8**(4), 04051 (2016). [https://doi.org/10.21272/jnep.8\(4\(1\)\).04051](https://doi.org/10.21272/jnep.8(4(1)).04051)
18. Artyukhov, A.E., Voznyi, A.A.: Thermodynamics of the vortex granulator's workspace: the impact on the structure of porous ammonium nitrate. In: *2016 International Conference on Nanomaterials: Application & Properties (NAP), Lviv*, pp. 02NEA01-1–02NEA01-4 (2016). <https://doi.org/10.1109/NAP.2016.7757296>

19. Artyukhov, A.E.: Kinetics of heating and drying of porous ammonium nitrate granules in the vortex granulator. In: 2016 International Conference on Nanomaterials: Application & Properties (NAP), Lviv, pp. 02NEA02—02NEA02-3 (2016). <https://doi.org/10.1109/NAP.2016.7757297>
20. Artyukhov, A.E., Sklabinskyi, V.I.: Thermodynamic conditions for obtaining 3D nanostructured porous surface layer on the granules of ammonium nitrate. *J. Nano- Electron. Phys.* **8**(4), 04083-1–04083-4 (2016). [https://doi.org/10.21272/jnep.8\(4\(2\)\).04083](https://doi.org/10.21272/jnep.8(4(2)).04083)