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Nadhem, Al-Khyatt Muhamad; Sklabinskyi, Vsevolod; Ostroha, Ruslan et al.

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Kontakt/Contact
ZBW – Leibniz-Informationszentrum Wirtschaft/Leibniz Information Centre for Economics
Düsternbrooker Weg 120
24105 Kiel (Germany)
E-Mail: *rights[at]zbw.eu*
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**Al-Khyatt Muhamad Nadhem,
Vsevolod Sklabinskyi,
Ruslan Ostroha,
Maksym Skydanenko,
Mykola Yukhymenko,
Jozef Bocko,
Denys Ostroha,
Dmitry Zabitsky,
Oleksii Moskalchuk,
Andrii Serhiienko**

STUDY OF TEMPERATURE CHANGES IN MINERAL FERTILISER GRANULES AFTER CONTACT WITH AIR IN A GRANULATION TOWER

The object of research is the process of granulation of nitrogen mineral fertilizers by the method of sprinkling. One of the most problematic areas is the lack of certainty regarding the dynamics of the temperature change of the granule when it is cooled by air in the granulation tower. The paper considers the process of urea granulation using a rotating vibrating granulator. The scheme of the rotating vibrating granulator as part of the experimental stand for granulating liquid urea is presented, the method of conducting experimental studies and the design parameters of the granulator are described. It is indicated that in the process of experimental research, the temperatures of the melt, granules and cooling air were recorded. It is emphasized that the contact of the cooling air with the flow of hot granules leads to a constant increase in air temperature due to the heat transferred from the granules, which makes it necessary to determine the final temperature of the air leaving the granulation tower. For this purpose, a mathematical model was developed and calculation equations were obtained to determine the temperature of the air in contact with the surface of the pellet and the temperature profile inside the pellet. Numerical calculations of the calculation equations made it possible to obtain temperature profiles of the granule along its radius. It is emphasized that the theoretically obtained temperature profile cannot be an accurate indicator of the real temperature of the pellet when it falls in the granulation tower. Analysis of the calculated results shows that the temperature of the granules in the lower part of the granulation tower is 60–62 °C. This temperature corresponds to the practically confirmed final temperature of the granule, which was measured on the experimental stand.

Keywords: *granule, urea, pouring, rotating vibrating granulator, convective cooling, heat exchange, thermal conductivity, temperature profile.*

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1. Introduction

In the range of nitrogen fertilizers used in all soil and climatic zones, urea and ammonium nitrate predominate. These concentrated mineral salts can be used as the main fertilizer to stimulate the general growth of plants, as well as for fertilizing during the moments of their active vegetative growth [1]. The main macroelement of this class of fertilizers is nitrogen, which is present in a concentration of at least 35 % (in terms of dry matter) [2].

The granulation process is one of the most important processes in the entire chain of technological operations for the production of such mineral fertilizers as urea and ammonium nitrate, the granules of which are created by pouring in granulation towers, the schematic design of which is presented in Fig. 1 [3].

There are several important stages in this process. First, the melt is fed with a high temperature to the granulator. Then, in the granulator, the melt of mineral fertilizers in the form of a liquid is divided into jets or films of liquid. Further, with the help of a perforated shell, the jets are dispersed (sprayed) on drops. Granulators, in which liquid jets are divided into drops, are in great demand among mineral fertilizer manufacturers. This is explained by the fact that such a process can be controlled in order to obtain a granule flow structure that is close to monodisperse. Granulators, in which the separation of water jets, in the form of a liquid with a high temperature, is divided into drops using the mechanical influence of vibrations are in particular demand recently. This makes it possible to further narrow the range of granule sizes in the spray torch and bring it even closer to monodisperse [4].

