

This paper has substantiated the expediency and prospects of obtaining organomineral fertilizers by encapsulating mineral granules with an organic suspension in fluidized bed apparatuses. An overview of existing approaches to the mathematical description of the kinetics of granule growth in granulation processes in fluidized bed apparatuses is presented. A mathematical model of the kinetics of the formation of a hard shell around granules in a fluidized bed has been built. It shows that the kinetics depend on the size of the return particles, the specific flow rate of the suspension, the density of the suspension and granules, and the time of the process. Equations have been derived for determining the thickness of the hard shell and the specific flow rate of the suspension for individual granulation stages in a multi-stage granulator of the fluidized layer. Analytically, graphical dependences were built, which showed an increase in the thickness of the hard shell due to an increase in the specific flow rate of the suspension, the diameter of the return particles, and the time of the encapsulation process. The equations make it possible to determine the rational regime and technological parameters of the encapsulation process in order to obtain a coating of the predefined thickness at the surface of the granules. This ensures that a quality product is obtained, with a granulometric composition in a narrower range of particle size. To obtain granules of 2.5–4 mm in size, it is necessary to carry out the process in three- or four-stage granulators of the fluidized bed at specific suspension consumption of $(10-20) \cdot 10^{-4}$ kg/(kg·s). It is shown that with uniform growing of granules with a constant increase in the thickness of the shell in multistage granulators, the suspension consumption decreases by 2–3 times from the first stage to the subsequent ones. This approach reduces the operating and energy costs of the process

Keywords: granulation, fluidized bed, encapsulation, organic suspension, shell thickness, growth kinetics

DETERMINING THE MAIN REGULARITIES IN THE PROCESS OF MINERAL FERTILIZER GRANULE ENCAPSULATION IN THE FLUIDIZED BED APPARATUS

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Received date 07.07.2021 **How to Cite:** Ostroha, R., Yuhymenko, M., Bocko, J., Artyukhov, A., Krmela, J. (2021). Determining the main regularities in the process of mineral fertilizer granule encapsulation in the fluidized bed apparatus. *Eastern-European Journal of Enterprise Technologies*, 4 (6 (112)), 23–32. doi: <https://doi.org/10.15587/1729-4061.2021.239122>
Accepted date 17.08.2021
Published date 31.08.2021

1. Introduction

Nitrogen granular fertilizers that are produced at an industrial scale are widely used in the agro-industrial sector for the mass cultivation of agricultural plant raw materials.

The range of nitrogen fertilizers, which are used in all soil and climatic zones, is dominated by ammonium nitrate and urea. Along with the known advantages, these types of nitrogen fertilizers have significant disadvantages – high solubility in water, increased washability from the arable layer, which leads to contamination of surface and groundwater. In addition, the application of large doses of fertilizers is often associated with the accumulation in the main agricultural produce, as well as in the soil, of a significant amount of nitrate nitrogen, which leads to environmental degradation and a decrease in the quality of the resulting products.

In this regard, it is extremely important to ensure the creation of such forms of nitrogen fertilizers that have a reduced

physiological acidity and prolonged effect, which contributes to the effective use of nitrogen during the entire growing season. One of the promising ways to improve the properties of various materials is to modify the starting substances by applying a protective shell to their surface (encapsulation). Such a coating changes the physical and chemical properties of substances, improves their quality, expands functionality, thereby optimizing performance characteristics.

The main purpose of encapsulation of mineral fertilizers is to ensure the slow or controlled dynamics of the release of target components, which increases the utilization rate of the fertilizers obtained and makes it possible to sharply reduce the volume of their application to the soil.

Obtaining an encapsulated product in a suspended layer is used by world-famous manufacturers of fertilizers and pharmaceutical products: Urea Casale S. A. (Switzerland), Kahl Group (Germany), Stamicarbon (Netherlands), Toyo Engineering Corporation (Japan), Changzhou Xianfeng Drying Equipment

Company Ltd (China), Glatt (Germany), Uhde Fertilizer Technology (Netherlands), Rottendorf Pharma (Germany), etc. [1]. Paraffin wax, synthetic and natural rubbers, polyolefins, sodium silicate and calcium chloride solutions, etc. are widely used as the shell material [2]. Most encapsulating materials do not dissolve under the influence of moisture, and with each application of such fertilizers, the soil becomes more polluted.

In economically developed countries, organic production is rapidly spreading – an integrated system of management and production of food. This system, first of all, takes into consideration the preservation of the environment, the level of biological diversity, the conservation of natural resources, the use of high standards and methods of fertilizer production. Organic farming aims to improve public health by producing high-quality food, preserving soil fertility and the environment, and stimulating local and regional production. Therefore, the use of chicken manure as a capsule shell is very relevant since it solves the issue of obtaining an organomineral fertilizer of prolonged action and, at the same time, the problem of organic waste disposal [2].

One of the qualitative indicators of granular mineral fertilizers is the granulometric composition of the finished product. The increased content of small (less than 1 mm in size) and large (more than 4 mm) fractions leads to an uneven introduction of granules into the soil by scattering mechanisms, while small granules are overcrushed, resulting in increased dust formation.

Making granular fertilizers in fluidized bed devices leads to the formation of a product of polydisperse granulometric composition. Consumer requirements for granular mineral fertilizers in terms of granulometric composition are very strict, standards for mineral fertilizers imply the content of the commodity fraction with granule sizes of 1–4 mm in the range of 85–90 %. The fluidized bed granulation method does not warrant obtaining a product with such a narrow range of granule sizes. The technique of granulation in a multistage apparatus, in comparison with a single-stage (single-section) device, has features in the form of distribution of the granulated substance at individual stages (chambers). In this case, the variance of the size of the resulting granules is much less than that in a single-section apparatus. That is, the final product is more homogeneous in particle size in terms of granulometric composition.

