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Decay of the melt stream during dispersion in granulation devices

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ABSTRACT

The aim of the article is a theoretical description and experimental study of the melt jet expiration process from a perforated shell. Mathematical modeling of hydrodynamic flows was carried out based on the points of classical fluid and gas mechanics and technical hydromechanics. Mathematical model equations were solved by using computer mathematics of Maple and wxMaxima. Reliability of the obtained experimental results is based on the application of time-tested in practice methods. Hydrodynamic properties of the liquid jet outflow were obtained. The presented mathematical model allows calculation of radial component of the jet outflow velocity, as well as determination of the influences of physical and chemical properties of the liquid and the outflow hole diameter on the jet length and flow velocity along the axis to its disintegration into separated drops. The developed mathematical model extended with the theoretical description of the melt dispersion process from rotating perforated shells allowed us to improve design of the granulator to stabilize hydrodynamic parameters of the melt movement. Consideration of hydrodynamic parameters of the fluid jet flowing out of the holes of the perforated membrane provides improvement of the construction of nitrogen fertilizers melt dispersant, affect to the parameters of the process of jet decay into drops, its size and monodispersity. Basket tests of the granulator was confirmed the theoretical research and provided a basis for modernization of the equipment construction.

Keywords: jet decay, vibration granulator, hydrodynamic of flows movement, melt dispersion process, rotating perforated shell

1. INTRODUCTION

Liquid dispersion processes forming micro- or macro drops are used in power generation, medicine, chemical industry, agriculture and other spheres of human activity. Efficiency of these technological processes and equipment is largely determined by the quality of liquid dispersion, which usually involves obtaining monodisperse drops [1].

This fully applies to the production of the commodity form of nitrogen fertilizers, which is carried out in two main ways [2]:

- granulation starting from the liquid phase by dispersion on the surface of suspended particles in a fluidized bed that can be variously configured (technologies of Casale S.A., Switzerland; Kahl Group, Germany; Stamicarbon, Netherlands; Toyo Engineering Corporation, Japan; Thyssenkrupp Fertilizer Technology GmbH, Germany, etc.) [3-8], including vortex granulation [9, 10];
- granulation starting from the liquid phase by dispersion into drops followed by crystallization of the solute by dewatering and cooling (prilling) (devices of Norsk Hydro, Norway; Didier Engineering GmbH, Germany;, Imperial Chemical Industries, UK; Kaltenbach-Thuring S.A., France et al.) [11].

In these methods, among others, devices with different forms of a perforated shell, generally being axially symmetrical can be used for dispersion of the nitrogen fertilizer melt.

Devices for melt dispersion can be classified by the form of the working part (*i.e*. perforated shell) and by the presence of internal devices in the perforated shell. Additionally, these devices differ in the nature of force acting on the melt and can be static, swirl (tangential introduction of the melt into a perforated shell or to the turbine for the melt spin), and dynamic (rotating) [12].

In recent years, preference is mainly given to conical or cylindrical rotating devices and devices with the cup-shaped shell. This is due to simplicity of operation and high uniformity of resulting liquid drops and commodity granules in comparison to analogue devices.

For example, ammonium nitrate granulators (dispersers), which are currently in operation, provide manufacturing of products with following granulometric composition in terms of mass fraction: 0.5 - 1.5 % of granules < 1.0 mm in size, 90 – 98 % of granules in the size range 2.0 - 4.0 mm, where granules in the size range 2.0 - 2.5 mm comprise 42 - 71% and granules in the size range 2.0 - 3.0 mm comprise 85 - 95% [13, 14]. Dispersion of melts producing more than 2 % of dust-forming particles of less than 1.0 mm and over 3.5 mm in size, which can be also destructed making dust, leads to dust formation of nitrogenous fertilizers in air in the tower.

In existing equipment calculation of hydrodynamic characteristics of the liquid jet that is dispersed is often not performed, resulting in lower uniformity of the obtained drops [15]. Hydrodynamic parameters of the liquid jet issuing from a single hole or holes of the perforated shell, and design features of devices for fluid dispersion influence the process of jet decay into drops.

The problem of creating the adequate model of jet decay into drops at the opening in a thin wall is highly relevant for dispersion improvement in granulation devices in the mineral fertilizers production. By controlling the jet decay process, we can optimize the performance of dispersant and create favorable conditions to produce a product with a high degree of monodispersity.

The aim of the article is a theoretical description and experimental study of the melt jet outflow process from a perforated shell (basket).

2. DESCRIPTION OF THE OBJECT AND METHODS OF RESEARCH

Mathematical modeling of hydrodynamic flows was carried out based on the postulates of classical fluid and gas mechanics and technical hydromechanics [16, 17]. Solving equations of mathematical models was carried out by using the Maple software (Maplesoft, Canada) [18] and the open-source computer algebra system wxMaxima [19, 20]. These systems have proven to provide reliable and efficient symbolic and numerical algorithms for a wide range of mathematical problems, including a well-known library of numerical algorithms NAG (Numerical Algorithms Group, UK). Adequacy of calculated dependences for the process that was investigated, is validated by the comparison of calculated data with known and experimentally obtained results.

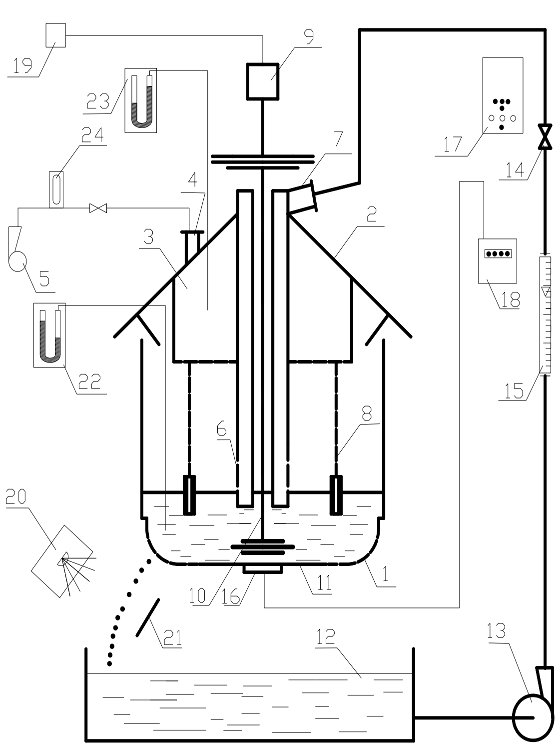
2.1 Experimental vibrating granulator

A vibrating granulator (manufacturer – Sumy State University, Processes and Equipment of Chemical and Petroleum-Refineries Department, Ukraine; granulator diameter is 560 mm, granulator height is 590 mm) is the main unit of the experimental unit (Fig. 1), which consists of a variable perforated membrane 1 with holes to discharge the fluid, housing 2 with a distributive drive 3 and a pipe 4 for introducing air from the fan 5. The housing 2 is also supplied with a fixed liquid distributor 6 with a pipe 7 and a filter element 8.

At the top of the fluid atomizer, a mechanical, electrical or electromagnetic vibrator 9 is installed, which is connected by a rod 10 with the resonator 11 in the form of an elastic disc or plate.

When the granulator is working, liquid that goes through the pipe 7 and the distributor 6 to the bottom part of the granulator flows out of the holes of the perforated membrane.

Simultaneously, air at a given pressure is supplied by the fan 5 through the pipe 4 into the cavity of the granulator.



