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DETERMINATION OF THE ENERGY EFFICIENCY OF GRANULATION EQUIPMENT BASED ON EXERGY ANALYSIS

The object of research is the process of granulation of mineral fertilizers by applying rolling and pouring methods, as well as in fluidized and suspended layers with active hydrodynamics of flows. It is noted that the development of the main technological stages of the production of granulated fertilizers should be aimed at improving the hardware design of granulators, establishing the most rational regime and technological parameters of the process in order to increase its efficiency and reduce energy costs. It is noted that the main indicators of the efficiency of granulation plants using heat are economic costs, exergy losses, as well as reduced costs. The method of exergy analysis for the assessment of energy costs for granulation processes in different types of granulators is presented, which allows to justify the choice of rational parameters of the specified processes, taking into account energy costs and equipment efficiency. Equations are presented for determining the amount of exergy of material flows and exergy losses caused by heat exchange at finite temperature differences of technological flows at the entrance to the device and at the exit from it. The equation for determining the exergy efficiency, which characterizes the energy efficiency of the technical system, is presented. The smaller the temperature difference for the technological flows at the exit from the device, the smaller the exergy losses, the higher the value of the exergy efficiency. and, accordingly, the device will have greater energy efficiency. An exergy analysis of granulation processes in granulation towers without a cooler, in granulation towers with a cooler, fluidized bed devices and multi-stage (shelf) devices was carried out. The analysis showed that the exergy efficiency for the specified granulation plants is equal to: 64 %, 71 %, 32 % and 96 %, respectively. The obtained research results can be applied in production conditions where granulation towers and devices of fluidized or suspended layers are used. Enterprises that plan to reduce energy costs and increase the environmental safety of their technological processes can implement improvements based on the proposed methods and equations. The application of research results will contribute to the selection of more rational indicators of the granule production process, which will increase the productivity and quality of the final product.

Keywords: *granulation of mineral fertilizers, granulator, urea, filling, rolling, active hydrodynamics, granulation, exergy.*

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1. Introduction

The production of granular products was and remains relevant in the modern world. Granulation processes are widely used in the production of fertilizers, pharmaceuticals, food additives and other technical materials. At the same time, Ukraine is an agrarian state. The agrarian sector of its economy (agriculture, food and processing industry) ensures the country's security and food independence both on the domestic and international markets. Therefore, the production and rational use of fertilizers is a promising and extremely relevant issue for science.

In its essence, granulation is a set of physico-chemical and mechanical processes that ensure the formation of particles of certain sizes, shapes, and internal structure with appropriate physico-chemical properties [1]. Among the variety of phosphorus-containing granular fertilizers, the most common are superphosphates, amphos and other complex mineral fertilizers [2–4]. In turn, in the range of nitrogen fertilizers used in all soil and climatic zones, ammonium nitrate and urea predominate [5]. At the current stage, in the production of granular fertilizers, various kinds of inorganic compounds are added to the basic mineral components [6], as well as components of organic origin [7–9].

At present, the production of granules is based on three main methods: priming [10], rolling [11] and expansion in fluidized or suspended layers [12]. Further development of the main technological stages of the production of granular fertilizers should be aimed at improving the hardware design of granulators, establishing the most rational regime and technological parameters of the process in order to increase its efficiency and reduce energy costs.

The main indicators of the efficiency of granulation plants using heat are economic costs, exergy losses, as well as reduced costs. Therefore, *the object of research* is the process of granulation of mineral fertilizers by applying the methods of rolling and pouring, as well as in fluidized and suspended layers with active hydrodynamics of flows. And *the purpose of the paper* is to conduct a thermodynamic and exergy analysis of the granulation process of mineral fertilizers from the point of view of estimating energy costs.

2. Materials and Methods

Exergy is a value that characterizes the efficiency of thermal energy [13]. Exergy costs are determined with the help of exergy or thermodynamic analysis, and reduced costs are determined with the help of technical and economic analysis.

The reduced costs for the unit installation are equal to:

$$R=(E_n+E_{am})\cdot K, \tag{1}$$

where E_n – normative coefficient of efficiency of capital investments, units/year; E_{am} – normative coefficient of deductions for depreciation and repair of equipment, unit/year; K – capital costs, unit/year.

Operating costs are determined from the expression:

$$O=\Sigma S_{en}+S_{eq}, \tag{2}$$

where ΣS_{en} – energy costs and material flows (product, cooling agent, intermediate coolant), unit/year; S_{eq} – costs for equipment and overheads, units/year.