The granulometric composition of the finished product is a function of a series of regime and technological parameters of the granulation and encapsulation process. Therefore, it is important to find out the trends in the influence of regime and technological parameters on the process of encapsulation of granules in fluidized bed devices, including individual chambers in multistage granulators. That would make it possible to choose such regime and technological parameters, optimal in their values, as the specific flow rate of the suspension, the size of the return particles, and the encapsulation time. A technological mode to be selected could ensure obtaining a quality product with a more monodisperse granulometric composition.

2. Literature review and problem statement

Encapsulation of dispersed materials in a state of fluidization is a common physical method of applying shells. However, the design and implementation of fluidized bed devices in most industries are constrained by the lack of

reliable methods for their calculation. Therefore, much attention has been paid recently to the construction and use of fundamental mathematical models [3].

When building mathematical models, it should be remembered that an actual fluidized bed device contains a huge number of particles at the same time. These particles have different and continuously changing sizes and move at different speeds in different directions. In the process of periodic movements, the film of the solution or suspension falls on the granule, dries, and leaves a dehydrated residue on this surface. The build-up of a significant layer of sediment occurs during many such cycles. These circumstances allow the fluidized bed apparatus to be considered as a system with concentrated parameters, thereby considering all particles to be under the same conditions, as well as introducing averaged characteristics of the growth rate of granules [4].

The development of a mathematical model is based on the hypothesis of uniform growth of granules, whereby the material is deposited on granules in the form of rings of constant thickness. It is also assumed that all particles in the layer are the same size and have a regular (spherical) shape.

The simplest linear law of the growth rate of granules (zero-order kinetics) was proposed in work [5]. The conclusion of this law is based on the assumption of proportionality of the mass growth rate of the surface of particles:

$$\frac{dM}{d\tau} = C \cdot l^2, \tag{1}$$

where C is the coefficient; l is the linear size of the granules, m.

The expression of zero order, that is, the independence of velocity on the particle size, follows from ratio (1) automatically. The disadvantage of this approach is the use of an indefinite coefficient.

Much simpler and more legitimate reasoning is given in work [6]. Assumptions are made about the uniformity of each particle's entry into the irrigation zone, the stationarity of the system, and the identity of the mechanism of growth of the surface of each particle. In this case, the growth rate is

$$\lambda = \frac{dx}{d\tau} = \frac{(G_M / \rho_{gr})}{\sum_1^n A_i \cdot N_i} = \text{const}, \tag{2}$$

where λ is the growth rate of the granule, m/s; G_M – solid phase capacity, kg/s; ρ_T – density of the solid phase, kg/m³; A_i – particle surface, m²; N_i is the number of particles.

The disadvantage of a given approach is difficulties in determining the true number of particles, which requires the use of indirect determination methods.

Thus, the proposed hypotheses regarding the growth rate of individual particles during dehydration of solutions in the fluidized bed are based on the integrated nature of the dependence λ on the total surface of the particles in the layer:

$$G_M = 4 \cdot \pi \cdot \rho_{gr} \cdot \int_0^\infty \lambda \cdot x^2 \cdot \rho(x) dx. \tag{3}$$

It follows from expression (3):

$$\lambda = \frac{G_M}{4 \cdot \pi \cdot \rho_{gr} \cdot \int_0^\infty x^2 \cdot \rho(x) dx} = \frac{G_M}{\rho_{gr} \cdot F_i}. \tag{4}$$

As a result, the following equation for the growth rate of granules was proposed:

$$\frac{dD}{d\tau} = \frac{2 \cdot G_M}{\rho_{gr} \cdot F_l} \cdot (A + B \cdot D). \quad (5)$$

This formula contains such a parameter as the surface of the particles of the layer, which also depends on the uncertainty of the number of particles. The presence of empirical constants A and B predetermines the applicability of equation (5) only for specific experimental conditions and cannot be widely used.

If we consider the entire volume of the fluidized bed as a set of elementary volumes (cells), then, from the entire set of granules, the neighboring cell would be penetrated by particles whose size is greater than some critical value. And particles whose size is less than the critical value would continue to be granulated in the layer, or move to the higher cells due to their removal by the gas stream. Then the distribution function (distribution density) of the granules in terms of size is expressed as follows [7]:

$$\frac{\partial f(\delta, \tau)}{\partial \tau} = \text{div}(u_r f(\delta, \tau)) + \frac{\partial(vf(\delta, \tau))}{\partial \delta} - \frac{\partial f(\delta, \tau)}{\partial G_y} \cdot \frac{dG_y}{d\tau}. \quad (6)$$

According to equation (6), the function of changing the density of the distribution of granules in any local region of the layer is determined by the movement of the granules from one point of working volume of the apparatus to another. This is due to:

- 1) forced movement of the particle flow (the first component takes into consideration the convective transfer of granules);
- 2) increasing the diameter of the granules (the second component takes into consideration the rate of linear growth of granules);
- 3) removal of small particles from the layer (the third component).

Neglecting the change in the granular composition due to convective transfer, grinding, and abrasion, and also considering that the growth rate of the granules is constant ($v = \text{const}$), equation (6) is transformed:

$$\frac{\partial f(\delta, \tau)}{\partial \tau} = \frac{vf(\delta, \tau)}{\partial \delta}. \quad (7)$$

Solving equation (7) using the Laplace transform produces the following dependence:

$$\delta = \delta_0 + v \left[\ln f_f(\delta, \tau) - \ln f_{el}(\delta, \tau) \right]. \quad (8)$$

Equation (8) describes the function of increasing the particle size depending on the growth rate of the granules and changing the density of the distribution of granules by size in the fluidized bed over time τ .