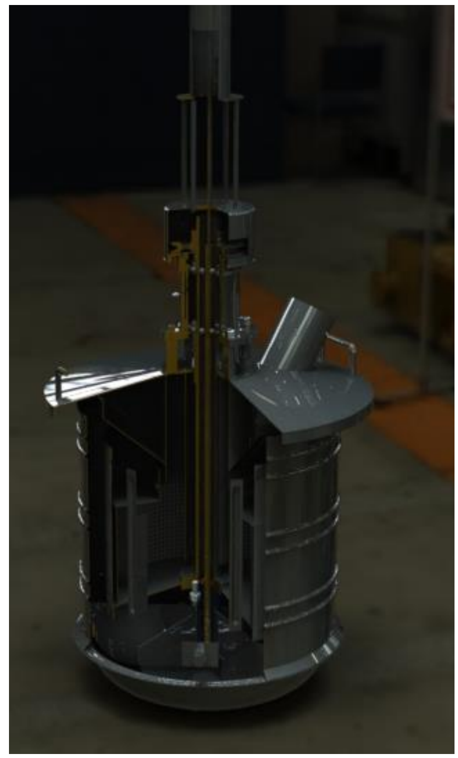


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Fig. 1. Experimental installation of the vibrating granulator. a) A schematic presentation of the granulator (design features of elements which are not described – see [21]): 1- perforated membrane (diameters of holes are 1.0 mm, 1.1 mm, 1.2 mm, 1,3mm, 1,4 mm, number of holes is 1800-2300, bottom shape is toroidal, length is 650 mm, diameter is 560 mm), 2 – housing (height is 590 mm, diameter is 560 mm), 3 – distributive drive, 4 – pipe (diameter is

45 mm), 5 – fan, 6 – liquid distributor, 7 – pipe (diameter is 100 mm), 8 - filter element (metal grid), 9 – vibrator (MFR OTY 77 actuator, range of output frequency 120-1200 is Hz), 10 – rod, 11 - resonator, 12 - buffer bunker, 13 – circulation pump (model Calpeda NC3 25-50/180), 14 – valve, 15 – rotameter (model Raifil RF FM 10), 16 - oscillations sensor, 17 – oscillograph (model C1-65A), 18 – digital frequency meter (model VC3165), 19 – electronic controller, 20, 21 – elements of stroboscope, 22, 23 – manometers (model МТ-2У), 24 – controller (model Euroaqua SKD-1); b) 3D model of vibrating granulator; c) 3D model and photo of experimental installation

The installation is equipped with a buffer bunker 12 for liquid with a circulation pump 13. Valve 14 and rotameter 15 are used to regulate and measure the liquid flowrate . The oscillations sensor 16 is connected with an oscillograph 17 to observe fluctuations while the digital frequency meter 18 is used to measure the oscillation frequency. When the electrodynamic or electromagnetic vibrator is used, regulation of oscillations is carried out by the electronic controller 19. A stroboscope (20 and 21) is installed for visual observation of the process of liquid dispersion into drops. Measurements of the liquid pressure in holes and air at the free surface of the liquid are carried out by manometers 22 and 23, respectively. The controller 24 is aimed to regulate the air pressure in the granulator.

Next, the electronic oscillator 19 is switched on and the electrodynamic vibrator 9 started resulting in vibration of the resonator at a certain frequency, which is fixed for the testimony of digital frequency meter 18, which is connected to the vibration sensor 16 (measurer of frequency) of the granulator basket. Air is supplied into the granulator volume by turning the fan 5 on, then when the interstitial position is changed, the given pressure is installed based on manometer data. The process of jets dispersion into drops is simultaneously monitored by using a stroboscope 20. When formation of monodisperse drops (without satellite droplets) is observed, measurements are recorded at the manometer 22 , which corresponds to the total liquid pressure in the leakage holes, and at the digital frequency meter 18 showing the vibration frequency (upper limit). These liquid and air parameters are changing by changing the vibration frequency with electronic generator 19 by the lower limit of granulator stable operation range. Ranges of stable operation are determined for different liquid leakage velocities from holes in the basket, which can be achieved by changing the granulator performance under constant air pressure or by changing the air pressure by using the pressure regulator at the constant granulator performance. When operating the vibration granulator at different liquid leakage velocities, the fluid flow rate is measured by a graduated cylinder.

Physical modeling is based on methods of the similarity theory. The geometric similarity is maintained by equality of appropriate constants and invariants [22].

The special frequency generator is designed to generate vibration on the radiator of rotating vibrational melting granulator by feeding electric signals of a special shape on the MFR OTY 77 actuator (system operation description - in accordance with [23]).

Main parameters and characteristics:

- frequency range of reproducible oscillations, Hz – 200 –1000
- rated load, W – 50 – 100
- limits of the permissible relative basic error, setting of the oscillation frequency, % – 0.5
- voltage of the mains supply of the generator, V – 220±10
- frequency of the mains, Hz – 60
- active resistance of the moving coil, Ohm – 8
- established trouble-free operating time, h – 1000 (with a confidence probability 0,95)

Operating conditions:

- ambient temperature – -10 – + 70 ° C
- relative humidity – 50 – 80% at a temperature of +25 °C

- atmospheric pressure – 86 – 106.7 kPa

The special frequency generator consists of:

- Generator of electrical signals of a special form
- Actuator MFR OTY 77

The generator of electrical signals of a special form consists of:

- Block of digital synthesis of frequency
- The amplifier
- Power supply unit

Specifications of the electrical signal generator:

- frequency range – 200 – 1000 Hz
- the minimum frequency setting step is 0.01Hz
- output power – 60W
- load resistance – 3.7 Ohm
- harmonic coefficient at the frequency of 500 Hz – 0.1%
- load inductance – 7.3 mH

The digital synthesis unit performs direct digital frequency synthesis (DDS – Direct Digital Sinthesizer) and is implemented on a microprocessor. Due to this, the generator has a high frequency stability and a small step of its tuning. The unit allows you to store 10 preset frequencies in the non-volatile memory. Each of which can be easily changed during operation. Indication of the generated frequency is carried out on the liquid crystal display.

The amplifier provides the necessary amplification of signals from the generator to feed them into a low-resistance load. The amplifier is implemented on an integrated microcircuit. The output stage is made on field-effect transistors. This ensures a high efficiency amplifier. The amplifier has a built-in protection system against overload, overheating and "soft start" system.

To power the whole device a power supply made by the classical transformer scheme is used. Two bipolar rectifiers supply a +/- 12V – the circuit for digital synthesis of frequency, and +/- 24V – amplifier.

Actuator MFR OTY 77

Electromagnetic vibrator consists of control block and vibro-converter. Control block is used for delivery of a signal of set frequency and amplitude to vibro-converter. A signal received from the control block, is transferred to the vibro-converter where under influence of magnetic field a reorientation of crystal lattice of the core alloy material occurs. As a result the core changes its length. The radiator of granulator's vibrations is joined to the bottom part of the core. Cooling of vibro-converter is provided by cooling air expulsion. The vibro-system has an input and output signal 4-20 мА what will allow to automatically control the frequency of vibration depending on the change of the fusion level in granulator. Control block of the vibro-system is fixed on CPU.

2.2 Processing of the experimental results

Velocity, V, of the liquid leaking from the granulator holes is calculated as:

$$V = \phi \cdot \sqrt{2 \cdot g \cdot H}. \qquad (1)$$

where ϕ is the discharge coefficient and set to 0.96-0.98 [24].

According to experimental data of upper f_1 and lower f_2 limits of the frequency, which provides a monodisperse liquid jet decay, the maximum and minimum lengths of the wave are calculated:

$$\lambda_{max}=V/f_1;\ \lambda_{min}=V/f_2, \qquad (2)$$

The melt flowrate, G_S, through the granulator hole is calculated from the measured leaked melt volume, G_τ and time, τ:

$$G_s=G_\tau/\tau. \qquad (3)$$

Diameter of drops, formed by the decay of liquid jets at the average vibration frequency of the granulator, f_{avi}, is determined from the material balance according to the equation:

$$d_{dr} = \sqrt[3]{\frac{6 \cdot G_s}{\pi \cdot f_{avi}}}. \qquad (4)$$

The absolute difference of drop diameters and a relative deviation of drop diameters from the average drop diameter at the granulator maximum and minimum productivity are calculated as follows:

$$\Delta d_{dr}^{ab} = d_{dr}^{max} - d_{dr}^{min}. \qquad (5)$$

$$\Delta d_{dr}^{rel} = \frac{2(d_{dr}^{max} - d_{dr}^{min})}{d_{dr}^{max} + d_{dr}^{min}}. \qquad (6)$$

To define the optimal number of experiments and the highest accuracy degree and reliability of the obtained results, as well as for the processing of these results, methods of mathematical statistics were used [25].