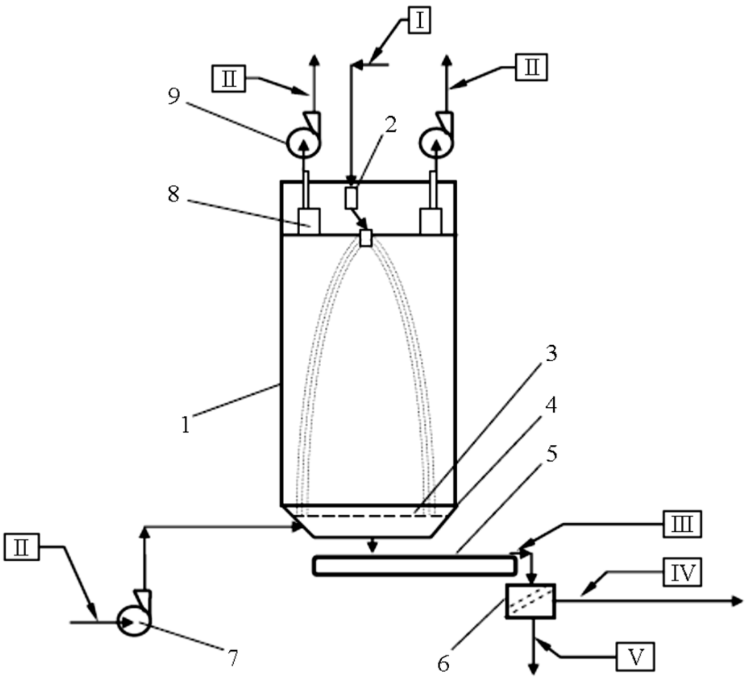
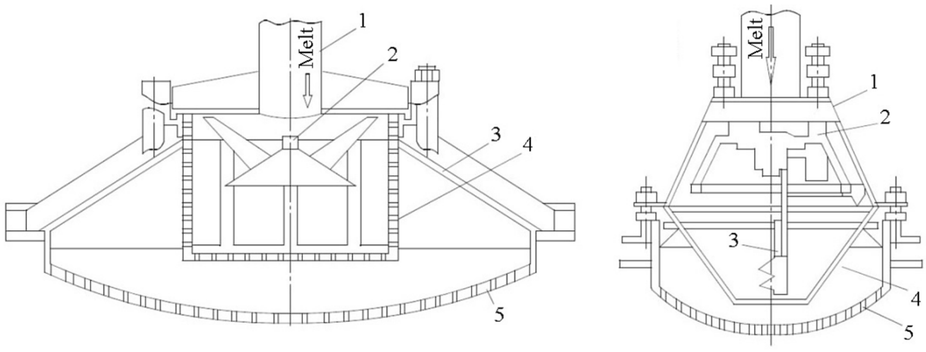


Fig. 1. Schematic representation of tower production of mineral fertilizers: 1 – granulation tower; 2 – equipment for supplying float to the granulator; 3 – «boiling layer»; 4 – collective cones; 5 – conveyor; 6 – separator of granules according to size; 7 – pressure fan; 8 – air cleaning equipment; 9 – exhaust fans; I – liquid fertilizer; II – air; III – release of pellets from the tower; IV – granules of finished products; V – substandard pellets for processing

Recently, the increased demand for mineral fertilizers forces manufacturers to increase the amount of these fertilizers. This leads to the development of new granulation towers with a large diameter or to the modernization of old tower granulation equipment with an increased load behind the float [5].

At the Department of Chemical Engineering of Sumy State University (Ukraine), a number of designs of static vibrating granulators were developed, some varieties of which are shown in Fig. 2.



a *b*

Fig. 2. Schemes of static granulators: *a* – funnel: 1 – nozzle; 2 – guiding cone; 3 – body; 4 – filter; *b* – acoustic: 1 – case; 2 – nozzle; 3 – guide plate; 4 – filter; 5 – perforated bottom

The paper [6] analyzed the results of mathematical modeling for a granulation tower for industrial conditions. Correlation of theoretical equations with data obtained for the granulation process of ammonium nitrate is discussed. The importance of the influence of process parameters such as moisture content, temperature, and speed of cooling air on the quality of the obtained granules was determined. The importance of taking into account the temperature gradient along the radius of the droplet is emphasized. But the temperature gradient data obtained for ammonium nitrate cannot be used for urea production conditions.