In work [8], it is proposed to divide working volume of the apparatus into two zones: granulation and drying of granules. This approach to modeling makes it possible to select the regime and technological parameters of the process, contributing to increasing the size and limiting the concentration of small particles in the finished product.

Paper [9] simulates the granulation process in an actual granulator based on a one-dimensional model of the balance

of particles, taking into consideration the number of particles, the frequency of collisions of particles with each other, the proportion of coating the surface of the particles with suspension. Determining these parameters causes considerable difficulties.

Numerical particle balance models were also used in modeling granulation processes. The authors of work [10] tested various numerical schemes to find simple but accurate enough schemes for solving the equation of the balance of granulated particles. Numerical schemes were applied taking into consideration the criteria of layering and agglomeration, which were taken into consideration in the particle balance equation. The resulting equations are quite cumbersome and require a lot of computation time.

The authors in work [11] prove the importance of the influence exerted on the process of coating the granules by such factors as the height of the fluidized bed and the rate of circulation of solid particles in the layer. It is shown that the regulation of these parameters leads to a change in the thickness of the particle coating. However, the effect of the processing time of the granules and the flow rate of the suspension sprayed on the fluidized bed is not shown.

In work [12], a new conceptual model of simultaneous control over the size and porosity of particles in the process of granulation in the fluidized bed was proposed, which ensured stable process operation, automatic adjustment of the desired properties of the finished product, and prevention of unforeseen violations of the technological regime. However, the particle size was adjusted by auxiliary processes – grinding and sifting of the finished granules and not by the influence of the regime and technological parameters of the main granulation process.

In work [13], a mathematical model of layer-by-layer granulation in the fluidized bed was proposed. Since a given model is based on the numerical linearization of nonlinearized dynamics of the object, it is quite difficult for practical implementation.

A mathematical model of granulation in a fluidized bed based on particle balance equations was proposed in [14]; its parameters depend on the growth rate of granules and the density of irrigation of the surface of granules with suspension [14]. A given model makes it possible to perform detailed modeling of granulation plants taking into consideration the physical microstructures of the material. The multiscale model, built in the cited paper, provides for several stages of calculation and is, therefore, quite complex.

In work [15], the multifactorial approach to modeling the granulation processes in fluidized beds was offered. The authors indicate that a given procedure is an acceptable alternative in modeling such a complex process as granulation. However, the regression equations were built for specific conditions and cannot be extended to a larger field of the granulation process in fluidized layers.

In work [16], the influence of the concentration of urea as a binder in the granulation process was investigated; the minimum possible concentration was experimentally selected to achieve the necessary quality of the finished product. The results were obtained specifically for urea as a binder and cannot be extended to granulation when organic matter is used as a binder.

In work [17], a mathematical model is proposed, which takes into consideration the hydrodynamics of the fluidized bed, the contact of the drop with the particles and their adhesion to the surface, as well as the kinetics of drying the solution on the surface of the particle. When building the model, the process of dehydration and granulation in the fluidized bed is considered as a heterogeneous three-phase

process, during which three separate phases interact: particles – granulation centers, the initial substance – ammonium sulfate in the form of droplets, and a heat carrier – air. However, similar to the previous work, an inorganic substance was used as a binder, so those results are limited.

In work [18], a mathematical model of the balance of mass and amount of motion has been built to describe the process of granulation of the melt by spraying in a periodic fluidized bed, where coating and agglomeration can occur simultaneously. The work formulates a criterion for predicting the limit of agglomeration. A given criterion was suitable for predicting the growth regime of granules for granulating urea melt with spraying in a fluidized bed. However, the results were obtained specifically for an inorganic substance (urea) as a binder and cannot be extended to granulation when organic matter is used as a binder.

Our literature review reveals that research is mainly aimed at studying the granulation process, that is, the kinetics of granule formation in general. At the same time, authors strive to detail the process and take into consideration hard-to-determine parameters, which greatly complicates the calculation algorithm. The process of applying the shell of organic origin, namely chicken manure, on the surface of the finished granule, has not been studied in detail. This is due to the fact that the limiting factor among consumers of such fertilizers is a higher price compared to traditional fertilizers, limited shelf life, the lack of data on the technological modes of manufacture. Consequently, it is expedient to construct such a mathematical model that would reflect the relationship of the main regime and technological parameters in the process of encapsulation of granules with an organic shell in fluidized bed apparatuses. Comparison of the constructed mathematical model with the results of the experiment would reveal the physical mechanism of the processes that occur on a single granule and in the layer in general. In addition, confirmed mathematical models could reveal ways to control and optimize the technology of encapsulation of granular products with an organic shell.

3. The aim and objectives of the study

The aim of this work is to identify the basic regularities of the process of encapsulation of mineral fertilizer granules as a result of dehydration of organic suspensions in the fluidized bed apparatus. This will make it possible to obtain an organic coating of the predefined thickness on the surface of the granules and predict the optimal particle size of the granulometric composition of the resulting product.

To accomplish the aim, the following tasks have been set:

- to build a mathematical model of the kinetics of shell formation during encapsulation of granules;
- to investigate analytically the kinetics of enlargement of mineral particles at each stage of granulation by coating their surface with organic matter.

4. The study materials and methods

The object of research: the process of coating granular fertilizers with an organic shell.

Constructing a mathematical model of the kinetics of the formation of a shell around the granules in a fluidized layer is based on the hypothesis of uniform-surface growth, accord-

ing to which the material is deposited on the surface of the retour granules in the form of rings of constant thickness. It is also assumed that all particles in the layer are the same size and have the correct (that is, spherical) shape (Fig. 1).

Thus, the increase in the mass of the layer of the organic shell on the surface of the spherical granule of the retour is expressed by the following differential equation:

$$dM = (G_s \cdot x_{dm}) d\tau = G_{sh} d\tau, \tag{9}$$

where dM is the increase in organic mass, kg; G_s – mass suspension consumption, kg/s; x_{dm} – mass fraction of dry matter in suspension, kg/kg; G_{sh} – shell material consumption, kg/s; τ – time, s.

