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DETERMINATION OF THE TEMPERATURE OF MINERAL FERTILISER GRANULES AFTER CONTACT WITH THE AIR IN A GRANULATION TOWER

The object of research is the process of cooling mineral fertilizer granules in a granulation tower. The main problem that was solved was the analysis of the temperature mode of cooling the granules to increase their strength and quality, as well as to reduce the probability of their destruction during storage and transportation.

The design of a rotating vibrating granulator (RVG) and a mathematical model for calculating the temperature of granules and air at different stages of the granulation process are presented. Reynolds, Peclet and Prandtl criteria are used to describe hydrodynamic and thermodynamic processes.

In the course of the work, a calculation model and the possibility of predicting the final temperature of mineral fertilizer granules were created, which allows to avoid negative consequences, such as a decrease in the strength of the granules and their destruction during shipment, transportation and introduction into the soil. Improving the technological performance of the granulation tower, in particular the temperature regimes of granule cooling, contributes to the improvement of product quality. The calculation model allows to adjust the process parameters to ensure the formation of granules with specified properties that meet modern requirements for the monodisperse composition of mineral fertilizer granules.

Results were obtained that show the influence of hydrodynamic and thermodynamic factors on the process of cooling and crystallization of granules. This is due to the use of a rotating vibrating granulator, which ensures uniform distribution of liquid droplets across the cross section of the tower and their effective cooling due to contact with the air flow.

The results can be used in practice to improve the operation of granulation towers in the production of mineral fertilizers, which allows to improve the quality of products and improve their storage and use. Compared to similar methods, the use of the proposed models provides increased strength and uniformity of granules, which are key advantages in conditions of large-scale production of fertilizers.

Keywords: *granulation tower, heat transfer coefficient, rotating vibrating granulator, mineral fertilizers, thermodynamic processes, hydrodynamic parameters.*

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1. Introduction

Growing needs to increase the production of agricultural products leads to the need for more and more mineral fertilizers. In the global production of mineral fertilizers, the main direction of large-scale production of mineral fertilizers is the production of mineral fertilizers using tower methods. This method is based on building a tower with a floor diameter of several to tens of meters, the height of which reaches hundreds of meters (Fig. 1) [1].

A granulator or several granulators is located in the upper part of such a tower, depending on the loads on the products being produced. The task of this granulator is to receive the slurry of mineral fertilizers in the form of a viscous liquid, called slurry, from the technological line where this slurry is produced, and to divide it into drops of the same size as possible.

The drops move along the trajectories (Fig. 2) to the bottom of the granulation tower and during this movement they cool down (Fig. 3), coming into contact with the cold air flow and crystallize, forming granules.

At the moment, there is a big problem of ensuring the quality of mineral fertilizer granules, which is associated with insufficient rationalization of the cooling process in granulation towers. The requirements for the monodisperse composition of the granules are increasing, as this affects their storage, transportation, and the efficiency of application to the soil. Most of the existing technologies do not provide the necessary level of quality of granules due to the uneven distribution of liquid droplets along the cross-section of the tower and insufficient cooling efficiency, which leads to a decrease in the strength of the granules and their destruction [2–4].

The experience of various researchers shows that the use of innovative designs of granulators, such as rotating vibrating granulators, allows to significantly improve these indicators [5–7]. However, such solutions are not yet fully adapted to the specific conditions of production in Ukraine.

The approaches developed by Ukrainian scientists take into account the peculiarities of the national industry, but need further improvement [8]. The perspective of this research lies in the implementation of new methods of calculation and modeling of the process of cooling granules, which will allow to increase the efficiency of production and the competitiveness of products on the international market.

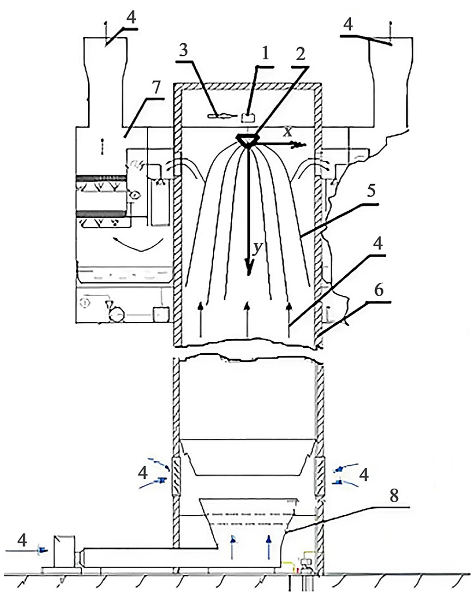

Fig. 1. Scheme of the granulation tower:
1 – granulator (RVG); 2 – granulator basket; 3 – float into the granulator; 4 – direction of air movement; 5 – granule movement trajectories; 6 – granulation tower; 7 – equipment for cleaning and removing air from the tower; 8 – pseudo boiling layer of granules