Total reduced costs are defined as:

$$R=(E_n+E_{am})\cdot K+\Sigma S_{en}+S_{eq}=\Sigma S_{nen}+\Sigma S_{en}. \tag{3}$$

From exergy positions, it is advisable to separate energy (ΣS_{en}) and non-energy costs (ΣS_{nen}).

The total indicated energy costs are determined according to the following equations:

– due to spent energy:

$$\Sigma S_{en}=E_n\cdot K_e\cdot W+W\cdot C_q/\eta_t; \tag{4}$$

– due to heat exchange surface:

$$\Sigma S_{en}=E_n\cdot K_F\cdot F+Q\cdot C_q\cdot L; \tag{5}$$

– due to exergy:

$$\Sigma S_{en}=E_n\cdot K_E\cdot G_m+\Delta E\cdot C_q\cdot L, \tag{6}$$

where K_e, K_F, K_E – the specific capital investments assigned according to the energy spent, heat exchange surface, cooled product, unit/kW·h, unit/m^2, unit/kg; W – amount of energy spent during cooling, kW·h; F – heat exchange surface, m^2; G_m – mass of material, kg; Q – heat load, kW; $\Delta E=E_{in}-E_{out}$ – amount of exergy spent on the process, kW; L – number of hours of equipment operation, h/year; C_q – cost of a heat unit, unit/kW·h; η_t – thermodynamic efficiency process.

A number of works are devoted to the analysis and accounting of energy losses during technological processes. However, the need to take into account in the analysis not only the amount of energy consumed and released by the technical system, but also the quality of this energy (that is, its ability to be transformed into useful work) led to the expediency of using exergy analysis. This approach is also determined by environmental factors, namely, the anthropogenic impact of energy flows leaving the environment, i. e. energy allows combining the main aspects of technical system optimization – primarily thermodynamic, techno-economic and environmental.

The energy (heat) balance unambiguously determines the equality of heat flows entering and leaving the technical system, and in the exergy balance, the expenditure part of the balance equation is always less than the income part. Thus, the heat balance by its nature cannot reflect losses from the irreversibility of processes in the technical system, since equality will be observed regardless of the degree of its perfection. The exergy balance, on the contrary, always shows the amount of irreversibility losses in the technical system.

In general, the exergy balance has the form:

$$\sum E_{in}=\sum E_{out}+\sum E_l, \tag{7}$$

where $\sum E_{in}$ – total exergy supplied to the technical system with technological flows, J; $\sum E_{out}$ – total exergy diverted from the technical system with technological flows, J; $\sum E_l$ – total exergy losses with technological flows, J.

Exergies of technological flows are determined depending on their aggregate state and are equal to:

– for solid and liquid aggregate state:

$$E_{s.l.}=G\cdot c\cdot\left[\left(T-T_0\right)-T_0\cdot\ln\frac{T}{T_0}\right]; \tag{8}$$

– for a gaseous or vapor state:

$$E_{g.v.}=G\cdot\left[\left(i-i_0\right)-T_0\cdot\left(s-s_0\right)\right], \tag{9}$$

where $E_{s.l.}$ – value of the exergy of the technological flow, which is in a solid or liquid aggregate state, J; $E_{g.v.}$ – value of the exergy of the technological flow, which is in a gaseous or vaporous aggregate state, J; c – heat capacity of substance, J/(kg·K); T – absolute temperature of the process flow under operating conditions, K; T_0 – absolute temperature of the process flow in ambient conditions, K; i, i_0 – respectively, enthalpy of gas or steam under certain conditions, J/kg; s, s_0 – respectively, the specific entropy of gas or steam under certain conditions, J/(kg·K).

For heat-using equipment, exergy losses are caused by three main factors:

1) by changing the value of the pressure of the medium at the «inlet-outlet» boundary (E_P);

2) heat losses through the walls of the device into the environment (E_0);