The large diameter of the granulation towers and the increase in the load behind the float set the granulator manufacturers the task of creating such structures that ensure an even distribution of drops over the entire cross-section of the working space of the tower. This contributes to the contact of almost all the cold air flow with the granules formed from the drops at the exit of the granulator, and creates favorable conditions for their crystallization process.

The process of droplet formation has already been sufficiently well studied and qualitatively implemented in production [7–13] and is only part of the process on the way to creating conditions for high-quality crystallization [14, 15].

Thus, the conditions of the process of contact with air and the rate of cooling of the granules have not been sufficiently studied. This task is relevant from the point of view of creating a quality product. The study of this process is complicated by the fact that it is impossible to experimentally investigate the temperature change in the granules during their movement from the upper part of the granulation tower to the lower one. Therefore, *the object of research* is the process of cooling urea granules by the method of pouring. And *the aim of the research* is to theoretically determine the temperature profile along the radius of the urea granule during its cooling in the granulation tower.

2. Materials and Methods

The work used the methods of physical modeling of granulation processes using the priming method. During the experimental studies, methods of multivariate planning of the experiment were used. Determination of the granulometric composition of particles was carried out by the method of sieve analysis. To generalize the obtained experimental data, differential methods of mathematical analysis and integral calculation were used, which were performed with the help of computer equipment and a package of application programs, namely: MathCAD, MS Office Excel.

3. Results and Discussion

The laboratory bench of the rotating vibrating granulator (RVG) was used for the research (Fig. 3).

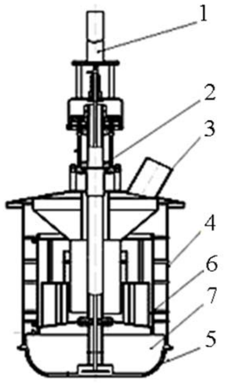


Fig. 3. Scheme of the rotating vibrating granulator: 1 – vibrating device; 2 – bearing attachment unit; 3 – float inlet; 4 – body; 5 – perforated bottom (basket); 6 – float distributor in the basket; 7 – shoulder blades

The research was conducted as follows. The melt of mineral fertilizers in the form of a liquid with a high temperature of 140–145 °C enters the OVG and is evenly distributed throughout the entire volume of the granulation basket, which has holes for the flow of melt jets into the granulation tower. The float, which is inside the basket, and the jet of liquid are subject to mechanical vibrations, which cause these jets to divide into drops of almost the same size. Further, these drops come into contact with the flow of cold air and, falling down, come into contact with the cold air and cool down. During cooling, the process of crystallization, the formation of granules and the quality of these granules takes place.

To solve the problem of determining the temperature of the granules, it is necessary to know the temperature of the air in contact with the surface of the granules. In the lower part of the granulation tower, air with ambient temperature enters. Then, during its movement to the upper part of the tower, this air is constantly in contact with the stream of hot pellets. This leads to an increase in air temperature due to the heat transferred from the granules. Therefore, at the first stage, it is necessary to determine how and according to which regularity this temperature increase occurs.

Such calculations are based on the heat balance equation:

$$G_{plava}\cdot\left(C_p\cdot\left(T_{pn}-T_{pk}\right)+z_f+C_g\cdot\left(T_{pk}-T_{gk}\right)\right)=$$
$$=G_v\cdot C_v\cdot\left(T_{vk}-T_{vn}\right), \qquad (1)$$

where C_p – the specific heat capacity of the liquid; z_f – the specific heat of the phase transition as a result of melt crystallization; C_g – the specific heat capacity of the granule; C_v – the specific heat capacity of air; T_{pn} and T_{pk} – the initial and final temperatures of the melt, respectively; T_{gk} – the final temperature of the granule; T_{vn} and T_{vk} – the initial and final air temperatures, respectively.