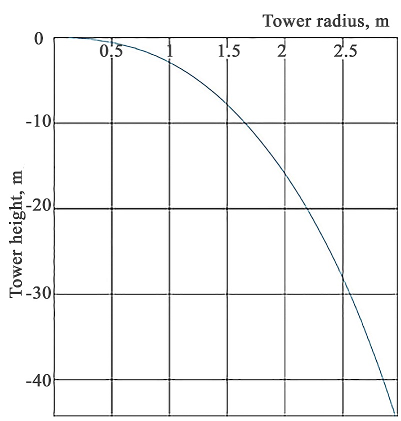

Fig. 2. The granule trajectory

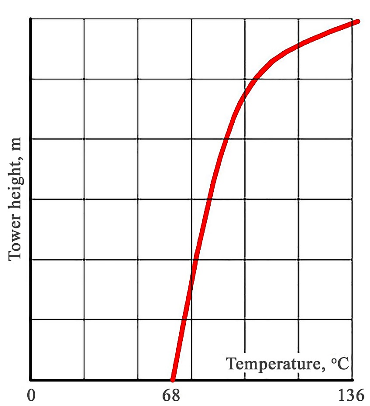

Fig. 3. Change in the granule temperature along the height of the tower

The aim of this research is to develop a mathematical model for calculating the temperature regimes of mineral fertilizer granule cooling in the granulation tower in order to increase their strength and quality. The scientific part includes the study of the influence of hydrodynamic and thermodynamic factors on the process of cooling and crystallization of granules. The practical part involves using the obtained results to improve the design of the rotating vibrating granulator (RVG) and setting process parameters to ensure stable product quality, which will minimize losses during transportation and storage of mineral fertilizers. This will make it possible to increase the competitiveness of production and meet modern requirements for the quality of granular fertilizers.

2. Materials and Methods

At the Department of Chemical Technology of Sumy State (Ukraine) a technology was developed for obtaining a monodisperse composition of granules in the tower production of mineral fertilizers. As well as the production of granulators using the vibrational effect on the jets of liquid flowing out of the so-called «basket» of the granulator.

The further development of production with the production of a large amount of mineral fertilizers in one granulation tower led to the creation and construction of towers of large diameter. For such towers, a design (Fig. 4) of a rotating vibrating granulator (RVG) was developed.

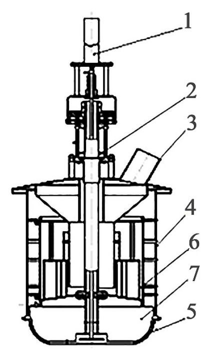

Fig. 4. Rotating vibrating granulator (RVG):
1 – vibrating device; 2 – bearing assembly; 3 – float inlet pipe; 4 – cylindrical body; 5 – perforated bottom (basket); 6 – distributor; 7 – pressure vanes

With the help of the rotation of the basket of the vibrating granulator and under the action of centrifugal forces, the float drops are distributed over the large cross-sectional area of the granulation tower evenly over the entire surface. Thanks to this, the melt droplets are in contact with the cold coolant, which is air, throughout the entire volume of the working space of the granulation tower. The same conditions for the crystallization process are created for all drops, which has a positive effect on improving the quality of products.

The technological factors of the granulator include the vibration effect on the melt of mineral fertilizers, the dispersion of jets of liquid (melt) on drops and the distribution of drops along the passage of the tower. However, their further contact with air flow is of great importance for the formation of the properties of fertilizer granules. This contact affects the process and depends on a number of important hydrodynamic and thermodynamic parameters.

Ultimately, all this variety of hydro and thermodynamic factors affects such an important indicator that characterizes product quality as the strength of granules. Therefore, determining the effect of hydro and thermodynamic factors on the formation of the granule and its strength, determining and calculating the temperature regime of granule cooling is an urgent task.

3. Results and Discussions

In order to solve the problem related to the optimal setting of the cooling temperature regime of mineral fertilizer granules in the granulation tower, and based on the experience of implementing rotary vibrating granulators (RVG) at various enterprises for the production of ammonium nitrate and urea, a comprehensive analysis of laboratory data of mineral fertilizer manufacturers was carried out and a theoretical description of thermodynamic processes occurring in the working space of the granulation tower.