3) heat exchange at finite temperature differences of technological flows at the entrance to the device and at the exit from it (E_T). Accordingly, the mentioned losses are equal to:

$$E_P = T_0 \cdot R \cdot \ln\left(\frac{(P_{out} + \Delta P)}{P_{out}}\right); \qquad (10)$$

$$E_P = Q \cdot \frac{T_{in} - T_0}{T_{in}} = Q \cdot \left(1 - \frac{T_0}{T_{in}}\right); \qquad (11)$$

$$E_T = \Delta s \cdot T_0 = T_0 \cdot \left(G_H \cdot C_H \int\limits_{T_{HFIN}}^{T_{HF}} \frac{\mathrm{d}T_H}{T_H} - G_C \cdot C_C \int\limits_{T_{CF}}^{T_{CFIN}} \frac{\mathrm{d}T_C}{T_C}\right) =$$

$$= T_0 \cdot \left(W_H \cdot \ln\frac{T_{HFIN}}{T_{HF}} + W_{XC} \cdot \ln\frac{T_{CFIN}}{T_{CF}}\right), \qquad (12)$$

where R – gas constant, J/mol·K; P_{in}, P_{out} – the pressure of the liquid or gas-vapor flow, respectively, at the entrance to the device and at its exit, Pa; ΔP – pressure drop in the system, $\Delta P = P_{in} - P_{out}$, Pa; Δs – sum of entropy increments of the heated and cold process flow, J/kg·K; Q – heat load of the device, W; W_H – water equivalent of the heated technological flow, equal to the product of the quantity of the flow (G_H) by its heat capacity (C_H), J/K; W_C – water equivalent of a cold process stream, equal to the product of the quantity of the stream (G_C) by its heat capacity (C_C), J/K; T_H – current absolute temperature of the heated technological stream, K; T_C – current absolute temperature of the cold process flow, K; T_{HF}, T_{CF}, T_{HFIN}, T_{CFIN} – respectively, the initial temperature of the heated and cold process flow at the entrance to the device, the final temperature of the heated and cold process flow at the exit from the device, K; T_{in} – average temperature of the insulation of the device walls (chosen according to DSTU EN 563-2001 (ISO 13732-1:2006) and should not exceed 43 °C).

The first two types of losses are technical, that is, to reduce them, it is necessary to take only technical measures: increase the cross-section of the working volume of the device, reduce the number of contact elements, and increase the thickness of the thermal insulation layer on the outer walls of the equipment. This approach is extensive and its implementation often requires significant capital expenditures. The third type of exergy losses can be classified as technological and to reduce them, it is necessary to strive to maximize the final temperature of the cold flow and minimize the final temperature of the heated flow at the exit from the device (intensive approach). Thus, the smaller the temperature difference for the technological flows at the exit from the device, the smaller the exergy loss, the higher the value of the exergy efficiency. (η_e) and, accordingly, the device will have greater energy efficiency.

Exergy efficiency, without taking into account losses from changes in the pressure of the environment, given its smallness, is equal to:

$$\eta_e = \frac{E_{out}}{E_{in}} = \frac{E_{in} \cdot (E_T + E_0)}{E_{in}} =$$

$$= 1 - \frac{T_0 \cdot \left(W_H \cdot \ln\left(\frac{T_{HFIN}}{T_{HF}}\right) + W_C \cdot \ln\left(\left(\frac{T_{CFIN}}{T_{CF}}\right)\right) + Q \cdot \left(1 - \frac{T_0}{T_{in}}\right)\right)}{Q \cdot \left(1 - \frac{T_0}{T_{HF}}\right)}. \qquad (13)$$

Exergy efficiency will be more accurate, in comparison with the thermal efficiency, to determine the exergy value of technological flows. Moreover, the exergy efficiency fully meets the general requirements. For an ideal process, when there are no exergy losses, $\eta_e = 1$ (100 %). If the supplied exergy is completely lost in the process, then $\eta_e = 0$. The difference between the entry of exergy into the object and the exit from it is always equal to the total losses and in real processes – $0 < \eta_e < 1$. That is, the value of exergy losses is the most important characteristic of exergy analysis. It can be used to judge the energy efficiency of the considered technological equipment. The greater the exergy loss, the smaller η_e and vice versa. Thus, the energy efficiency of the equipment used in production will be higher or lower. If the technological equipment has low energy efficiency (conditionally $\eta_e < 50$ %), then it is necessary to outline the ways of reducing exergy losses and, accordingly, increasing the exergy efficiency. The nature and magnitude of the negative impact of heat flows released by the technical system into the environment is directly dependent on the exergy of these flows. Therefore, in order to develop energy-saving measures, it is necessary to determine the conditions that allow reducing the exergy of waste heat flows. This can be done in the following ways. First, to increase the exergy efficiency of the technical facility, and secondly, before discharge, create conditions that would ensure the maximum reduction of exergy losses of these flows.