Two types of measurement errors - random and systematic, may occur during the experiment conducting [26].

A random error reduces the accuracy of experiment results. An analysis of this type of error is possible by using the root-mean-square deviation σ, calculated by the following equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (\bar{x} - x_i)^2}{n-1}}, \qquad (7)$$

where $\bar{x}$ is the arithmetic mean value; x is the single parameter value; n is the number of measurements.

The maximum possible error of a single measurement, Δ, was determined by the three sigma rule:

$$\Delta = 3\sigma. \qquad (8)$$

The bilateral confidence interval of the arithmetic mean value ε was determined by the following function [26], provided that this parameter is located in the confidence interval with the probability not less than 95%:

$$\varepsilon = t\frac{\sigma}{\sqrt{n}}, \tag{9}$$

where t is the Student's criterion [27].

The root-mean-square error of indirect measurements is calculated as:

$$\sigma_y = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial y}{\partial x}\cdot\Delta\cdot x_i\right)^2} \quad , \tag{10}$$

where $y=f(x_1,x_2,\ldots x_n)$.

The accuracy of the obtained regression equations is determined by the least-squares method [28].

The systematic measurement error had an identical effect on all parameters that were controlled during the experiment. All measurement devices were calibrated by calibration instruments by comparing their accuracy with declared in the technical documentation in order to exclude the above error. Connection between measurement devices and controllers was provided with a maximum error of processing signals within 1.5%.

Creation of graphical dependences was carried out by differential methods of mathematical analysis and integral calculus. Reliability of the obtained experimental results is due to application of time-tested methods in practice.

2.3 Materials

Melt of ammonium nitrate and urea was used. Manufacturer of ammonium nitrate (agrotechnical chemical) - PSC "Azot", Ukraine. Main parameters of ammonium nitrate –

according to [29].

3. RESULTS AND DISCUSSION

The model of the jet decay is based on the solution of Navier-Stokes equations (11) - (12) and the flow continuity equation (13) in cylindrical coordinates [9], with the following simplifications:

- flow is axially symmetric;
- cross-section of the jet is circular, there is only jet restriction and extension (the tangential component of jet velocity υ_θ=0).

$$\upsilon_r \frac{\partial \upsilon_r}{\partial r} = -\frac{1}{\rho}\cdot\frac{\partial p}{\partial r} + \nu\cdot\left[\frac{\partial^2 \upsilon_r}{\partial z^2} + \frac{\partial}{\partial r}\cdot\left(\frac{\frac{\partial}{\partial r}\left(r\cdot\upsilon_r\right)}{r}\right)\right], \qquad (11)$$

$$\upsilon_z \frac{\partial \upsilon_z}{\partial z} = -\frac{1}{\rho}\cdot\frac{\partial p}{\partial z} + \nu\cdot\left[\frac{\partial^2 \upsilon_z}{\partial z^2} + \frac{1}{r}\cdot\frac{\partial}{\partial r}\cdot\left(r\cdot\frac{\partial \upsilon_z}{\partial r}\right)\right], \qquad (12)$$

$$\frac{\partial \upsilon_z}{\partial z} + \frac{1}{r}\cdot\frac{\partial}{\partial r}\cdot\left(r\cdot\upsilon_r\right) = 0. \qquad (13)$$

By assuming that the axial velocity component at the time of leaving the hole varies parabolically with the radial coordinate:

$$\upsilon_z = A_1\cdot r^2\cdot z^2 + A_2\cdot r + A_3, \qquad (14)$$

and transforming the equation (13), we obtain the value of the radial component of the jet velocity:

$$\upsilon_r = \frac{-\frac{1}{2}\cdot A_1\cdot r^4\cdot z + F_1\left(z\right)}{r} \qquad (15)$$

where $F_1(z)$ is polynomial function.

Given the fact that the pressure change in a jet in the radial direction is insignificant compared to the axial component, and by substituting (14) into (12) we get:

$$2\cdot\ A_1\cdot r^2\cdot z^2+A_2\cdot r+A_3\ \ A_1\cdot r^2\cdot z=\frac{1}{\rho}\cdot\frac{dp}{dz}+\nu\cdot\left(2\cdot A_1\cdot r^2+\frac{4\cdot A_1\cdot r\cdot z^2+A_2}{r}\right). \qquad (16)$$

By solving the equation (16) for dp/dz and by integration the expression for pressure change along the jet axis is obtained:

$$p(z)=-\frac{1}{r}\cdot\left(\rho\cdot\left(\frac{1}{2}\cdot A_1^{\ 2}\cdot r^5\cdot z^4+A_1\cdot r^4\cdot z^2\cdot A_2+A_1\cdot r^3\cdot z^2\cdot A_3-2\cdot\nu\cdot A_1\cdot r^3\cdot z-\frac{4}{3}\cdot\nu\cdot A_1\cdot r\cdot z^3-\nu\cdot A_2\cdot z\right)\right)+C_1 \qquad (17)$$

By setting the origin of the coordinate system at the hole exit (z=0) and by introducing the assumption that the liquid outflow occurs at a constant pressure ($p=const$), then according to (17) it is obtained that $C_1=p_1$.

After insertion of this constant we get:

$$p(z)=-\frac{1}{r}\cdot\left(\rho\cdot\left(\frac{1}{2}\cdot A_1^2\cdot r^5\cdot z^4+A_1\cdot r^4\cdot z^2\cdot A_2+A_1\cdot r^3\cdot z^2\cdot A_3-2\cdot\nu\cdot A_1\cdot r^3\cdot z-\frac{4}{3}\nu\cdot A_1\cdot r\cdot z^3-\nu\cdot A_2\cdot z\right)\right)+p_1 \ (18)$$

By inserting (18) into (11):

$$\frac{\left(-\frac{1}{2}\cdot A_1\cdot r^4\cdot z+F_1\ z\ \right)\left(-2\cdot A_1\cdot r^2\cdot z-\frac{-\frac{1}{2}\cdot A_1\cdot r^4\cdot z+F_1\ z}{r^2}\right)}{r}=-\frac{1}{\rho}\cdot\left(\frac{1}{r^2}\cdot\left(\rho\cdot\left(\frac{1}{2}\cdot A_1^2\cdot r^5\cdot z^4+A_1\cdot r^4\cdot z^2\cdot A_2+\right.\right.\right.$$

$$\left.\left.\left.+A_1\cdot r^3\cdot z^2\cdot A_3-2\cdot\nu\cdot A_1\cdot r^3\cdot z-\frac{4}{3}\cdot\nu A_1\cdot r\cdot z^3-\nu\cdot A_2\cdot z\right)\right)-\frac{1}{r}\cdot\left(\rho\cdot\left(\frac{5}{2}\cdot r^4\cdot A_1^2\cdot z^4+4\cdot A_1\cdot r^3\cdot z^2\cdot A_2+\right.\right.\right.$$

$$\left.\left.\left.+3\cdot A_1\cdot r^2\cdot z^2\cdot A_3-6\cdot\nu\cdot A_1 r^2\cdot z-\frac{4}{3}\cdot\nu\cdot A_1\cdot z^3\right)\right)\right)+\nu\cdot\left(\frac{1}{r}\cdot\frac{d^2F_1\ z}{dz^2}-4A_1\cdot r\cdot z\right) \qquad (19)$$

we obtain the differential equation of total derivatives in respect to the function $F_1(z)$. Based on the fact that the derivative $d\upsilon_r/dz$ is equal to:

$$\frac{d\upsilon_r}{dz} = \frac{-\frac{1}{2}\cdot A_1 \cdot r^4 \cdot z + \frac{dF_1\ \ z}{dz}}{r}, \qquad (20)$$

and the radial velocity component of the jet at z=0 becomes υ_r=0, we obtain:

$$\frac{1}{2} A_1 \cdot r^4 \cdot z = \frac{dF_1\ \ z}{dz}. \qquad (21)$$

By using the boundary conditions F_1(z=0)=0 and dF_1/dz (z=0)=0, and put them into the equation (14) we obtain the value of the function F_1 as a polynomial:

$$F_1(z) = \frac{1}{6}\cdot\frac{(-A_2 + 8\cdot A_1 \cdot r^3)\cdot z^3}{r} + \frac{1}{48}\cdot\frac{A_1 \cdot r^2 \cdot (3\cdot A_1 \cdot r^4 - 12\cdot A_2 \cdot r - 8\cdot A_3)\cdot z^4}{v}. \qquad (22)$$