To describe the hydrodynamics of the movement of granules in the tower, the Reynolds criterion is used. Peclet and Prandtl criteria are used to describe thermodynamic conditions. The creation of a mathematical model for calculating the final temperature of granules and determining the heat transfer coefficient is based on these criteria. For this, an approach was chosen that uses the Nusselt criterion dependence, tested for calculations of the interaction of ammonium nitrate or urea granules with air. At the same time, for air, the Prandtl criterion is practically easy to find, depending on various factors, according to reference data [9]. The Reynolds, Peclet and Nusselt criteria have the following form:

$$Re = \frac{W_g R_k \rho_{vozd}}{\mu_{vozd}}, \quad (1)$$

$$Pe = \frac{W_g R_k}{\alpha_{vozd}}, \quad (2)$$

$$Nu = 2 + 0.35\, Re^{0.58}\, Pr^{0.33} + Pe^{0.54}\, Pr^{0.35}, \quad (3)$$

where W_g – granule speed; R_k – granule radius; ρ_{vozd} – air density; α_{vozd} – air heat transfer coefficient.

Based on the well-known expression for the value of the Nusselt criterion:

$$Nu = \frac{R_k\, \alpha_{vozd}}{\lambda_{vozd}}, \quad (4)$$

where λ_{vozd} – coefficient of thermal conductivity of air, can be obtained by using equations (1) and (2) and substituting these values into the mathematical equation (3), a slightly modified expression for the Nusselt criterion depending on such a hydrodynamic parameter as the granule speed W_g:

$$Nu = 2 + 0.35\left(\frac{W_g\, R_k\, \rho_{vozd}}{\mu_{vozd}}\right)^{0.58} Pr^{0.33} + 0.03\left(\frac{W_g R_k}{\alpha_{vozd}}\right)^{0.54} Pr^{0.35}, \quad (5)$$

and taking into account equation (4), it is possible to obtain an expression for determining the air heat transfer coefficient α_{vozd}, which in previous calculations was an undetermined value, but necessary for calculating the overall heat transfer coefficient between the granules and the air flow:

$$\alpha_{vozd} = \frac{\left(2 + 0.35\left(\frac{W_g\, R_k\, \rho_{vozd}}{\mu_{vozd}}\right)^{0.58} Pr^{0.33} + 0.03\left(\frac{W_g R_k}{\alpha_{vozd}}\right)^{0.54} Pr^{0.35}\right)\lambda_{vozd}}{R_k}. \quad (6)$$

Using the well-known dependences of the heat transfer coefficient K on the air heat transfer coefficients and the thermal conductivity coefficient α_{vozd} of the granule [1, 10], it is possible to obtain a mathematical expression of the dependence for the heat transfer coefficient. This expression is necessary to calculate the amount of heat transferred from the granule flow to the air flow in the granulation tower:

$$K = \frac{2\alpha_{vozd}\, \lambda_{karb}}{R_k \alpha_{vozd} + 2\lambda_{karb}}. \quad (7)$$

Knowing the float load in the granulation tower G_{plava}, which corresponds to the amount of granulated product, G_v – the amount of air supplied to the tower to cool the float and granules. As well as the radius R_k or diameter d_k of the granules formed as a result of the granulator's operation, and the time the granules remain in the process of movement in the tower τ, which is determined using the hydrodynamic calculation of the movement of the granules in the air stream, a system of heat balance equations can be drawn up. This system reflects the transfer of heat flow between granules and air:

$$\begin{cases} G_{plava}\left(C_p\left(T_{pn} - T_{pk}\right) + z_f + C_g\left(T_{pk} - T_{gk}\right)\right) = \\ = G_v C_v\left(T_{vk} - T_{vn}\right), \\ K\,F\left(\left(\left(T_{pn} - T_{vk}\right) + \left(T_{gk} - T_{vn}\right)\right)/2\right) = \\ = G_{plava}\left(C_p\left(T_{pn} - T_{pk}\right) + z_f + C_g\left(T_{pk} - T_{gk}\right)\right), \end{cases} \quad (8)$$

where C_p – specific heat capacity of the liquid; z_f – specific heat of the phase transition as a result of melt crystallization; C_g – specific heat capacity of the granule; C_v – specific heat capacity of air; T_{pn} and T_{pk} – initial and final temperature of the liquid; T_{gk} – final temperature of the granule; T_{vn} and T_{vk} – initial and final air temperature; $F = \frac{5.99 G_{plava}\, \tau}{d_k\, \rho_s}$ – heat transfer area.