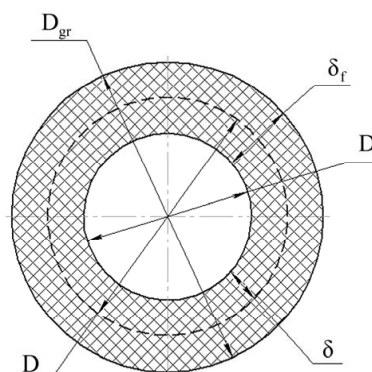


Fig. 1. Scheme of the granule coated with a shell: D_r , D , D_{gr} – respectively, the initial diameter of the retour granule, the current and final diameters of the resulting granule; δ , δ_f – current and final thickness of the shell

We studied the basic laws of the process of encapsulation of granules at a laboratory bench (Fig. 2).

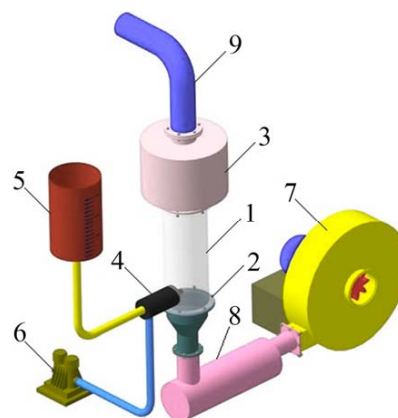


Fig. 2. Scheme of experimental installation for encapsulation of granules: 1 – encapsulation chamber; 2 – gas distribution grid; 3 – separation chamber; 4 – pneumatic nozzle; 5 – measuring tank; 6 – compressor; 7 – gas blower; 8 – heater; 9 – corrugation

As a nucleus, urea was used, which is a polydisperse mixture of granules measuring 1–4 mm in the range of 90–95 % by weight. A solution of chicken droppings was used as an organic suspension. Chicken manure is a concentrated organic substance containing all the main nu-

trients. It is used as a fast- and potent fertilizer since the nutrients in it are in an easily accessible form for plants.

The acidity (pH factor) of chicken droppings varies depending on the age and diet of the birds. The acidity of chicken droppings is in the pH range of factor 6.5–8.0, which is close to moderately alkaline. With this trend, chicken droppings are suitable for use on almost all types of soils.

The unit includes encapsulation chamber 1 of plexiglass, which makes it possible to visualize the process under study. Granulation occurs directly in the fluidized bed, which is created on the surface of gas distribution grid 2 when the operating velocity of the gas flow in the free section of the apparatus reaches 4.8 m/s. At the top of the apparatus, there is separation chamber 3, in which granules smaller than the limit size are separated from the flow and lowered back into the fluidized layer. In the wall of the encapsulation chamber, at approximately the average height of the layer, pneumatic nozzle 4 is mounted, through which compressed air and a suspension of chicken manure are supplied. Preliminarily, before entering measuring container 5, the organic matter is processed to obtain a fine homogeneous mass, which is a mixture of the liquid suspension phase and small (10–20 μm) organic particles. The unit is equipped with compressor 6 for supplying compressed air to the nozzle, and gas blower 7 for supplying air heated in heater 8 to the encapsulation chamber. The exhaust gas is sent to the exhaust device of the laboratory through air corrugation 9.

The experimental study of the encapsulation process in the fluidized bed was carried out by feeding a suspension of chicken manure through a pneumatic nozzle with a flow rate of 25 ml/min. The retour batch, consisting of urea particles with an average diameter of 2 mm, was loaded on the surface of the gas distribution grid. Under the grate, air was supplied, heated to a temperature of 80–85 °C. The necessary speed of the ascending air flow was set, which was created by a fluidized layer. The temperature in the granule layer was in the range of 60–65 °C, at which the shell encapsulation mode was implemented as the most rational [2]. The chicken manure suspension was sprayed into a layer of suspended granules using an air nozzle and compressor. Every 20 minutes of operation of the plant, it was turned off and a sieve analysis of the formed granules was performed. Then the experiment continued. Thus, for each subsequent 20-minute process, the output granules loaded into working chamber were the final granules obtained in the preceding experiment.

According to estimates [19], in single-stage fluidized bed apparatus, the average residence time of particles in the layer is in the range of 2–6 minutes, that is, an average of 4 minutes (240 s). Therefore, this time range is selected for further analytical calculations.

The methods of physical and mathematical (computer) modeling were used in this work when coating mineral fertilizer granules in a state of fluidization. An experimental study of the regime parameters of the main technological equipment of the laboratory installation for encapsulation of mineral fertilizers was carried out. We determined the granulometric composition of the particles by the method of sieve analysis. To determine the structure of two-layer organo-mineral granules, a microscope method was used. Processing and generalization of experimental and analytical results were performed using the Microsoft Excel and Mathcad software.

5. The results of studying the process of encapsulation of granules in a fluidized bed

5.1. Mathematical model of the shell formation kinetics during granule encapsulation

It is accepted that the increase in the mass of the layer of organic shell on the surface of the spherical granule of the retour occurs at a time from $\tau_0=0$ to τ . At the same time, the sizes of the granules vary from D_p to D , respectively ($D_p < D$). Consequently, the following is obtained:

$$M = \int_0^{\tau} G_{sh} d\tau = G_{sh} \cdot \tau. \quad (10)$$

The total mass of organic shell of granules:

$$M = \rho_{sh} \cdot V_{sh} = \rho_{sh} \cdot (V_{gr} - V_r) = \rho_{sh} \cdot n \cdot \frac{\pi}{6} \cdot (D_{gr}^3 - D_r^3), \quad (11)$$

where V_{gr} , V_{sh} are the volumes of the obtained granule and shell, respectively, m^3 ; D_{gr} , D_r are the diameters of the obtained granule and retour granules, respectively, m; n is the number of particles in the layer; ρ_{sh} is the density of shell material, kg/m^3 .