Substituting the relation (22) in the equation (15) leads to:

$$\upsilon_r = \frac{1}{48}\cdot\frac{z\cdot\ -24\cdot A_1 \cdot r^5 \cdot v - 8\cdot v \cdot z^2 \cdot A_2 + 64\cdot v \cdot z^2 \cdot A_1 \cdot r^3 + 3\cdot A_1^2 \cdot r^7 \cdot z^3 - 12\cdot A_1 \cdot r^4 \cdot z^3 \cdot A_2 - 8\cdot A_1 \cdot r^3 \cdot z^3 \cdot A_3}{v\cdot r^2}. \qquad (23)$$

The coefficient A_2 can be found by assuming that on the jet surface r=r_s the pressure p is equal to the pressure of the surrounding environment p_0. This boundary condition can be written as:

$$p_0 = -\frac{1}{r_s}\cdot\left(\rho\cdot\left(\frac{1}{2}\cdot A_1^2 \cdot r_s^5 \cdot z^4 + A_1 \cdot r_s^4 \cdot z^2 \cdot A_2 + A_1 \cdot r_s^3 \cdot z^2 \cdot A_3 - 2\cdot v \cdot A_1 \cdot r_s^3 - \frac{4}{3}\cdot v \cdot A_1 \cdot r_s \cdot z^3 - v \cdot A_2 \cdot z\right)\right) + p_1 \qquad (24)$$

Thus, the coefficient A_2 is now calculated as:

$$A_2 = -\frac{1}{6}\cdot\frac{(r_s \cdot (3\cdot z^4 \cdot A_1^2 \cdot \rho \cdot r_s^4 + 6\cdot z^2 \cdot A_1 \cdot \rho \cdot r_s^2 \cdot A_3 - 12\cdot z \cdot A_1 \cdot \rho \cdot v \cdot r_s^2 - 8\cdot \rho \cdot v \cdot A_1 \cdot z^3 - 6\cdot p_1 + 6\cdot p_0))}{\rho\cdot z\cdot(A_1 \cdot r_s^4 \cdot z - v)}. \qquad (25)$$

The coefficient A_3 can be defined by assuming that that if r=0, υ_r=0:

$$A_3 = -\frac{1}{6}\cdot\frac{3\cdot z^4 \cdot A_1^2 \cdot \rho \cdot r_s^4 + 6\cdot p_0 - 12\cdot z \cdot A_1 \cdot \rho \cdot v \cdot r_s^2 - 8\cdot \rho \cdot v \cdot A_1 \cdot z^3 - 6\cdot p_1}{z^2 \cdot r_s^2 \cdot \rho \cdot A_1}. \qquad (26)$$

Accordingly,

$$\upsilon_z = A_1 \cdot r^2 \cdot z^2 - \frac{1}{6} \cdot \frac{3 \cdot z^4 \cdot A_1^2 \cdot \rho \cdot r_s^{\,4} + 6 \cdot p_0 - 12 \cdot z \cdot A_1 \cdot \rho \cdot \nu \cdot r_s^{\,2} - 8 \cdot \rho \cdot \nu \cdot A_1 \cdot z^3 - 6 \cdot p_1}{z^2 \cdot r_s^2 \cdot \rho \cdot A_1}. \qquad (27)$$

The coefficient A_1 is determined by assuming that at a point close to the origin of the coordinate system $z = z_0$, the exhaust velocity has not yet changed its value and is equal to the flow velocity jet in the hole $\upsilon_z = \upsilon_{z_0}$ that is:

$$\upsilon_{z_0} = \frac{1}{6} \cdot \frac{6 \cdot A_1^2 \cdot r^2 \cdot z_0^4 \cdot r_s^2 - 3 \cdot z_0^{\,4} \cdot A_1^2 \cdot \rho \cdot r_s^{\,4} - 6 \cdot p_0 - 12 \cdot z_0 \cdot A_1 \cdot \rho \cdot \nu \cdot r_s^{\,2} + 8 \cdot \rho \cdot \nu \cdot A_1 \cdot z_0^{\,3} + 6 \cdot p_1}{z_0^{\,2} \cdot r_s^2 \cdot \rho \cdot A_1}. \qquad (28)$$

When we solve the resulting equation (28) for the coefficient A_1, we obtain:

$$A_1 = \frac{1}{3} \cdot \frac{1}{z_0^3 \cdot r_s^2 \cdot \rho \cdot (2 \cdot r^2 - r_s^2)} (-4 \cdot \nu \cdot \rho \cdot z_0^2 + 3 \cdot \upsilon_{z0} \cdot r_s^2 \cdot \rho \cdot z_0 - 6 \cdot \rho \cdot \nu \cdot r_s^2 + (16 \cdot \nu^2 \cdot \rho^2 \cdot z_0^4 -$$

$$-24 \cdot \nu \cdot \rho^2 \, z_0^3 \cdot \upsilon_{z0} \cdot r_s^2 + 48 \cdot \nu^2 \cdot \rho^2 \cdot z_0^2 \cdot r_s^2 + 9 \cdot \upsilon_{z0}^2 \cdot r_s^4 \cdot \rho^2 \cdot z_0^2 - 36 \cdot \upsilon_{z0} \cdot r_s^4 \cdot \rho^2 \cdot z_0 \cdot \nu + 36 \cdot \rho^2 \cdot \nu^2 \cdot r_s^4 +$$

$$36 \cdot z_0^2 \cdot r^2 \cdot r_s^2 \cdot \rho \cdot p_0 - 36 \cdot z_0^2 \cdot r^2 \cdot r_s^2 \cdot \rho \cdot p_0 - 36 \cdot z_0^2 \cdot r^2 \cdot r_s^2 \cdot \rho \cdot p_1 - 18 \cdot z_0^2 \cdot r_s^4 \cdot \rho \cdot p_0 + 18 \cdot z_0^2 \cdot r_s^4 \cdot \rho \cdot p_1)^{1/2}) \qquad (29)$$

The presented mathematical model allows calculating radial and axial components of the velocity jet outflow, as well as to establish the influence of physical and chemical properties of the liquid and the hole diameter on the jet length and velocity along the axis to its disintegration into separate drops (Figs 2, 3).

