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THEORETICAL ANALYSIS OF GRANULES MOVEMENT HYDRODYNAMICS IN THE VORTEX GRANULATORS OF AMMONIUM NITRATE AND CARBAMIDE PRODUCTION

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Abstract. Mathematical calculations for determining the hydrodynamic characteristics of granules movement in the workspace of the vortex granulator, which is the main ultimate process of chemical technology and forms properties of ordinary and porous ammonium nitrate and carbamide, are presented in this paper. Components of a granule velocity and the granulator design impact on them are analytically determined. Comparison of theoretical and experimental studies is performed.

Keywords: vortex granulator, granule, ammonium nitrate, carbamide, hydrodynamics, trajectory, velocity.

1. Introduction

The chemical technology of obtaining granulated ammonium nitrate (NH_4NO_3) and carbomide ($CO(NH_2)_2$) focuses on a hardware support of the melts granulation stage in the granulation towers and fluid bed apparatuses. Considering a constant increase of NH_4NO_3 and $CO(NH_2)_2$ production in domestic and foreign chemical industries the problem of improvement of existing designs of granulation devices used in chemical processes and development of new equipment with new techniques of flow movement is urgent.

Production of granules with special features, including production of porous ammonium nitrate (PAN), is distinguished as a separate branch of industry. At present, production of PAN is performed by the following methods.

1. Melt granulation in granulation towers with adding cellulating and modification agents.

The essence of this group of methods is that by distributing uniformly in the bulk of melt or solution of NH_4NO_3, cellulating substances evaporate when using such stages of chemical technology as crystallization and drying. As a result, voids and capillaries are formed in the product granules increasing its absorption properties. When adding nonvolatile cellulating substances with sorption properties to a solution or melt of nitre porosity of NH_4NO_3 granules increases both at the expense of the additives properties and the creation of synthetic melt crystallization centers, changing the crystal structure of the granules.

2. Heat treatment of granules.

Thermal methods of treatment are based on the properties of NH_4NO_3 lattice that undergoes polymorphic transformations at certain temperatures that occur with a change in the volume of crystals. Under certain conditions, the granules increase in volume a little and become less dense and more porous.

3. Wetting and drying of granules.

This method is based on the fact that in NH_4NO_3 granules or crystals, in the process of their drying, the process of pore formation occurs. Moisture is removed in different ways: in devices that operate in a vacuum, in a series of rotating drums, or in fluid bed apparatus.

The main indicator of the PAN quality is its absorbing and holding capacities as compared with diesel fuel. Each of these methods provides the necessary values of these parameters: decreasing of the environmental performance of production (method 1), loss of granules strength (method 2), and plant flow diagram becomes more complicated (method 3). A promising method of obtaining PAN is combination of moisture and heat treatment methods in small vortex granulators [1].

The application of the vortex granulators in such processes of chemical industry is also characterized by their high specific power, relatively small size, process intensity and the ability to control the movement of granules in the structure formation [1].

Despite the widespread use of the vortex devices in various fields of chemical industry, such as granulation, theoretical description of the motion of the granules in the swirling gas flow needs further study. The trajectory of the granules movement depends on the hydrodynamic characteristics of their flow while in the working space of the vortex granulator, which ultimately affects the properties of the finished product. In turn, the distribution of the gas velocity components in the working space of the granulator, the design characteristics and mode conditions of its operation, as well as the physical and chemical properties of the granules influence the hydrodynamic motion parameters of the granule. The optimum combination of these parameters determines the trajectory of the granule which provides favorable conditions for its structural formation. In some granulation processes we have to ensure both a long-term (thermostable material) and a short-term (granulation of materials that are susceptible to modification under changing process thermodynamic conditions, obtaining a granule of porous structure) contact with a gas flow.

When producing PAN by moisture and heat treatment of ordinary NH_4NO_3 granules, it is necessary to create such conditions that polymorphic transformation would lead to an increase in its volume and porosity. Taking into account that each cycle of heat treatment leads to the destruction of the nucleus of NH_4NO_3 granule, the optimal temperature range is that one in which NH_4NO_3 undergoes minimal amount of modification changes. Thus, providing the necessary residence time of NH_4NO_3 granules in the workspace of the vortex granulator, which undergoes an impact of hydrodynamic movement conditions of the granule and its trajectory, it is possible to avoid overheating (intensive NH_3 release) or underheating (insufficient amount of removed moisture) of the granule.