Substituting equation (10) into equation (11), the following is obtained:

$$G_{sh} \cdot \tau = \rho_{sh} \cdot n \cdot \frac{\pi}{6} \cdot (D_{gr}^3 - D_r^3), \quad (12)$$

Hence, the value D_{gr}^3 :

$$D_{gr}^3 = \frac{6}{\pi \cdot n} \cdot \frac{G_{sh} \cdot \tau}{\rho_{sh}} + D_r^3 = \frac{D_r^3 \cdot G_{sh} \cdot \tau}{V_{gr} \cdot \rho_{sh}} + D_r^3. \quad (13)$$

The shell material consumption:

$$G_{sh} = g_0 \cdot M_{gr} = g_0 \cdot V_{gr} \cdot \rho_{gr}, \quad (14)$$

where g_0 is the specific consumption of the shell material (suspension of organic matter), $\text{kg}/(\text{kg}\cdot\text{s})$; ρ_{gr} is the density of retour granules, kg/m^3 .

Substituting equation (14) in equation (13), thereby expressing the thickness of the shell as the difference in the diameters of the granule, after the transformations, a dependence is obtained that makes it possible to predict the value of the thickness of the organic shell at any given time:

$$\delta = \frac{1}{2} \sqrt[3]{\frac{D_r^3 \cdot \rho_{gr} \cdot g_0 \cdot \tau}{\rho_{sh}} + D_r^3} - D_r = \frac{D_r}{2} \cdot \left(\sqrt[3]{g_0 \cdot \frac{\rho_{gr}}{\rho_{sh}} \cdot \tau + 1} - 1 \right). \quad (15)$$

From equation (15), an expression is obtained to determine the consumption of the shell material depending on the specified thickness of the shell and the processing time of the granule in the fluidized bed:

$$g_0 = \frac{2\delta^3 \cdot \rho_{sh}}{\rho_{gr} \cdot D_r^3 \cdot \tau}. \quad (16)$$

Equations (15), (16) hold for single-stage fluidized bed granulators. For multistage granulators of the fluidized layer,

these equations are recorded, according to the cell model, for each step in the form of the following equations:

$$\left\{ \begin{aligned} \delta_1 &= \frac{D_r}{2} \cdot \left(\sqrt[3]{g_{01} \cdot \frac{\rho_{gr}}{\rho_{sh}} \cdot \tau_1 + 1} - 1 \right), \\ \delta_2 &= \frac{(D_r + 2\delta_1)}{2} \cdot \left(\sqrt[3]{g_{02} \cdot \frac{\rho_{gr}}{\rho_{sh}} \cdot \tau_2 + 1} - 1 \right), \\ \delta_3 &= \frac{(D_r + 2\delta_1 + 2\delta_2)}{2} \cdot \left(\sqrt[3]{g_{03} \cdot \frac{\rho_{gr}}{\rho_{sh}} \cdot \tau_3 + 1} - 1 \right), \\ \delta_n &= \frac{(D_r + 2\delta_1 + 2\delta_2 + 2\delta_n)}{2} \cdot \left(\sqrt[3]{g_{0n} \cdot \frac{\rho_{gr}}{\rho_{sh}} \cdot \tau_n + 1} - 1 \right), \end{aligned} \right. \quad (17)$$

$$\left\{ \begin{aligned} g_{01} &= \frac{2\delta_1^3 \cdot \rho_{sh}}{\rho_{gr} \cdot D_r^3 \cdot \tau}, \\ g_{02} &= \frac{2\delta_2^3 \cdot \rho_{sh}}{\rho_{gr} \cdot (D_r + 2\delta_1)^3 \cdot \tau}, \\ g_{03} &= \frac{2\delta_3^3 \cdot \rho_{sh}}{\rho_{gr} \cdot (D_r + 2\delta_1 + 2\delta_2)^3 \cdot \tau}, \\ g_{0n} &= \frac{2\delta_n^3 \cdot \rho_{sh}}{\rho_{gr} \cdot (D_r + 2\delta_1 + 2\delta_2 + 2\delta_n)^3 \cdot \tau}. \end{aligned} \right. \quad (18)$$

Analysis of the obtained dependences (17) and (15) shows that the kinetics of granule growth in the suspended layer depends on the initial size of the retour particles, the specific flow rate, the density of the suspension and the granules themselves, as well as the time of applying a coating on the surface of the granule.

5.2. The results of the analytical calculations based on the mathematical model

Fig. 3 shows the dependence of the thickness of the shell on the time of the process of encapsulation of granules in the fluidized bed. The calculation was carried out according to equation (15) at $g_0=2 \cdot 10^{-4}$ kg/(kg·s); $\rho_{gr}=1,330$ kg/m³ (urea granule); $\rho_{sh}=1,100$ kg/m³ (chicken dropping suspension); $D_r=2$ mm.