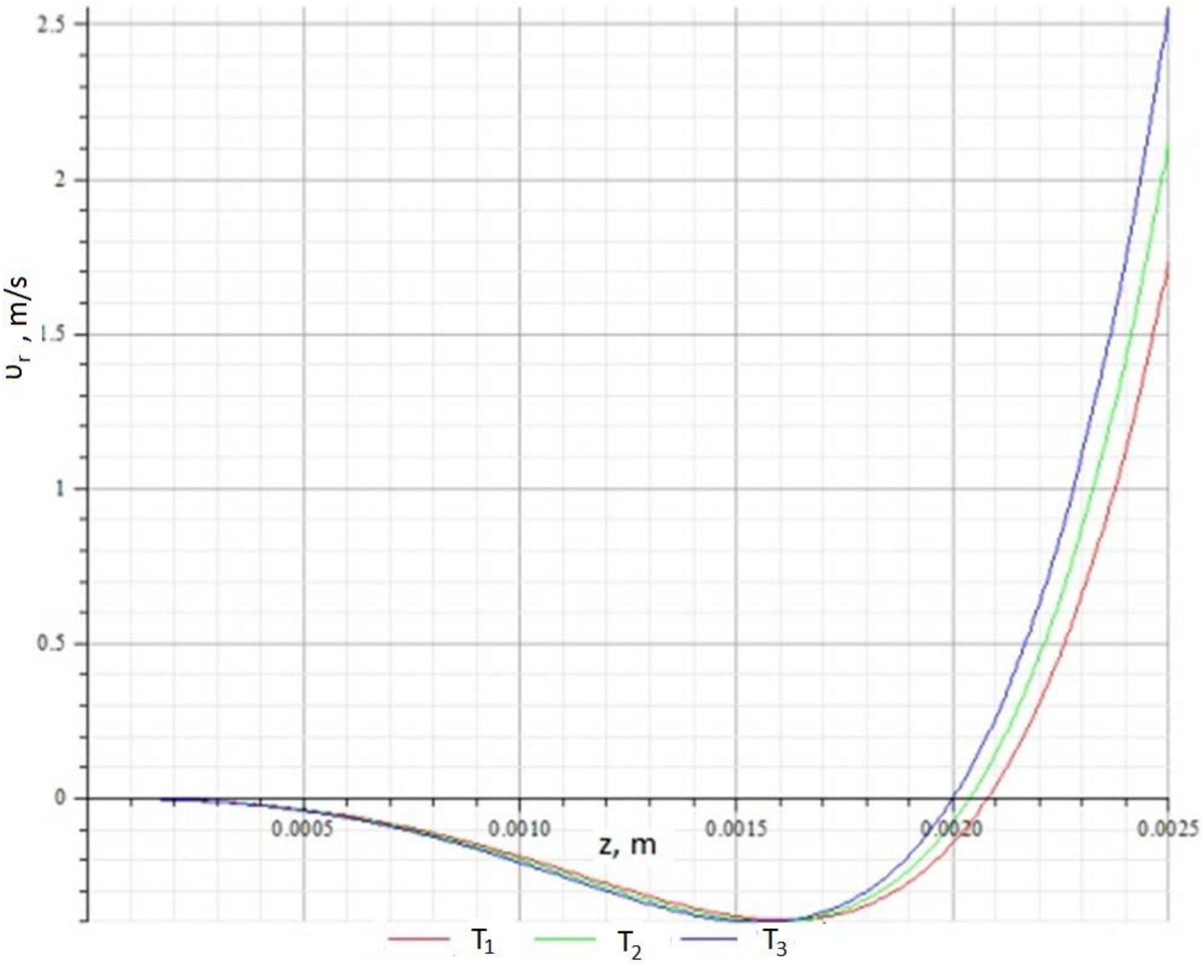


Fig. 2. Dependence of the radial component of the jet velocity of the ammonium nitrate melt on the axial distance, z, from the hole diameter of 1.3 mm at different temperatures of the melt at T_1 = 175°C, T_2 =180°C, T_3 = 185°C and the vibration frequency of 340 Hz (viscosities were 5.36, 5.03, 4.74 mPa·s, densities were 1434, 1431, 1428 kg/m^3 respectively). Granulator basket rotation velocity was n = 60 rpm and a load of 37 t/h.

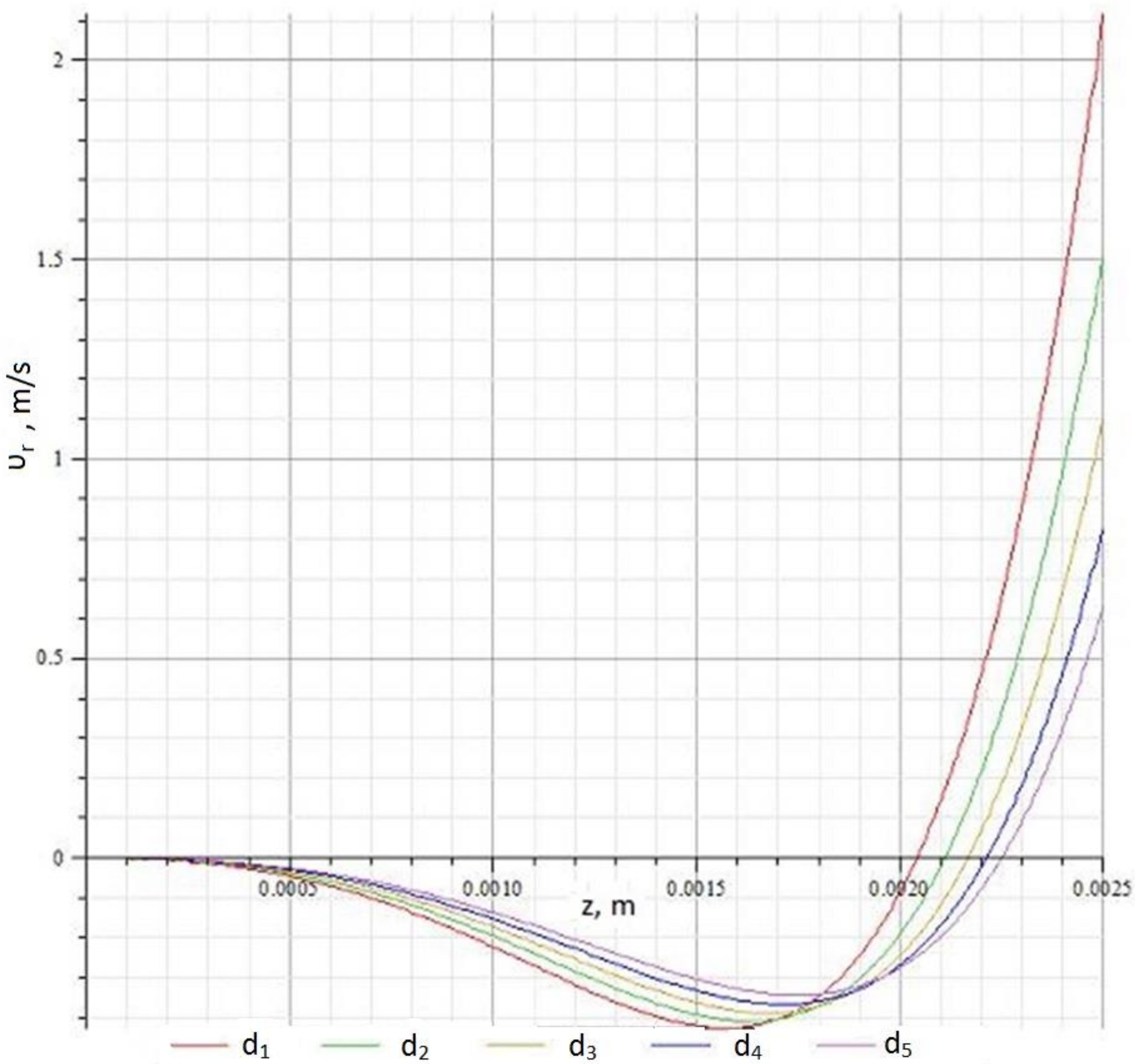


Fig. 3. Dependence of the radial component of the jet velocity of the ammonium nitrate melt on the axial distance, z, from the holes of different diameters: d_1=1.0 mm, d_2=1.1 mm, d_3=1.2 mm, d_4=1,3mm, d_5=1,4 mm at the temperature of 185°C (viscosity was 4.74 mPa·s, density was 1428 kg/m^3) and the vibration frequency of 340 Hz. Granulator basket rotation velocity was n = 60 rpm and a load of 37 t/h.

The radial component of the velocity scarcely appears at the short distance from the hole. When the distance increases, there are radial flows in the jet, which cause its breaking-up into drops. It is indicated by the significant increase of the radial component. An increase in the temperature of the melt and the diameter of the perforated shell hole leads to the reduction of the distance from the hole, at which the radial component becomes critical, at which the jet is broken up. The negative velocity indicates the breakoff of flow (detachment of the jet with the formation of the vortex flows), which disappears with an increase of parameter z.

The smaller the distance from the outflow hole during jet breaking-up, the smaller the length of the jet portion, which forms the volume of drop during jet breaking-up. This hypothesis coincides with the results of other scientists' studies [30].