Analyzing the system of equations (8), it can be seen that practically all the values of the physical quantities included in these equations are determined either from reference sources or from the mathematical equations given above. Two quantities remain undetermined: the temperature of the air at the outlet of the tower after contact with the granules, and the temperature of the granules in the lower part of the granulation tower. These quantities can be determined by solving the system of equations (8) relative to them. The following result was obtained:

To calculate the air temperature at the outlet of the granulation tower:

$$T_{vk} = \frac{\begin{pmatrix} 2C_g\, C_v G_v T_{vn} G_{plava} + C_g FKT_{pk} G_{plava} + \\ + C_g FKT_{pn} G_{plava} - C_g FKT_{vn} G_{plava} - C_p FKT_{pk} G_{plava} + \\ + C_p FKT_{pn} G_{plava} - C_v FG_v KT_{vn} + FKz_f G_{plava} \end{pmatrix}}{2C_g C_v G_v G_{plava} + C_g FKG_{plava} + C_v FG_v K}. \quad (9)$$

But to calculate the temperature of the granules after contact with air, for granules that have already formed and fall either into a pseudo-liquefied layer or onto a device for their removal from the granulation tower, let's obtain the following equation:

$$T_{gk}=\frac{\begin{pmatrix}2C_gC_vG_vT_{pk}G_{plava}+C_gFKT_{pk}G_{plava}-\\-2C_pC_vG_vT_{pk}G_{plava}+2C_pC_vG_vT_{pn}G_{plava}-\\-C_pFKC_pFKT_{pk}G_{plava}+C_pFKT_{pn}G_{plava}-\\-C_vFG_vKT_{pn}+2C_vFG_vKT_{vn}+\\+2C_vG_vz_fG_{plava}+FKz_fG_{plava}\end{pmatrix}}{2C_gC_vG_vG_{plava}+C_gFKG_{plava}+C_vFG_vK}. \qquad (10)$$

The temperature of the formed granule is an important indicator of its quality. If the temperature of the granule does not decrease to the required level, and this level is different for each type of mineral fertilizer, the granule may not acquire the required strength. This can lead to the destruction of granules in the fluidized bed, sticking of fertilizers on the metal structures of the tower, which can lead to the need to stop the entire production of mineral fertilizers.

To illustrate such calculations, an example of calculations for a urea production tower can be given:

– with a diameter of 22 m;
– air and water consumption, respectively, 600,000 m^3/h and 123 t/h;
– the initial temperature of the melt is 136 °C;
– initial air temperature of 35.5 °C;
– the time the granules are in contact with air is 10 s;
– with an average speed of movement of granules of 7 m/s.

The results of the calculations give the value of the air temperature at the exit from the tower and the final temperature of the granules of 60.45 °C.

Practical significance: The obtained results can be applied to improve the structures of granulation towers and regulate temperature regimes in the production of mineral fertilizers. This will help increase the strength of the granules, reduce their losses during transportation and ensure compliance with modern requirements for product quality. For example, the use of a rotating vibrating granulator makes it possible to reduce the formation of defects and increase the uniformity of granules.

The main limitations of the research are the specific conditions of the experiments, which cannot always be reproduced on the scale of real production. To implement the results in practice, it is necessary to conduct additional tests in industrial conditions. It is also necessary to take into account the features of the technical equipment used in a specific production.

The conditions of martial law in Ukraine had a significant impact on the conduct of the research. In particular, restrictions on access to laboratory equipment, interruptions in the supply of necessary materials and the transition to remote forms of education and research affected the duration of experiments. These circumstances could limit the possibilities of large-scale testing and required adaptation of work methods.

Further research can be aimed at expanding the modeling of granule cooling processes, studying new materials and additives that increase the quality of granules, as well as the implementation of automated temperature control systems in granulation towers.

4. Conclusions

In the course of the work, a model was created for calculation and the possibility of predicting the final temperature of mineral fertilizer granules, which allows to avoid negative consequences, such as a decrease in the strength of granules and their destruction during shipment, transportation and introduction into the soil. Improving the technological performance of the granulation tower, in particular the temperature regimes of granule cooling, contributes to the improvement of product quality. The calculation model allows to adjust the process parameters to ensure the formation of granules with specified properties that meet modern requirements for the monodisperse composition of mineral fertilizer granules. On the basis of the obtained mathematical models, the key parameters that affect the cooling process of the granules are determined. In particular, the results showed that the change in temperature of air and granules depends on the hydrodynamic and thermodynamic conditions of the process. Calculations showed that with an air consumption of 600,000 m^3/h and a liquid temperature of 136 °C, the final temperature of the granules is 60.45 °C, which significantly reduces the probability of their destruction during transportation.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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