This paper deals with solution of the scientific task of creation of optimal conditions for granule movement and is a continuation of a series of works dedicated to investigation of hydrodynamics of two-phase and single-phase vortex flows in small granulators for the production of ordinary and porous NH_4NO_3 and $CO(NH_2)_2$. The purpose of the work is to explore the flow field of granules based on analytical solutions of the equations of the mathematical model. The object of the study are small vortex devices for obtaining of a granulated product of NH_4NO_3 and $CO(NH_2)_2$. The purpose of the study relates to the hydrodynamic movement conditions of granules in the working space of the vortex granulator.

2. Theoretical Basis of the Granules Motion in the Working Volume of the Vortex Granulator

For simulation of two-phase flows, in which one of the phases in question is presented in the form of dispersed particles, the Lagrangian approach is used [2]. Based on this method, we examine the motion of the dispersed phase under the action of a continuous phase. The flow of the continuous phase, whose stream is modeled by the system of the Navier-Stokes equations and the equation of the flow continuity [3], gives up a part of the angular momentum to dispersed particles. In the case of liquid phase in the working volume of the device it is pulled into a rotary motion due to the energy of the gas flow [4]. To simplify the mathematical model it is assumed that the particles of the dispersed phase are of a globular shape with a uniform distribution of stresses on the surface [5].

Differential equations of the granule motion under the action of mass forces F_r, F_j, F_z in a cylindrical coordinate system [6]:

$$\left.\begin{aligned} j_r &= \frac{F_r}{m} = \frac{dW_r}{dt} - \frac{W_j^2}{r}, \\ j_j &= \frac{F_j}{m} = \frac{dW_j}{dt} + \frac{W_r W_j}{r}, \\ j_z &= \frac{F_z}{m} = \frac{dW_z}{dt}, \end{aligned}\right\} \quad (1)$$

where r – the current radius of the granulator working space; W_r, W_j, w_z – radial, circumferential, and axial (longitudinal) velocity components of the granules.

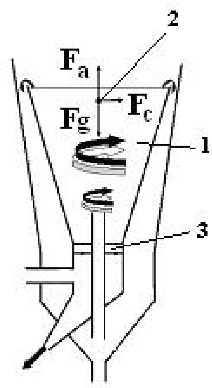


Fig. 1. Forces acting on a granule in a vortex granulator working space: granulator working space (1); granule (2) and gas distribution unit (3)

The motion dynamics equation of the granule:

$$m\frac{d\bar{W}}{dt} = \bar{F}_g + \bar{F}_c + \bar{F}_a, \quad (2)$$

where $\bar{F}_{gr}, \bar{F}_c, \bar{F}_a$ – gravity force, centrifugal force, and force of aerodynamic resistance, respectively (Fig. 1).

The values of forces modules are calculated according to the dependencies:

$$F_g = m \cdot g, \quad (3)$$

$$F_c = \frac{m \cdot W_j^2}{r}, \quad (4)$$

$$F_a = c \cdot \frac{p \cdot d_{gr}^2}{4} \cdot \frac{r_{gas} \cdot (V-W)^2}{2} =$$

$$= y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m} \cdot (V-W), \quad (5)$$

where m – mass of the granule of NH_4NO_3 or $CO(NH_2)_2$; g – acceleration of gravity; $c = y \,\mathrm{Re}$ – quadratic coefficient of the granule resistance to the gas flow [7]; ψ – linear coefficient of the granule resistance to the gas flow; ρ_{gas} – density of the gas flow; μ_{gas} – viscosity of the gas flow; d_{gr} – diameter of the granule of NH_4NO_3 or $CO(NH_2)_2$; V – velocity of the gas motion.

We replace the quadratic coefficient of the granule resistance to the gas flow by the linear coefficient in Eq. (5) considering the Stokes criterion.

The linear coefficient of the granule resistance to the gas flow, which is characterized by the mode of movement and the granule size, is determined according to [8]:

$$y = \begin{cases} 24/(\mathrm{Re} + 4/\mathrm{Re}^{0,33}) - at\ the\ value\ \mathrm{Re} < 1000 \\ 0.44 - at\ the\ value\ \mathrm{Re} \geq 1000 \end{cases} \quad (6)$$

The system of equations of granules motion:

$$\left.\begin{aligned} \frac{dW_r}{dt} &= \frac{W_j^2}{r} + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}(V_r - W_r), \\ \frac{dW_j}{dt} &= -\frac{W_r W_j}{r} + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}\left(V_j - W_j\right), \\ \frac{dW_z}{dt} &= -g + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}(V_z - W_z), \end{aligned}\right\} \quad (7)$$

where V_r, V_j, V_z – radial, circumferential and axial (longitudinal) gas velocity components, respectively.