Thermal efficiency of device is equal to:

$$\eta_T = \frac{Q_{fact}}{Q_{\max}} = \frac{W_S \cdot (t_{T1} - t_{TF})}{W_S \cdot (t_{T1} - t_{AI})} = \frac{t_{T1} - t_{TF}}{t_{T1} - t'_{AI}}, \qquad (14)$$

where W_S – water equivalent of the solid phase, J/K; t_{TI} – initial temperature of the solid phase, °C; t_{TF} – final temperature of the solid phase, °C; t_{AI} – initial temperature of the cooling air, °C.

By physical essence and definition, thermal efficiency is nothing but the C_{cool} cooling coefficient. To estimate the share of heat removed from the hot product by air, it is necessary to know the coefficient of air utilization (recovery coefficient), which is the ratio of the amount of actually transferred air heat to its maximum amount:

$$K_p = \frac{W_W \cdot (t_{AF} - t_{AI})}{W_W \cdot (t_{T1} - t_{AI})} = \frac{t_{AF} - t_{AI}}{t_{T1} - t'_{AI}}, \qquad (15)$$

where W_W – water equivalent of the cooling air, J/K; t_{AF} – final temperature of the cooling air, °C.

With the maximum use of the heat of the exhaust gases, the values of η_e, η_t and K_p tend to 1.

3. Results and Discussions

Exergy analysis of the granulation equipment was carried out on the example of urea granulation with a flow rate of 5000 kg/h in granulation towers, fluidized bed devices and multi-stage (shelf) devices.

The results of calculations on the articles of the exergy balance for each of the material flows of the granulation tower without a cooler are presented in the Table 1.

The exergy balance of the granulation process in the tower shows that from the total input of exergy flows to the process (13.84 kW), the exergy heat flow leaves the tower together with the exhaust air flow (8.78 kW or 63.5 % of the exergy input). In the calculations of exergy flows, the ratio of the amount of cooling air to the productivity by product was used, as $m = 4:1$.

The analysis of exergy costs when reducing the parameter m to 3:1, 2:1, 1.5:1 showed that exergy losses increase (5.82 kW, 6.4 kW, 6.74 kW, respectively), and the value of exergy efficiency decreases (53 %, 41 % and 33 %, respectively). This confirms that simply reducing the amount of cooling air does not reduce exergy losses. It is necessary to raise the temperature of the exhaust gases after the tower and lower the temperature of the finished pellets at the outlet. One solution is to have a fluidized bed cooler at the bottom of the granulation tower. The results of exergy analysis for a tower with a cooler are presented in the Table 2.

Table 1

Exergy balance of a granulation tower without a cooler

Balance sheet	Exergy, kJ/h (kW)	Share of the sum of input items, %	Exergy efficiency, %
Heat arrival:			64
– with flow (5000 kg/h, 136 °C);	27500 (7.64)	55.2	
– with cooling air (20000 kg/h, 20 °C).	22200 (6.20)	44.8	
Total	49700 (13.84)	100.0	
Heat consumption:			
– with granules (5000 kg/h, 90 °C);	248 (0.069)	0.5	
– with exhaust air (20000 kg/h, 42 °C).	31600 (8.78)	63.5	
Total	31848 (8.85)	64.0	
Exergy losses	17852 (5.0)	36.0	

Table 2

Exergy balance of a granulation tower with a fluidized bed cooler at the bottom

Balance sheet	Exergy, kJ/h (kW)	Share of the sum of input items, %	Exergy efficiency, %
Heat arrival:			71
– with flow (5000 kg/h, 136 °C);	27500 (7.64)	55.2	
– with cooling air (20000 kg/h, 20 °C).	22200 (6.20)	44.8	
Total	49700 (13.84)	100.0	
Heat consumption:			
– with granules (5000 kg/h, 60 °C);	14025 (3.90)	28.2	
– exhaust air (20000 kg/h, 42 °C).	21200 (5.89)	42.6	
Total	35225 (9.79)	70.8	
Exergy losses	4075 (1.16)	29.2	

According to the Table 2 it is possible to see that for a tower with a fluidized bed cooler in its lower part, exergy losses decrease by 1.2 times (from 36 % to 29.2 %). The temperature of the exhaust air at the exit from the tower increases from 40–45 °C to 50–55 °C, and the temperature of the finished pellets after the tower decreases to 60 °C against 90 °C in the absence of a cooler. At the same time, the exergy efficiency increases to 71 %.