The dependence of the change in air temperature depends on the time of its contact with the granules moving in the tower. Based on this, it is possible to consider the limits of air contact in the time from the beginning of its entry into the granulation tower until the time that is equal to the time the pellets stay in the tower or the time the pellets fall. The time the pellet falls can be determined from the hydrodynamic calculation of the pellet's movement, while knowing the height of the granulation tower [4].

On the basis of laboratory studies, knowing the temperature of the granules in the lower part of the granulation tower, the final temperature of the air leaving the granulation tower can be determined by equation (1).

Considering the structure of equation (1) and taking into account the hydrodynamic calculations regarding the time of movement of the pellet and the change in its speed, it can be assumed that the dependence of the change in the temperature of the air in contact with the surface of the pellet varies according to the linear dependence from the initial temperature T_{vn} to the final temperature T_{vk} with time τ, which is a variable. Let's also take into account that the time when the air has already heated up to the temperature T_{vk} is taken as the initial measurement of the air contact time with the pellets, and for the pellet it will be the initial temperature of contact with the air. Then the equation for determining the temperature of the air in contact with the surface of the pellet will be written in the form:

$$T_v=\frac{\tau\cdot T_{vk}-\tau\cdot T_{vn}+\tau_n\cdot T_{vn}-\tau_k\cdot T_{vk}}{\tau_n-\tau_k}. \qquad (2)$$

Determining the temperature of the air on the surface of the pellet and changes in this indicator over time allows to approach the next stage of calculations. This is a determination of the temperature in the middle of the pellet based on the known thermophysical properties of the material from which the pellet is made. The basis of such calculations was the well-known differential equation of thermal conductivity, which, under the condition of a symmetric problem, has the form [16]:

$$\frac{\partial T(r,\tau)}{\partial\tau}=a\cdot\left(\frac{\partial^2 T(r,\tau)}{\partial r^2}+\frac{2}{r}\frac{\partial T(r,\tau)}{\partial r}\right), \qquad (3)$$

where $\tau>0$; $0<r<R$; a – coefficient of thermal conductivity; R – radius of the outer surface of the drop; r is a variable value of the radius of the granule.

The solution of equation (3) regarding the change of temperature along the radius of the pellet as a function of time in general form will be:

$$T(r,\tau)=T_{\mathrm{v}}+\left(T_g-T_{\mathrm{v}}\right)\times$$
$$\times\left(\sum_{n=1}^{\infty}\frac{2\cdot(-1)^{n+1}\cdot R\cdot\sin\left(\frac{n\cdot\pi\cdot r}{R}\right)\cdot e^{-\frac{n^2\cdot\pi^2\cdot a\cdot\tau}{R^2}}}{r\cdot n\cdot\pi}\right), \qquad (4)$$

where T_g – the granule surface temperature at the present time, which is determined by numerical calculation as the value of the granule surface temperature calculated during the previous iteration.

Equation (4) can be solved using specific data by numerical methods. Therefore, in order to check the possibility of analyzing the cooling rate not only on the surface of the granule, but also in its middle part, a theoretical analysis of the temperature profile of the granule was carried out. At the same time, the methodology and algorithm were developed and the corresponding calculations were carried out.

An example of such a calculation of the granule cooling process in the production of urea is the following data, obtained under the condition of the initial temperature of the granules t_{gn}=141 °C, the initial air temperature t_{vn}=40 °C. The obtained calculation results are shown in Fig. 4.

a *b* *c*

Fig. 4. Temperature distribution along the radius of a urea pellet with a diameter of 1.4 mm: *a* – after 0.8 s; *b* – after 3.5 s; *c* – after 6.85 s (end of movement)

Analysis of the calculated results shows that the temperature of the granules in the lower part of the granulation tower is 60–62 °C. This temperature corresponds to the practically confirmed final temperature of the granule, which was measured on the experimental stand.