The found system of equations (7) incorporates three equations and four unknown values to be determined.

The first derivative of the displacement in time is the velocity of the drop movement at the appropriate coordinate axes directions:

$$\frac{dr}{dt} = W_r; \ \frac{dj}{dt} = W_j; \ \frac{dz}{dt} = W_z, \quad (8)$$

where

$$dt = \frac{dr}{W_r}; dt = \frac{dj}{W_j}; dt = \frac{dz}{W_z}. \quad (9)$$

In view of (9), the system of Eq. (7) may be written as:

$$\left.\begin{aligned} \frac{dW_r}{dr}W_r &= \frac{W_j^2}{r} + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}(V_r - W_r), \\ \frac{dW_j}{dj}W_j &= -\frac{W_r W_j}{r} + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}\left(V_j - W_j\right), \\ \frac{dW_z}{dz}W_z &= -g + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}(V_z - W_z). \end{aligned}\right\} \quad (10)$$

The left side of the second equation of the system (10), incase of axisymmetry of the vortex gas flow equals to zero:

$$-\frac{W_r W_j}{r} + y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}\left(V_j - W_j\right) = 0. \quad (11)$$

Let's introduce the designation

$$a = y \cdot \frac{p \cdot m_{gas} \cdot d_{gr}}{8 \cdot m}. \quad (12)$$

Thus,

$$-\frac{W_r W_j}{r} + a \cdot \left(V_j - W_j\right) = 0. \quad (13)$$

Let's solve the Eq. (13) with respect to W_j :

$$W_j = \frac{a \cdot r \cdot V_j}{a \cdot r + W_r}. \quad (14)$$

Using (14) the first equation of the system (10) has the form:

$$\frac{dW_r}{dr}W_r = \frac{\left(\dfrac{a \cdot r \cdot V_j}{a \cdot r + W_r}\right)^2}{r} + a \cdot (V_r - W_r). \quad (15)$$

The Eq. (15) allows for setting the change pattern of the radial velocity component of the granule when setting data for calculation (ψ, m_{gas}, d_{gr}) and values of the radial and circumferential velocity components of the gas flow that are known in advance.

The third equation of the system (10) has the form:

$$\frac{dW_z}{dz}W_z = -g + a(V_z - W_z). \quad (16)$$

3. Results and Discussion

A numerical solution of the equations of the mathematical model allowed us to obtain basic graphic dependences of the hydrodynamic characteristics of the dispersed phase in a small conical vortex apparatus with a variable cross section over the height, showing the influence of the device working space geometry, process characteristics and the properties of the granules (particularly, density and diameter) on the velocity of their fields applied to chemical processes of nitrogen fertilizer or PAN production. The analysis of these graphical dependencies is presented below.

The following factors influence the value of the velocity components of the granules in the working space of the vortex granulator:

– velocity components of the gas flow in accordance with the law of conservation of angular momentum [2];

– magnitude and direction of mass forces according to the Eq. (2);

– properties of a dispersed phase (density and diameter);

– design of the vortex granulator.

The analysis of Figs. 2-4 shows that the law of variation of the circumferential velocity of the granule along the radius of the device in the ascending part is of identical character to the law of variation of the circumferential velocity of the gas flow. At that, the downward part of the functional dependence is smooth due to, firstly, the influence of the radial velocity component of the granule and secondly, the influence of inertial forces. The granule approaching the wall of the device reduces the intensity of the rotation about the axis of the device but proceeds with movement along a spiral trajectory.

The change of the radial velocity component of the granule is characterized by graphical dependencies in Figs. 5 and 6. The analysis showed that their ascending part repeats qualitative dependence of the circumferential velocity component of the gas flow due to the presence of this value in the calculation Eq. (15). The descending part of the functional dependence follows the variation law of the radial velocity component of the gas flow.

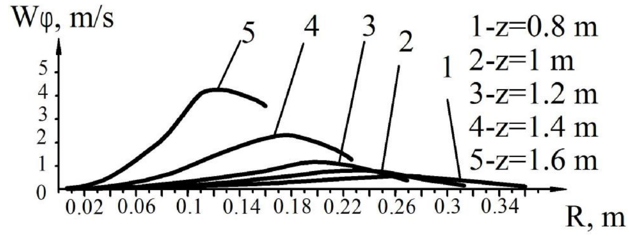


Fig. 2. The calculated change of the circumferential velocity of the granule depending on the height of the working space of the vortex granulator (at α = 13°, Q = 0.63 m^3/s) at different heights of the device

The calculation results of the longitudinal velocity component of the granule are shown in Figs. 7 and 8. According to the calculation conditions this is a monotonic curve with values reducing throughout the height of the vortex granulator (as a function of the reduction of the longitudinal component of the gas flow velocity). Similar to the law of changing the longitudinal velocity of the gas flow, the form of the graph is determined by the action of the gravity force and aerodynamic drag in the vertical axis.