The results of the exergy analysis of the fluidized bed granulator are presented in the Table 3.

Exergy analysis of fluidized bed granulation shows that the predominant exergy flow (more than 98 % of the total input) comes with the drying agent. The exergy output with the spent drying agent flow is much lower (32 % of the total input). At the same time, exergy losses are significant (68 %), and exergy efficiency low (32 %). This is explained by the fact that the fluidized bed granulator works according to the scheme of ideal mixing. The boiling layer is maintained at a sufficient height (up to 300–500 mm) to ensure hydrodynamic stability during float irrigation, preventing its «settlement».

With active mixing, the driving force of heat and mass exchange processes is equalized, and the speed of such processes reaches a certain constant value. As a result, the temperature of the waste gases decreases moderately (to a maximum of 50 °C), which leads to exergy losses.

The results of the exergy analysis of the multi-stage (shelf) granulator are presented in the Table 4.

Table 3

Exergy balance of the fluidized bed granulator

Balance sheet	Exergy, kJ/h (kW)	Share of the sum of input items, %	Exergy efficiency, %
Heat arrival:			32
– with flow (5000 kg/h, 136 °C);	22413 (6.23)	1.0	
– with return (1500 kg/h, 20 °C);	9405 (2.60)	0.4	
– with a drying agent (65000 kg/h, 120 °C).	2275000 (632)	98.6	
Total	2306818 (640.8)	100.0	
Heat consumption:			
– with granules (6500 kg/h, 65 °C);	3539 (0.98)	0.2	
– with spent drying agent (65000 kg/h, 50 °C).	737750 (204.9)	32.0	
Total	740289 (205.9)	32.2	
Exergy losses	1566529 (434.9)	67.8	

Table 4

Exergy balance of a multi-stage (shelf) granulator

Balance sheet	Exergy, kJ/h (kW)	Share of the sum of input items, %	Exergy efficiency, %
Heat arrival:			96
– with flow (5000 kg/h, 136 °C);	22413 (6.23)	2.2	
– with return (1500 kg/h, 20 °C);	9405 (2.60)	1.0	
– with a drying agent (65000 kg/h, 120 °C).	975000 (270.8)	96.8	
Total	1006818 (279.7)	100.0	
Heat consumption:			
– with granules (6500 kg/h, 45 °C);	14479 (4.0)	1.4	
– with spent drying agent (65000 kg/h, 40 °C).	947050 (263.1)	94.1	
Total	961529 (267.1)	95.5	
Exergy losses	45289 (12.6)	4.5	

A shelf granulator is device that generally works according to the scheme of ideal displacement, but with local cells in which the hydrodynamic structure of the solid phase flow approaches the scheme of ideal mixing. With such an organization of flows, the driving force of heat and mass exchange processes is not a constant value, which leads to the intensification of phase contact and a more optimal range of temperature changes of solid and gas phase flows. Therefore, this device is characterized by minimal exergy losses (up to 5 %) and fairly high exergy efficiency (96 %).

The obtained research results can be used for the development and production of more effective granular fertilizers. Achieving rational indicators of the granulation process helps to ensure uniform distribution of nutrients in the soil, improves absorption by plants, increases yield and reduces fertilizer losses. In turn, improving the technological parameters of granulation and reducing energy consumption can be used in the development of equipment for the chemical industry. This will ensure more energy-efficient production of various granular products such as catalysts, absorbents and other chemical reagents.

The equations and models developed in the research can be applied in the process of designing granulators and cooling systems. This will make it possible to create devices with improved characteristics, which will help reduce production energy costs and increase environmental safety in general.

The prospect of further research is the development of new shell materials for granules (encapsulation), which will ensure the controlled release of nutrients and improve the environmental friendliness of fertilizers. In addition, further modeling and simulation of granulation processes will contribute to more accurate prediction of product characteristics and adaptation of the technology for various industries such as remediation of contaminated soils, pharmaceuticals and food industry.

4. Conclusions

An exergy analysis of mineral fertilizer granulation processes has been carried out, which made it possible to determine rational technological parameters for increasing efficiency and reducing energy costs for the process.

It has been established that multi-stage granulators have the highest energy efficiency with exergy efficiency. 96%, and the minimization of the temperature differences of the flows increases the overall energy efficiency of the installations.

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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 paper has no associated data.

Use of artificial intelligence

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

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