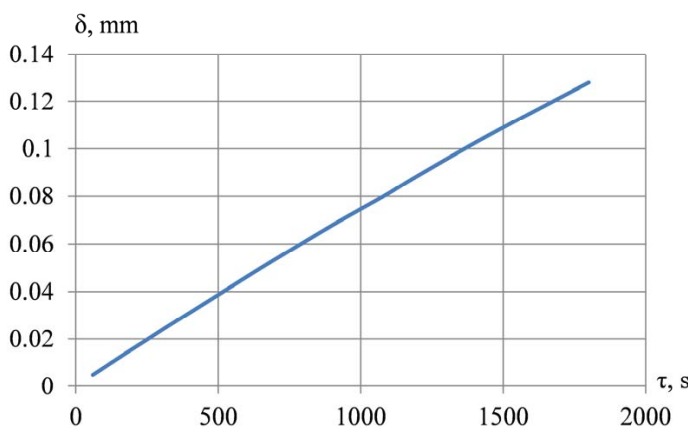


Fig. 3. Dependence of shell thickness on the time of the encapsulation process

Fig. 4 shows a dependence of how much organic matter suspensions need to be served into the layer to obtain granules with a certain shell thickness. The calculation was carried out according to equation (16) at $\rho_{gr}=1,330$ kg/m³ (urea granule); $\rho_{sh}=1,100$ kg/m³ (chicken dropping suspension); $D_r=2$ mm, and $\tau=360$ s (6 min).

Table 1 gives the results of calculations of the thickness of the shell by granulation stages in a multistage granulator of the fluidized layer according to equations (17).

Fig. 5 shows the dependence of the thickness of the granule shell on the diameter of the retour particles supplied to the fluidized bed. The calculation was carried out according to equation (15) at $g_0=2 \cdot 10^{-4}$ kg/(kg·s); $\rho_{gr}=1,330$ kg/m³ (urea granule); $\rho_{sh}=1,100$ kg/m³ (chicken dropping suspension), and $\tau=360$ s (6 min).

Plots (Fig. 3–5) confirm that the kinetics of granule growth in the fluidized bed depends mainly on such parameters as the time of applying a coating on the surface of the granule, the specific flow rate of the suspension, and the size of the retour particles.

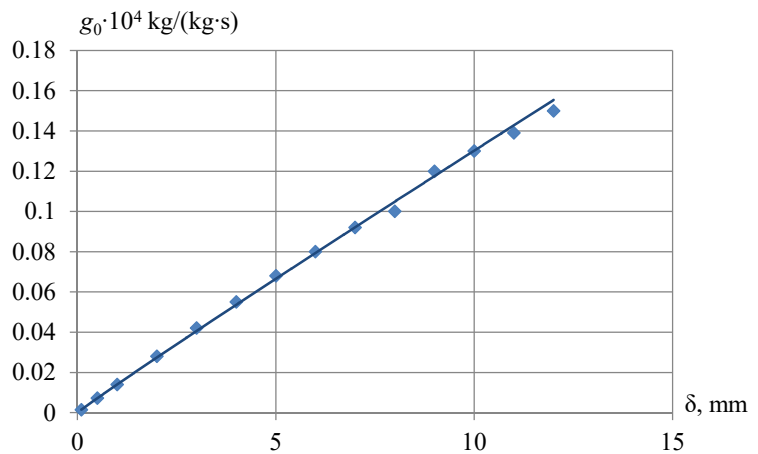


Fig. 4. Dependence of the thickness of the shell on the specific flow rate of the suspension

Table 1

Shell thickness at granulation stages

Granulation stage	Suspension specific consumption, kg/(kg·s)	Shell thickness, mm
I	$2 \cdot 10^{-4}$	0.0282
	$3 \cdot 10^{-4}$	0.042
	$4 \cdot 10^{-4}$	0.055
II	$2 \cdot 10^{-4}$	0.0289
	$4 \cdot 10^{-4}$	0.056
	$10 \cdot 10^{-4}$	0.132
III	$2 \cdot 10^{-4}$	0.0298
	$20 \cdot 10^{-4}$	0.92

Fig. 6 shows the results of experimental studies into the kinetics of organic shell build-up.

In the process of encapsulation, the distribution curve changes its shape and has one maximum (Fig. 7). This means that under the operating conditions of encapsulation, organic matter is fixed on the surface of the particles with a strong layer and does not chip in certain places of the granule. The presence of a maximum in the distribution curve is also observed with an increase in the time of the encapsulation process and the suspension load.

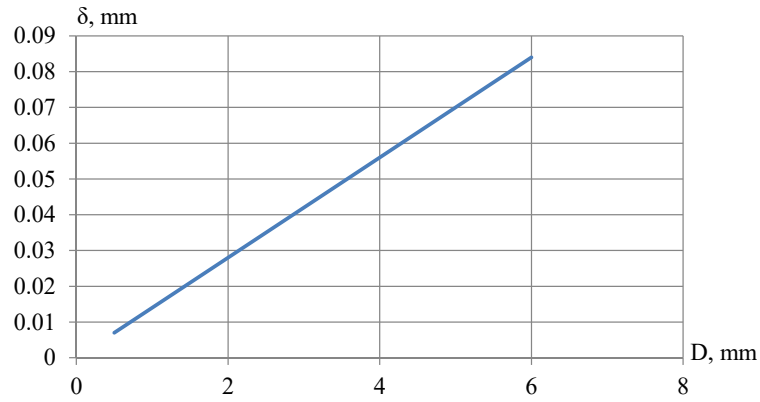


Fig. 5. Dependence of shell thickness on retour particle diameter

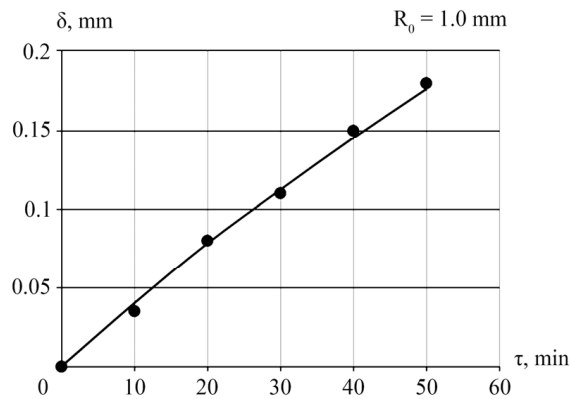


Fig. 6. Experimental values of the organic shell build-up kinetics at suspension flow rate $g_0=1.86 \cdot 10^{-4}$ kg/(kg·s)