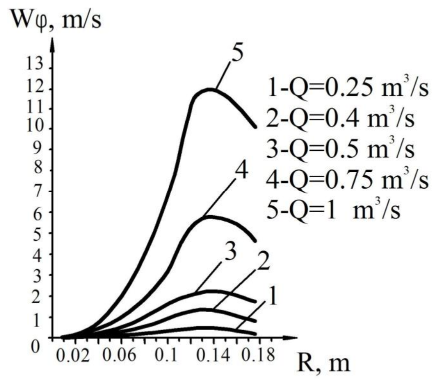


Fig. 3. The calculated change of the circumferential velocity of the granule depending on the gas flow rate (at α = 13°, z = 0.8 m)

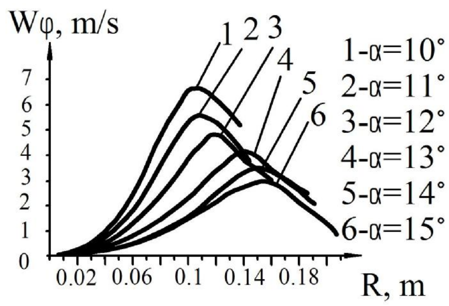


Fig. 4. The calculated change of the circumferential velocity of the granule depending on the angle of the cone opening (at Q = 0.63 m^3/s, z = 0.8 m)

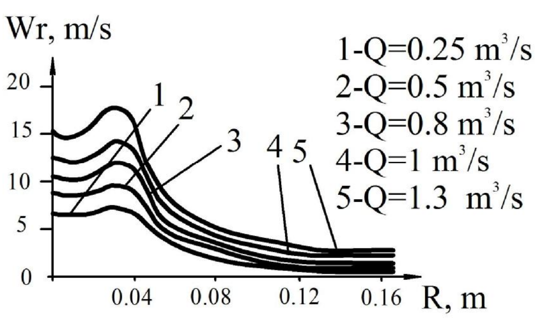


Fig. 5. The calculated change of the radial velocity of the granule depending on the gas flow rate (at α = 13°, z = 0.8 m)

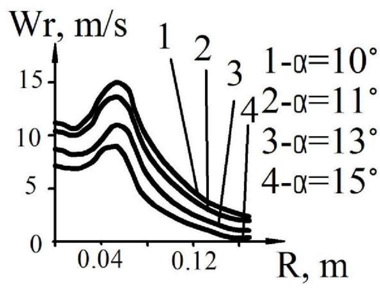


Fig. 6. The calculated change of the radial velocity of the granule depending on the angle of the cone opening (at Q = 0.63 m^3/s, z = 0.8 m)

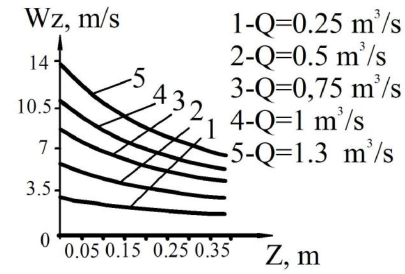


Fig. 7. The calculated change of the longitudinal velocity of the granule throughout the height depending on the gas flow rate (at $\alpha = 13°$)

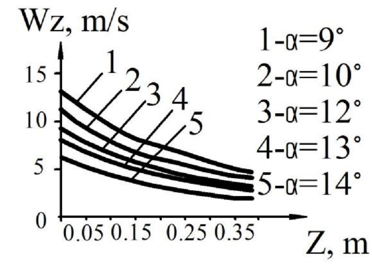


Fig. 8. The calculated change of the longitudinal velocity of the granule throughout the height depending on the angle of the cone opening of the vortex granulator working space (at $Q = 0.63$ m^3/s)

The values of granule velocity components, which we received as the result of theoretical calculations, allow to draw up their movement trajectories in the working space of the vortex granulator depending on the set of technological and design characteristics as well as on the properties of the granules.