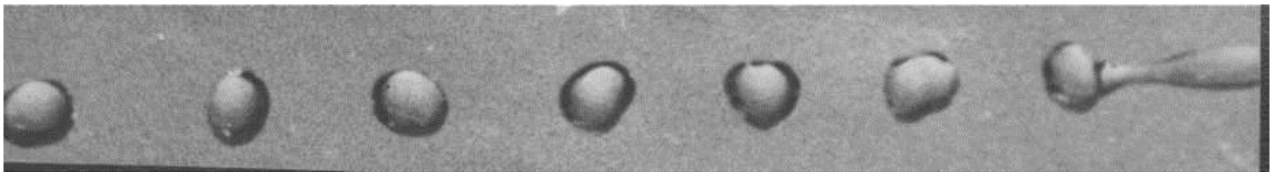
For granulator basket rotation velocity n = 60 rpm and a load of 37 t/h optimal diameter of the hole is d=1.2 mm, the melt temperature is 185°C.

An example of comparison of theoretical calculations and experimental results of velocity radial component measurement was shown in Table 1.

Table 1. An example of comparison of theoretical calculations and experimental results of υ_r measurement (hole diameter was 1.3 mm, temperatures of the melt was 175°C (viscosity was 5.36 mPa·s, density was 1434 kg/m^3), vibration frequency was 340 Hz, granulator basket rotation velocity was n = 60 rpm and a load was 37 t/h)

z=0 m			z=0.0005 m		
$\upsilon_{r.theor}$,m/s	No of measurement	$\upsilon_{r.exp}$,m/s	$u_{r.theor}$,m/s	No of measurement	$\upsilon_{r.theor}$,m/s
0	1	0	-0.05	1	-0.04
0	2	-0.003	-0.05	2	-0.02
0	3	0.002	-0.05	3	-0.08
0	4	0	-0.05	4	-0.07
0	5	0.004	-0.05	5	-0.09
0	6	-0.005	-0.05	6	-0.04
z=0.001 m			z=0.0015 m		
$\upsilon_{r.theor}$,m/s	No of measurement	$\upsilon_{r.exp}$,m/s	$u_{r.theor}$,m/s	No of measurement	$\upsilon_{r.theor}$,m/s
-0.2	1	-0,21	-0,4	1	-0,4
-0.2	2	-0,19	-0,4	2	-0,42
-0.2	3	-0,19	-0,4	3	-0,39
-0.2	4	-0,19	-0,4	4	-0,38
-0.2	5	-0,18	-0,4	5	-0,4
-0.2	6	-0,2	-0,4	6	-0,41
z=0.002 m			z=0.0025 m		
$\upsilon_{r.theor}$,m/s	No of measurement	$\upsilon_{r.exp}$,m/s	$u_{r.theor}$,m/s	No of measurement	$\upsilon_{r.theor}$,m/s
0	1	-0,01	2.5	1	2,44
0	2	0,01	2.5	2	2,53
0	3	0,02	2.5	3	2,51
0	4	0	2.5	4	2,41
0	5	-0,03	2.5	5	2,56
0	6	0	2.5	6	2,6

Basket tests of the granulator (shown in Fig. 1) confirmed the theoretical research and provided a basis for modernization of the equipment construction. During the tests, a stable jet breakup into drops at a distance of 2-5 mm from the wall of the perforated shell was obtained (Figs 4, 5).



a

b

Fig. 4. Jet disintegration into drops after the outflow from the perforated shell: a) ammonium nitrate drops, vibration frequency of 200 Hz; b) ammonium nitrate drops, vibration frequency of 340 Hz. Diameter of hole was 1.1 at the temperature of 185°C (viscosity was 4.74 mPa·s, density was 1428 kg/m^3). Granulator basket rotation velocity was n = 60 rpm and a load of 37 t/h.

Fig. 5. Steady jet disintegration into drops after the outflow from the perforated shell: ammonium nitrate drops, vibration frequency of 340 Hz. Diameter of hole was 1.1 at the temperature of 185°C (viscosity was 4.74 mPa·s, density was 1428 kg/m^3). Granulator basket rotation velocity was n = 60 rpm and a load of 37 t/h.

The developed mathematical model was extended with the theoretical description of the melt dispersion process from rotating perforated shells, which allowed us to improve the granulator design to stabilize hydrodynamic parameters of the melt movement within it. By applying of a weighted vortex layer in combination with the vibrating material liquid spray and rotation of liquid jets by their decay will further improve the quality of the granulated product.

Scheme of the modernized granulator is shown in Fig. 6, and layout solutions for granulator installation in the granulation tower in Fig. 7. Similarity of respective particles movements and their trajectories in industrial design and in experimental models as maintained.

Installation of a guiding element in the form of an auger into the granulator, when the melt contacts with the shoulder blade, increases the melt total pressure by transforming the screw mechanical energy into the melt kinetic energy and then turning it into the internal energy. The possibility of screw rotation provides the option for increasing the pressure before the outflow holes.

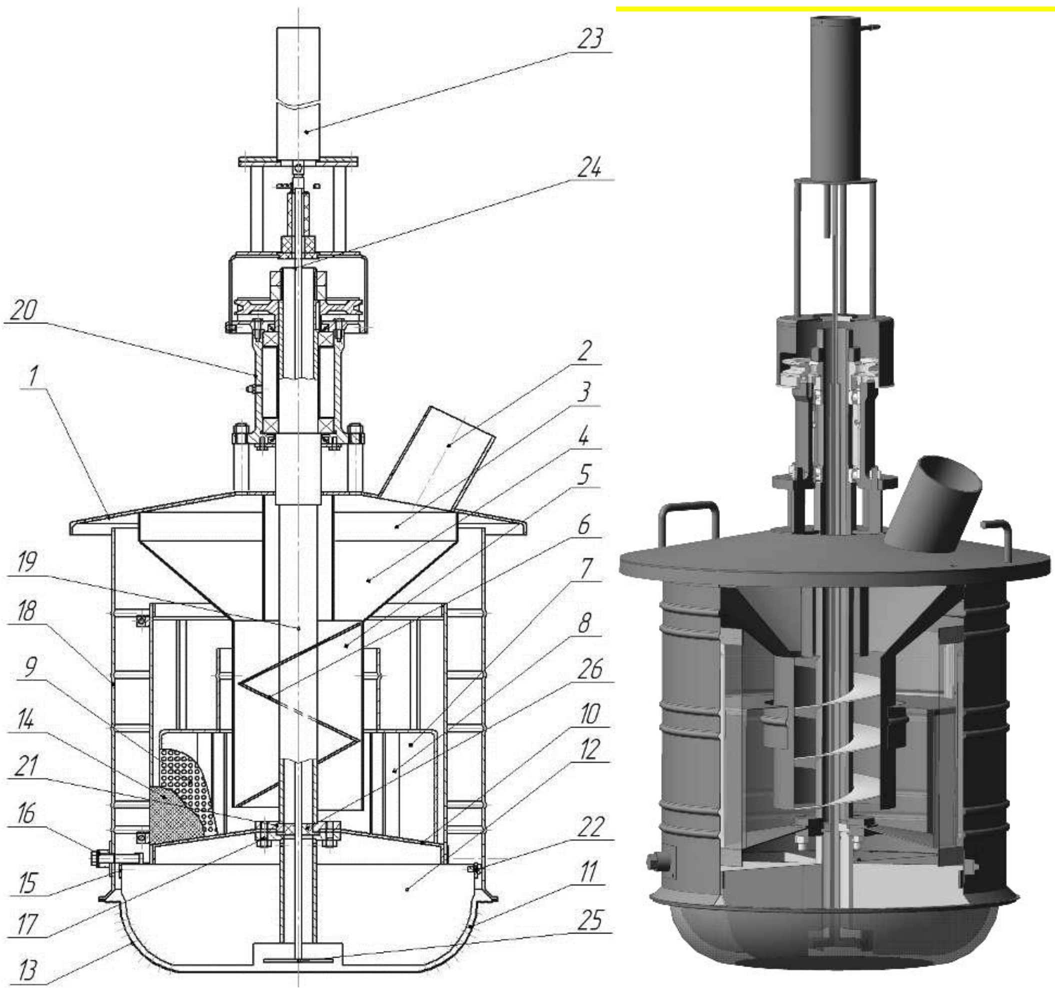


Fig. 6. Rotating vibration granulator of solutions (melts): 1 - housing; 2 - pipe for introducing the solution (melt); 3 - ring collector; 4 - reverse cone; 5 - annular channel; 6 - auger; 7 - distributor of the solution (melt); 8 - directing blades; 9 - perforated cylinder; 10 - directing cone for the solution (melt); 11 - perforated bottom (basket); 12 - pressure blades; 13 - hole;

14 - mesh for the final melt filtration; 15 - ring; 16 - bolts; 17 - pins; 18 - cylindrical chamber; 19 - hollow shaft; 20 - bearing assembly; 21 - flange connection; 22 - bulge for centering the cylindrical chamber; 23 - vibration device; 24 - rod; 25 - disc radiant; 26 - hub.

