The study of specific energy consumption in devices with controlled segregated flows

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Abstract. According to the research by the Lighthouse company, energy consumption in the Russian industry exceeds the level of similar enterprises in other countries by 40-220%. In this regard, the study of energy consumption for production and selection of rational parameters using a new hardware design of processes is an urgent task. As research object a line for the production of granulated feed was selected. Based on the results of literature data analysis and patent review, a new design of drum vibration device with controlled segregate flows was proposed. The results of study of specific energy consumption for the drying process allowed to determine the percentage ratio between the values of energy consumption from each component of the process, and the coefficient of accounting for the conditional moisture evaporated from the granules. It allowed establishing rational parameters of the process. The use of phase volume characteristics of dispersed systems allows to improve the method for determining the thermal characteristics of dry and wet dispersed systems. The application of the developed methods will significantly reduce energy costs for the production of granulated feed, which eventually creates a competitive enterprise.

1. Introduction
According to the research by the Lighthouse company, energy consumption in the Russian industry exceeds the level of similar enterprises in other countries by 40-220%. In the latest governmental report of the Ministry of economy on energy saving and energy efficiency in the Russian Federation there was noted the lack of progress in these areas and a “significant lag” in achieving the President's goal on energy efficiency. While maintaining the current pace, it will be possible to reduce the energy intensity of GDP by 60% only by 2043 [1].

In the agro-industrial complex, in most cases, compound feed is made in the form of granules of a certain size in devices of various types. After obtaining a dispersed medium, it is dried to increase the shelf life. This process is one of the most energy-intensive, so reducing energy costs for the drying process of dispersed systems is an urgent task. One of the ways to increase the efficiency of devices for drying bulk products is to increase the specific contact surface of the dried product with the drying agent, as well as the selection of rational process parameters.

2. The purpose of the study
To confirm the economic feasibility of the project being developed, aimed at improving the drying process, reducing abrasion and increasing the strength of the resulting granules, it is necessary to determine the specific energy consumption for the process.
3. The object of the study
In the agro-industrial complex, drum-type devices are often used for the granulating and drying process [2]. Based on the results of the literature and patent review, a new design of the drum vibration device was proposed (Patent No. 2693772 IPC B01J 2/18).

The drum vibration device (figure 1) works as follows: the initial mixture of bulk components enters the drum vibration granulator. A binding solution is applied to its surface. Thanks to the off-balance type vibration exciter, the mixture is converted to a vibro-liquid state and a segregation process occurs as a result of which the small granules with less potential energy are transferred to the lower part, from where they are captured by a belt mixer and transported in the opposite direction, and the formed granules are transferred to a drum vibro-dryer. The transfer of granules occurs under the action of a vibrating field, since the device is installed at an angle, and for mixing them, belt mixers are used, equipped with blades that rotate in the opposite direction of the movement of particles, in order to increase the time spent in the device for the processed product.

![Figure 1. Drum vibration unit: 1 - drum vibration granulator; 2 - drum vibrocoiler-dryer; 3 - elastic sleeve.](image)

The heat agent enters the BVO-C pipe tangentially installed to the device body; due to this drying agent acquires a spiral trajectory of movement. Under the influence of a vibrating field, the dispersed product was transferred to a vibro-liquid state, resulting in a process of segregation of granules of different sizes, but the same density, i.e. large granules occupied the upper position, and small ones with less energy occupied the lower position, where they were captured by a mixer and moved on rectangular blades located at an angle of 45 ° on the periphery of the inner surface of the body, from where they were poured under the influence of gravity. The contact of the heat carrier and the dried material (figure 2) is observed in the lower part of the device \( Q_1 \), as well as in the zone of downward flow from the mixer blades conventionally represented \( Q_2 \) and \( Q_3 \) [3].
4. Materials and methods

The total energy consumption $N$ for the BVO-C pipe operation consists of energy costs for mechanical work: lifting and transferring granules, vibration exciter operation, as well as for friction in bearings, seals, etc., for overcoming the hydraulic resistance $N_{\Delta P}$ and energy costs for removing moisture from the dried material $N_W$ [4].

The energy consumption for performing mechanical work was determined at the idle speed $N_I$ of the device (without feeding the product), while the readings at the beginning and end of the experiment were averaged. At the second stage, the readings were determined in the operating mode $N_{WM}$ (with product feed). The amount of energy spent on mechanical work is determined by the following formula:

$$N_M = N_{WM} - N_I, \text{ m/c}$$  \hspace{1cm} (1)

The costs of mechanical work include: energy losses during the lifting the dispersed medium, the movement of granules in the direction of the discharge hole, the transfer of the dispersed medium to a vibro-liquid state. To compare the energy spent on performing mechanical work, overcoming the hydraulic resistance of the device and the downward flows of the dispersed medium, as well as the energy spent on drying the material, an indicator of specific energy consumption is introduced (the amount of energy spent on evaporation of one kg of moisture from the product) [5].