Fig. 9 gives a representation of the calculated trajectories for different gas flow rates. All trajectories have spiral forms with different geometric characteristics. The analysis of the trajectories showed that:

– an increase of the gas flow rate and in the angle of the cone opening of the vortex granulator working space reduces the number of turns in the spiral, increases their step, and reduces the retention time of the granule in the vortex granulator working space;

– an increase of the size of the gas flow initial swirl (defined by the angle and number of blades of the swirler) and in the diameter of the granule changes the trajectory of its motion by increasing the number of turns of the spiral, reducing their step, increasing the diameter of the upper section of the spiral and increasing the retention time of the granule in the working space of the vortex granulator.

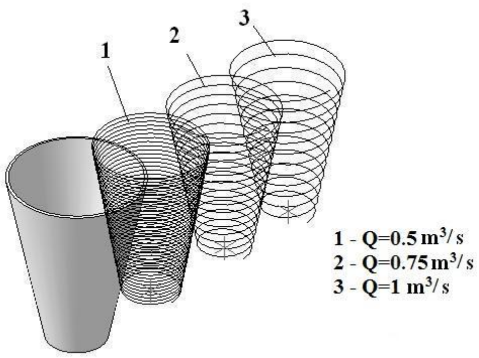
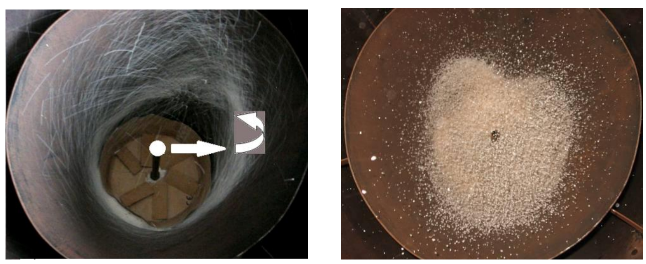


Fig. 9. Effect of the gas flow rate on the trajectory of the granules in the vortex granulator (at $\alpha = 13°$, $d = 3$ mm, $V_{\varphi 0} = 10$ m/s)

The comparison of theoretical calculations with data from [9] indicates compliance of the calculated and the experimental trajectories of the granules (Fig. 10). Their spiral motion within the prescribed working space of the vortex granulator (depending on the size of the granules) was observed throughout the vertical movement of the upper section of the unit (Fig. 10a). The granules move along the wall of the vortex granulator and actually are not retained in its central area. This is explained by the direction of the full speed vector of their movement from the center to the periphery due to the predominance of the radial component of the granules motion to two-thirds of the radius of the device. Closer to the granulator walls performance of the radial component decreases and granules begin to get involved in a rotary motion of the vertical displacement. We can control the movement of the granules until their retention in a certain section of the vortex granulator by the rational selection of the angle of the cone opening, the angle of the swirler blades and their number, and by the rate of the gas flow. (Fig. 10b).



a) b)

Fig. 10. Experimental trajectory of the granules movement in the vortex granulator: spiral upward movement (a) and movement in a specified section (b)

4. Conclusions

According to the results of the equations of the proposed mathematical model we determined the basic hydrodynamic movement characteristics of the gas flow and granules in small vortex devices with a variable chamber cross-section and trajectories of their movement.

The offered mathematical tools allow to perform the analysis of the conditions of one of the key processes in chemical technology of granular products, identify opportunities of motion control of granules in the working space of the vortex device and to select their optimal trajectory and retention time. In this case design of the vortex granulator for the production of ordinary and porous NH_4NO_3 as well as $CO(NH_2)_2$ is based on the optimization calculation [10]. The results of the calculation of the hydrodynamics in vortex granulator with suspended layer can also be useful for other areas of the chemical technology [11-13].

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ТЕОРЕТИЧНИЙ АНАЛІЗ ГІДРОДИНАМІКИ РУХУ ГРАНУЛ У ВИХРОВИХ ГРАНУЛЯТОРАХ ВИРОБНИЦТВА АМІАЧНОЇ СЕЛІТРИ ТА КАРБАМІДУ

Анотація. *Запропоновано математичний розрахунок визначення гідродинамічних характеристик руху гранул у робочому просторі вихрового гранулятора, що є основним кінцевим процесом хімічної технології та формує властивості рядової та пористої аміачної селітри і карбаміду. Аналітично визначено складові повної швидкості руху гранул та вплив на них конструкції гранулятора. Проведено співставлення результатів теоретичних та експериментальних досліджень.*

Ключові слова: *вихровий гранулятор, гранула, аміачна селітра, карбамід, гідродинаміка, траєкторія, швидкість.*