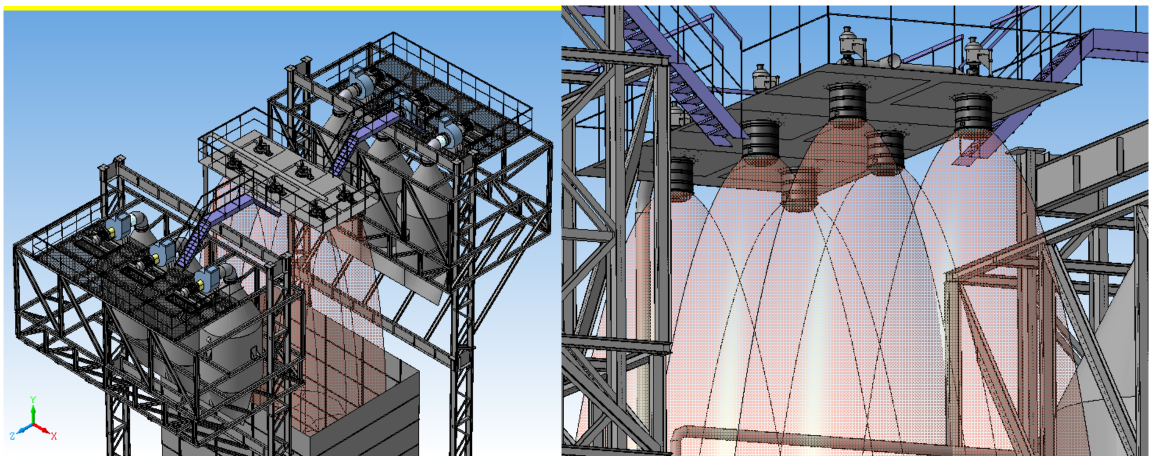


Fig. 7. The layout solutions for granulator installation in the granulation tower

Pilot testing of the modified granulator of the total capacity of **37 t/h** in production of ammonium nitrate for different climatic conditions (humid and hot climate, temperate continental type) showed a higher yield of marketable fractions and reduction of dust content in flue gases.

High level of monodispersity of granules is achieved by improving the fusion hydrodynamics in the granulator, improving the process of applying vibration to the jets of substance that leak out from the basket perforated bottom.

Also the modified granulator significantly reduced the granulated product dust level in the air coming out of the tower. Axial flow fans capture from 16 to 38 mg/m^3 of dust so that the granulator enables the company to reduce the considerable funds necessary for purchasing expensive new equipment to clean the air coming out of the tower.

The basic granulator test results are shown in Figs 8-9.

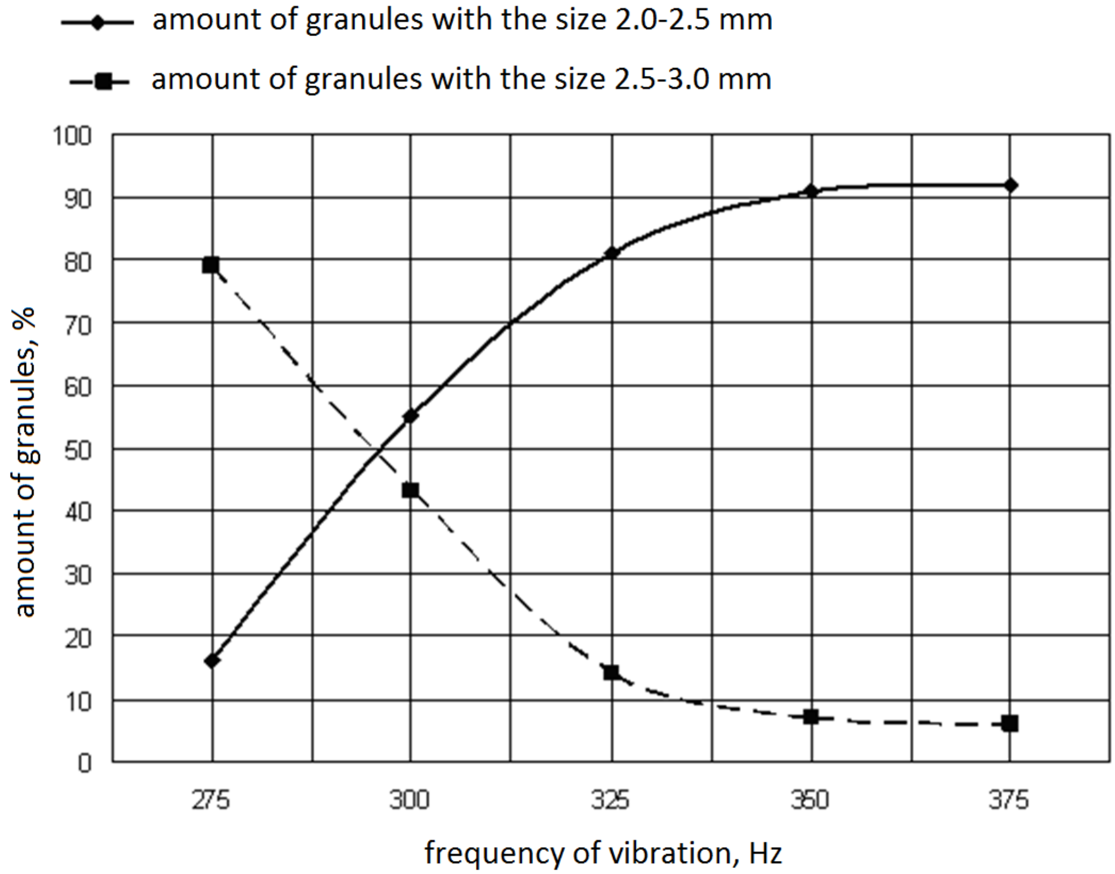
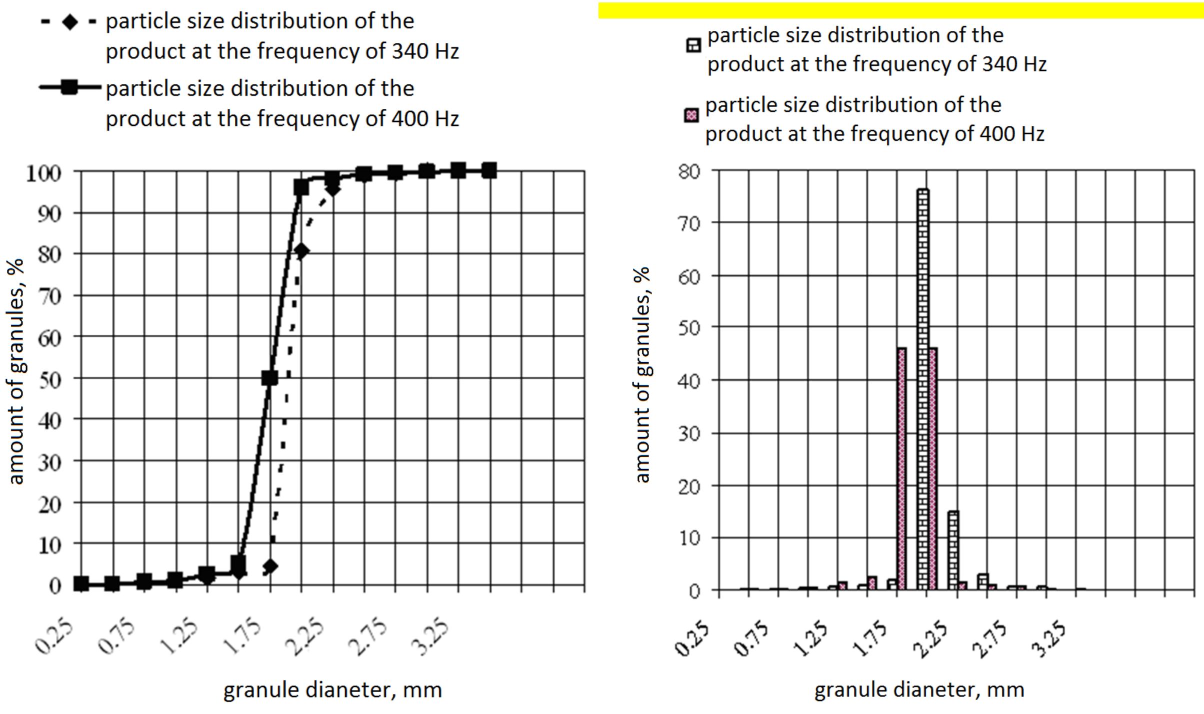