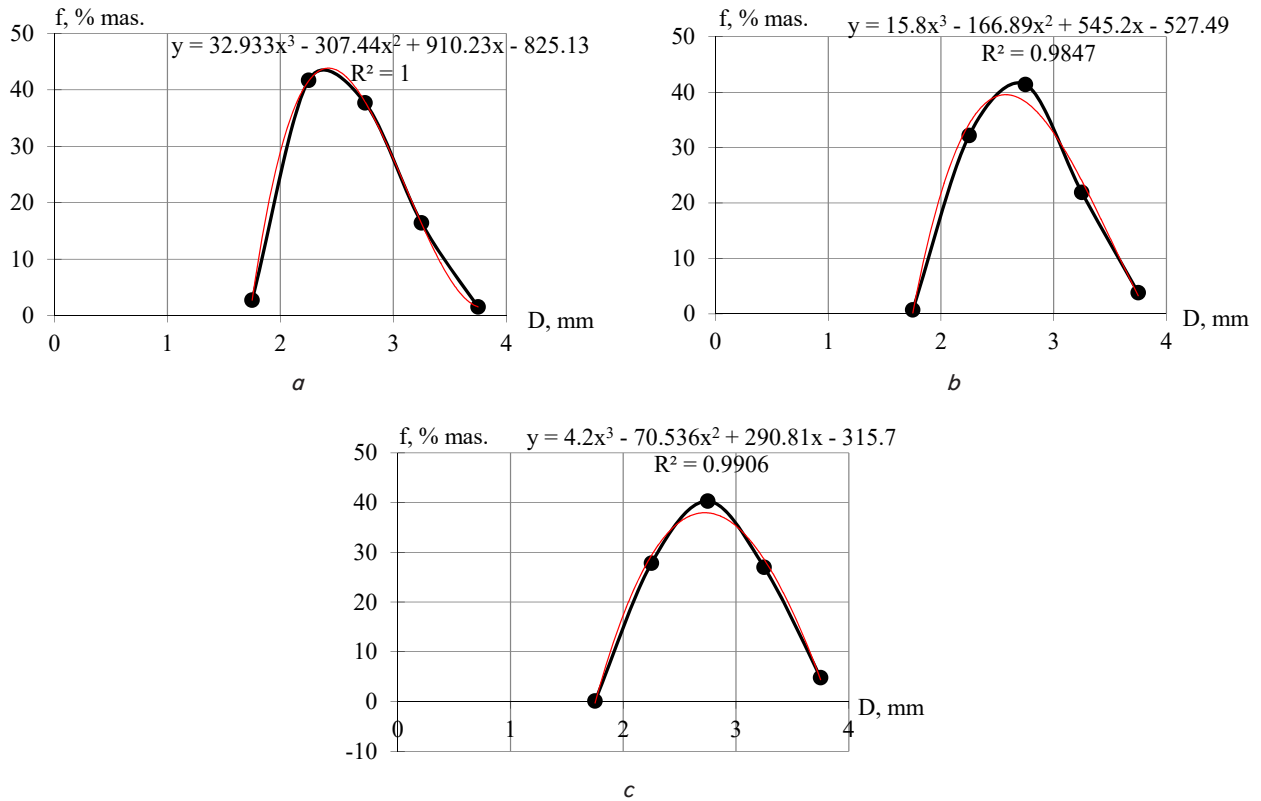


Fig. 7. Particle size distribution at suspension flow rate $g_0=1.86 \cdot 10^{-4}$ kg/(kg·s) at times: a – 20 min; b – 40 min; c – 60 min

6. Discussion of results of the analytical study into the influence of regime and technological parameters on the encapsulation process

The dependence (Fig. 3) shows a monotonous increase in the thickness of the shell on the processing time of granules in the fluidized bed in the study range. Then, based on the dependence (Fig. 3), in single-stage granulators of the fluidized bed, when encapsulating urea granules with an average diameter of 2 mm, organomineral granules with a shell thickness of 0.019 mm and a diameter of 2.04 mm can be obtained. Accordingly, for two-stage – 0.04 mm and 2.08 mm, three-stage – 0.055 mm and 2.1 mm. That is, it is possible to predict the choice of granulator design in order to obtain finished granules of the required average diameter.

The increase in the thickness of the shell is due to the uniform distribution of the liquid phase on the surface of the granule with a continuous renewal of the surface under conditions of active circulation of particles in the fluidized bed. It should be noted that the average time of stay of particles in the layer, equal to the processing time of granules in the layer, affects the size of the granules under conditions of only the periodic process. For continuous processes, this parameter does not affect the kinetics of granule growth since the granules are constantly removed from the layer. That is, the nature of the dependence (Fig. 3) is characteristic only of periodically working fluidized bed granulators.

Comparing the graphical dependences obtained analytically (Fig. 3) and experimentally (Fig. 6), we determine that the absolute error of calculations is 5–15 %.

Data in Table 1 show that with a small specific flow rate of suspension of $(2-5) \cdot 10^{-4}$ kg/(kg·s) we obtain a slight increase in the thickness of the shell with an increase in the number of granulation stages. That is, in order to grow granules from the initial diameter of 2 mm to the diameter of the finished granules of 2.5–4 mm, it is necessary to carry out the process in three- or four-stage granulators of the fluidized bed. In this case, the specific flow rate of the suspension is $(10-20) \cdot 10^{-4}$ kg/(kg·s).