The final temperature of pellet cooling is of important practical importance. It determines the completion of the melt crystallization process and the end of the flow of modification transitions inside the granule. Solidification of a granule of a certain diameter will occur only when its temperature is lowered to a sufficient value. To complete the crystallization process (more than 90 %) in the urea granule, it is enough to lower the temperature of the granule from the initial 135–140 °C to a temperature below 100 °C. That is, minimal hypothermia in the range of 35–40 °C is sufficient. But the crystallization process can be influenced by other factors, in addition to temperature conditions. These are the physical and chemical properties of the melt, the presence of residual centers of crystallization, etc. Therefore, the time of the crystallization process in practice increases somewhat. For example, for urea, the solidification time of the granule surface is 4–5 s. Therefore, the granule cooling time within 6–7 s (supercooling by 80 °C) (Fig. 4, *c*) is quite sufficient to obtain a urea granule with a satisfactory structure, strength and quality characteristics.

It must be admitted that the theoretically obtained temperature profile according to equation (4) cannot be an accurate indicator of the real temperatures of the pellet when it falls in the granulation tower. This is caused by the influence of the process of layer-by-layer crystallization from the surface to the center of the granule. Therefore, in equation (3) it is necessary to add a term that would take into account the specified process. This will allow obtaining more correct calculation results, because the crystallization process will affect the temperature profile of the granule. This question determines the goals of further research in this direction.

Most of the research was conducted at the Department of Chemical Engineering of Sumy State University (Sumy, Ukraine). Taking into account the close proximity to the geographical border with the aggressor country, shelling, aerial alarms, as well as systematic interruptions in the power grid – all this negatively affected the overall results. However, thanks to foreign partners (Technical University in Kosice, Kosice, Slovakia), who provided access to their laboratory base, it was possible to carry out the research in its entirety.

It should also be noted that the presented calculation analysis is the basis for the further study of the process of crystallization and formation of granules in granulation towers, which, in turn, affects the mechanical characteristics of granules in order to improve their quality, and is additional information for improving the RVG operation.

4. Conclusions

A method of theoretical analysis of the temperature profile of mineral fertilizer granules not only of the surface layer of the granule, but also along the radius of this granule to its center has been developed. This allows to follow the process of the dynamics of the temperature change of the granule during its convective cooling in the granulation tower. For complete completion of the granule hardening process (more than 90 %), its maximum supercooling by 80 °C is sufficient. This is ensured by the time of falling (cooling) of the granule from the top to the bottom of the granulation tower within 6–7 s. The obtained calculated data can be used as a basis for recommendations regarding changes in the temperature of the air passing through the granulation tower. This can be additional introduction of cold air along the height of the tower through additional holes, redistribution of air flows across the cross section of the tower, and other recommendations to improve the performance of heat exchange processes and reduce the height of the tower. As a result, this leads to a significant reduction in capital costs for the construction and operation of the tower.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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Al-Khyatt Muhamad Nadhem, *PhD, Senior Engineer, The General Directorate Education of Iraq, Baghdad, Iraq, ORCID: https://orcid.org/0000-0003-4284-8125*

Vsevolod Sklabinskyi, *Doctor of Technical Sciences, Professor, Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0001-9388-5861*

✉***Ruslan Ostroha,*** *PhD, Associate Professor, Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, e-mail: r.ostroga@pohnp.sumdu.edu.ua, ORCID: https://orcid.org/0000-0003-0045-3416*

Maksym Skydanenko, *PhD, Associate Professor, Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0003-3811-8154*

Mykola Yukhymenko, *PhD, Associate Professor, Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0002-1405-1269*

Jozef Bocko, *Doctor of Technical Sciences, Professor, Department of Applied Mechanics and Mechanical Engineering, Technical University of Kosice, Kosice, Slovakia, ORCID: https://orcid.org/0000-0002-3158-3507*

Denys Ostroha, *Postgraduate Student, Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0009-0009-7552-6860*

Dmitry Zabitsky, *Cyclic Commission of Specialty «Industrial Machinery Engineering», Professional Machine Building College of Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0003-4761-0765*

Oleksii Moskalchuk, *Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0002-5773-5775*

Andrii Serhiienko, *Department of Chemical Engineering, Sumy State University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0003-2085-820X*

✉*Corresponding author*