Fig. 8. Mass fractions of ammonium nitrate granules with sizes 2.0 – 2.5 mm and 2.5 - 3.0 mm as functions of the vibration frequency at the granulator basket rotation velocity of n = 60 rpm and a load of 37 t/h and the hole diameter of 1.2 mm



a b

Fig. 9. The integral particle size distribution of ammonium nitrate granules at vibration frequencies of 340 and 400 Hz and the granulator basket rotation velocity of n = 60 rpm, load of 37 t/h and the hole diameter of 1.2 mm: a) line graph b) bar chart

Analysis of Fig. 6-8 provides determination of an optimal (operating) vibration frequency (frequency range), at which the maximal degree of monodispersity of the drops is achieved. Therefore, the melt jet disintegrates evenly and without formation of drop satellites.

The monodispersion process introduces a fundamental improvement in the fertilizer production technology. The use of uniform (monodisperse) granules, for example in agriculture, provides an even distribution of the fertilizer on the fertilized area resulting in the additional yield up to 10% [10-12].

Vibrating granulators provide production of strong monodisperse granules with a smooth glossy surface (the monodispersity degree is up to 99 %). It opens the possibility to intensify the granulation process and essentially improves the agrotechnical value of fertilizers.

Table 2 shows a comparative analysis of the granulometric composition of the final product in different types of granulators.

Table 2. Comparison of rotating vibration granulators with world analogues of the granulation equipment in granulation towers

Granulometric composition, %	Centrifugal granulator of firm “Kreber” (Netherlands) [31]	Acoustics granulator designed by Research Institute at the Chemical plant (Russia) [32]	Rotating vibration granulators (this work)
- 1-4 mm	97-99	98-99	more than 99
- 2-4 mm	83-92	85-95	90-97
- 2-3 mm	75-90	80-90	more than 90
- 2.0-2.5 mm	40-50	45-65	more than 80
- less than 1 mm	0.8-2,5	0.8-1.5	0.1-0.8

The improved granulator has the following advantages over other granulator types (on the basis of literature review, e.g. [33-37]):

- high safety in operation;
- production of more competitive uniform granules;
- avoidance of the product’s sticking in towers;
- decrease of dust arising;

- increase of the agro-technical value of fertilizers.

The vibrating granulators have a reliable vibration system, which provides a stable imposition of oscillations on the fluid jets, flowing out of perforated shell holes, regardless the changes in the load on the melt disperser. This vibration system provides measurements of the level of melt in the granulator and thereby, to control the clogging degree and the melt outflow velocity from the holes of the perforated shell.

The vibrating granulator (fig. 6) with an electromagnetic vibration system (vibration frequency of 340 Hz) provided production of a product with the following granulometric composition as mass fractions: 0.02-0.2% of granules < 1.0 mm and over 96% of granules 2.0 - 4.0 mm in size. Also, for the fraction of granules in the size range 2.0 - 2.5 mm was not lower than 88% with the main size in the range 2.1-2.5 mm. When the vibration frequency was changed to 400 Hz , the granulator provided production of the product with the main fraction (over 65 %) of granules of 2.5 - 3.0 mm simultaneously increasing the hardness of the main fraction granules (hardness value was confirmed in [12]).

Similar results of granulometric compositions of products were obtained on vibrating granulators with electromagnetic vibration systems in the ammonium nitrate production under tropical conditions in Cuba and urea with foaming additives of hydrohumates [12]. During the industrial operation of this device the product (urea) with the following granulometric composition in mass fractions was stably obtained during one month: 0.1 - 0.3 % of granules < 1.0 mm, 99.7 - 99.9 % of granules in the size range 1.0-4.0 mm where granules in the size range 2.0 - 4.0 mm comprised 96.5-98.9% while granules of a size larger than 4.0 mm were absent.

4. CONCLUSION

Consideration of hydrodynamic parameters of the liquid jet flowing out of holes of a perforated membrane allowed us to affect parameters of the process of jet decay into drops, drop size and dispersity and consequently to improve the construction of a nitrogen fertilizers melt granulator.

Main results:

- the mathematical model to calculate hydrodynamic properties of the melt jet expiration process from a perforated shell is formed;
- the influence of the holes diameter and melt properties on the radial velocity field is shown;
- the optimal conditions for prilling in a vibrating granulator for a given capacity of 37 t / h are defined: the rotation velocity of the basket, the diameter of the holes in the perforated shell, the melt temperature, the frequency range of the actuator's oscillation;
- the modernized construction of the vibrating granulator is given
- results regarding industrial tests of the modernized vibrating granulator are presented, the technological features of the work of which complied with the optimal conditions of the prilling.

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Symbols

A_1, A_2, A_3 – coefficients of parabolic equation;

C_1 – differential equation solution constant;

d_{dr} - diameter of drop, m;

$d_{dr}^{max}, d_{dr}^{min}$ – bigger and smaller diameter of drops, m (mm);

Δd_{dr}^{ab} – absolute difference of drop diameters, m;

Δd_{dr}^{rel} – relative deviation of drop diameters;

$F_1(z)$ – polynomial function;

f_1, f_2 – upper and lower limits of frequency, 1/s;

f_{avi} – average frequency of vibration, which provides monodisperse jets decay, 1/s;

g – acceleration of gravity, m/s^2;

G_S – melt flowrate, m^3/s;

G_τ – the measured volume of the melt, m^3;

H – liquid column height (head), m;

n – number of measurements; granulator basket rotation velocity, rpm;

p – the outflow jet pressure, Pa;

p_0 – pressure of the surrounding environment, Pa;

r – radius of the jet, m;

t – the Student's criterion;

V – velocity of the liquid leaking from the granulator holes, m/s;

$\bar{x}$ – arithmetic mean value;

x – single parameter value;

z_o – initial axial distance, holes, m;

z – axial distance, holes, m;

Δ – maximum possible error of a single measurement, %;

ε – bilateral confidence interval of the arithmetic mean value;

λ_{max}, λ_{min} – maximum and minimum lengths of the wave, m;

ρ – liquid density, kg/m^3;

σ – root-mean-square deviation;

τ – the experimental time of melt outflow through the granulator hole, s.

υ_θ υ_r, υ_z – tangential, radial and axial components of the jet velocity respectively, m/s;

υ_{z_0} – initial axial component of the jet velocity respectively, m/s;

ϕ – discharge coefficient.

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