As shown by equation (15), in the case of the growth of granules on their surface, the thickness of the shell and, accordingly, the final diameter of the granule is greater the larger the diameter of the return particles. This is confirmed by the dependence (Fig. 5), which shows a monotonous increase in the thickness of the shell dependent on the diameter of the return particles. However, the mode of growth of granules on their surface is possible under certain temperature conditions [20], with a deviation from which new small granules are formed in the layer, or their agglomeration occurs.

Equation (18) makes it possible to determine the values of the specific flow rates of the suspension by granulation stages in multistage granulators in order to obtain granules of specified sizes. Thus, it is necessary to ensure the thickness of the granule shells of about 0.25 mm at each stage of granulation. The initial size of the return particles is 1 mm. Then we have the diameter of the finished granules: after the first stage of granulation – 1.5 mm; after the second – 2.0 mm; after the third – 2.5 mm. The specific flow rate of the suspension are reduced: in the first section – $g_0=0.7 \cdot 10^{-4}$ kg/(kg·s); second – $g_0=0.2 \cdot 10^{-4}$ kg/(kg·s); third – $g_0=0.089 \cdot 10^{-4}$ kg/(kg·s). That is, under a given technological mode, which provides for a reduction in the specific flow rate of the suspension from the first section to

the subsequent ones, the operating and energy costs of the process are reduced.

If the flow rate is the same over steps ($0.7 \cdot 10^{-4}$ kg/(kg·s)), then, at the second stage, the growing would occur to a shell thickness of 0.75 mm, and finished granules of 3.0 mm would come out of it. That is, under a given technological mode, it would suffice to use a smaller number of stages, which could reduce the size and metal consumption of the granulator and, accordingly, the capital costs of the process.

Equations (15) to (18) include the average value of the diameter of the return particles. However, various regime and technological parameters affect the granulometric composition of the finished product. In the case of violation of the uniformity of irrigation of the layer with suspension, the formation of sufficiently large lumps or, to a greater extent, the formation of a small fraction can occur. That is, it is necessary to find out the influence of regime and technological parameters on the granulometric composition of the product. Therefore, in the future, it would be advisable to propose a dependence in the form of a function of the distribution of particles by size, which would clarify the calculations for equations (15) to (18).

Thus, the process of growing urea granules with chicken manure proceeds without new centers of granulation, that is, there is no generation within the system, the so-called internal return.

In the case of granule growth on the surface, their diameter is larger the diameter of the return particles. In this case, it is advisable to separate the small fractions from the return mixture before feeding it into the fluidized layer of the granulator. A given process is effectively carried out, as shown by study [21], in separators with a cascade of inclined shelves to capture small fractions.

The study reported here apply to the kinetics of coating mineral granules with a diameter of 1–4 mm with an organic shell in a fluidized bed in the range of operating fluidization rates for granules of these sizes. The mathematical model built implies that all granules in the layer are evenly covered with a shell. It does not take into consideration the mechanism of formation of small particles, which would inevitably be carried away with the flow, or part of them would pollute the finished product. Therefore, this issue is to be addressed in further research.

7. Conclusions

1. We have built a mathematical model of the kinetics of shell formation during encapsulation of granules, which shows that the kinetics of granule growth in the fluidized layer depends on the initial size of the return particles, the specific flow rate, and density of the suspension and the granules themselves, as well as on the time of applying a coating on the surface of the granule. The equations derived show a tendency to increase the thickness of the shell with an increase in the processing time of granules in the layer, the specific flow rate of the suspension, and the diameter of the return particles. In this case, the thickness of the shell in direct proportion depends on the diameter of the return particles and to a lesser extent depends on other parameters.

2. The analytical calculations, based on the model built, have made it possible to determine the rational regime and technological parameters of the encapsulation process in the fluidized bed. In single-stage fluidized bed granulators,

with an average processing time of 4 minutes, the thickness of the coating shell is 0.02 mm, the diameter of the granules is 2.04 mm. The suspension consumption is $2 \cdot 10^{-4}$ kg/(kg·s), the diameter of the retour particles is 2 mm.

To increase the thickness of the coating shell and, accordingly, the size of the granule, it is necessary to increase the number of granulation stages. In two-stage fluidized bed granulators with an average processing time of 8 minutes, the thickness of the coating shell is 0.04 mm, the diameter of the granules is 2.08 mm. The suspension consumption is $2 \cdot 10^{-4}$ kg/(kg·s), the diameter of the retour particles is 2.04 mm. In three-stage fluidized bed granulators with an average processing time of 12 minutes, the thickness of the coating shell is 0.055 mm, the diameter of the granules is 2.1 mm. The suspension consumption is $2 \cdot 10^{-4}$ kg/(kg·s), the diameter of the retour particles is 2.08 mm.

A small consumption of suspension, in the range of $(2-5) \cdot 10^{-4}$ kg/(kg·s), does not have a significant effect on the growth of granules. Therefore, to obtain granules of 2.5–4 mm in size, it is necessary to carry out the process in three- or four-stage granulators of the fluidized bed at specific suspension flow rates $(10-20) \cdot 10^{-4}$ kg/(kg·s). With

uniform growing of granules with a constant increase in the thickness of the shell in multistage granulators, the suspension consumption is reduced by 2–3 times from the first stage to the subsequent ones. This approach reduces the operating and energy costs of the process. With a constant specific flow rate of the suspension, it is possible to have a smaller number of stages, which would reduce the size and metal intensity of the granulator and, accordingly, the capital costs of the process.

Acknowledgment

This research work has been supported by the Slovak Grant Agency VEGA Grant No. 1/0500/20 “Research of mechanical properties of materials with complex internal structure by numerical and experimental methods of mechanics” and by the Ministry of Science and Education of Ukraine under the project “Small-scale energy-saving modules with the use of multifunctional devices with intensive hydrodynamics for the production, modification and encapsulation of granules” Project No. 0119U100834.

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