**Table 1.** Parameters and boundary conditions for experimental research.

| Factor                              | Designation of factors | Levels | Centre of the experiment | Variation step |
|-------------------------------------|------------------------|--------|--------------------------|----------------|
| Oscillation amplitude (A), (mm)     | $X_1$                  | 0.5    | 1                         | 0.5            |
| Frequency (f) Hz                    | $X_2$                  | 20     | 50                        | 10             |
| Mixer rotation frequency (n), rpm   | $X_3$                  | 1      | 9                         | 2              |
| DVO-C tilt angle ($\alpha$),°      | $X_4$                  | 0.5    | 2.5                       | 1              |
| The speed of the drying agent (V), m/s | $X_5$              | 1      | 3                         | 1              |
| Drying agent temperature (t),° C   | $X_6$                  | 45     | 65                        | 10             |
5. Discussion of the results

In the developed BVO-C, energy costs consist of energy costs for carrying out mechanical work on transferring and re-rolling granules and mechanical friction losses in bearings, seals, mixers on the device body, etc., overcoming the hydraulic resistance of both local structural elements and downdraft of the dried product, heat costs for drying granules of compound feeds. In order to find ways to improve and minimize the drying process in this device, a comprehensive assessment of the output values of the process and the selection of rational parameters is necessary.

The specific heat of vaporization \( r \) is calculated using the following expression

\[
r = 2500 - B \cdot \theta\]

In this expression the value \( B = \text{const} \). However, this expression is not entirely valid, since when the temperature of the product \( \theta \) increases, the value of \( B \) increases also. According to the calculations set out in [6], it was found that when drying dispersed products with the maximum permissible heating temperatures of the product, the specific heat of vaporization will be:

\[
r = 2500 - (2.3 + 0.0014 \theta) \theta\]  

When determining the specific value of the amount of heat \( \sum q \) required to remove 1 kg of moisture from the dried material, it can be noticed that it directly depends on the initial and final moisture content of the granules [7]. So, the lower the initial moisture of the product, i.e. the closer it is to the equilibrium value, the more energy must be expended to remove it. This is due to the fact that removing the bound moisture is a more expensive process in terms of the drying process. In order to make it possible to conduct a comparative analysis of various types of dryers, a coefficient was introduced for conversion to “conditional moisture”:

\[
K_{CM} = \frac{W_N}{W_A} = \frac{\sum q_A}{\sum q_N}\]  

where \( W_N, \sum q_N, W_A, \sum q_A \) is the normative and actual value of evaporated moisture, respectively, and the total specific value of heat expenditure for evaporation of 1 kg of moisture when drying the dispersed material, respectively, from 21 to 8 %. The results of determining the amount of vaporized moisture from the granules are summarized in Table 2.

| Initial moisture of the product, \( W_0, \% \) | Amount of evaporated moisture \( W, \, \text{kg} / \text{h} \) | Total specific heat consumption, \( \sum q, \, \text{kJ} / \text{kg} \) | \( K_{CM} \) |
|---|---|---|---|
| 18 | 0.198 | 7221.2 | 1.177414 |
| 20 | 0.22 | 4922.6 | 0.802628 |
| 22 | 0.242 | 4431.4 | 0.722538 |
| 24 | 0.264 | 4322.3 | 0.70475 |
| 26 | 0.286 | 4012.8 | 0.654286 |

As a result of analyzing the data given in the table 2, it can be concluded that when removing more strongly bound moisture in the material, when it decreases in the product, the specific heat energy \( \sum q \) for its removal from the granules increases proportionally and the \( K_{CM} \) coefficient also increases, so do not forget that the \( K_{CM} \) coefficient also depends on the performance of the dryer for the raw product.

In the research [8], dynamic efficiency criteria are introduced in order to more accurately assess the efficiency of heat energy use in drying equipment.

As a result of integrating the dynamic criterion along the device length \( l_{max} \) or by the time of the drying process you can get the overall energy efficiency

\[
E_E = \frac{l}{l_{max}} \int_0^{l_{max}} \varepsilon_E(\tau) d\tau\]  

\[
E_E = \frac{l}{l_{max}} \int_0^{l_{max}} \varepsilon_E(l) dl\]  

(4)  

(5)
where $E_E$ is the total energy efficiency; $\tau$ is the time, sec; $l$ is the length of the device, m.

In the research [8], a dynamic criterion is introduced (the drying efficiency). This criterion allows to more accurately determine the efficiency of the drying equipment.

$$E_D = \frac{l}{\tau_{\text{max}}} \int_{0}^{\tau_{\text{max}}} e_D(\tau) d\tau$$  \hspace{1cm} (6)

$$E_D = \frac{l}{l_{\text{max}}} \int_{0}^{l_{\text{max}}} e_D(l) dl$$  \hspace{1cm} (7)

where $E_D$ is the overall efficiency.

To evaluate the efficiency of the analysis of energy consumption of drying equipment, the results of research were analyzed in order to search for dynamic efficiency criteria using the following expressions:

$$\varepsilon_E = \frac{\Delta m \cdot r}{G_{DA}C_{DA}(t_i-t_E)}$$  \hspace{1cm} (8)

$$\varepsilon_D = \frac{\Delta m \cdot r}{G_{DA}C_{DA}(t_i-t_E)-G_{DA}C_{DA}(t_{CO}-t_E)}$$  \hspace{1cm} (9)

where $r$ is a specific heat of vaporization, kJ / kg; $\Delta m$ is amount of evaporated moisture at $\Delta \tau \rightarrow 0$, kg / h; $C_{DA}$ is heat capacity of the drying agent, kJ / kg·K; $G_{DA}$ is consumption of the drying agent, kg / h; $t_i$, $t_E$, $t_{CO}$ is respectively the temperature of the incoming drying agent, the environment, the outgoing drying agent.

Figure 3 shows the research results of the dependencies of the dynamic efficiency criterion on the length of the device, defined by the expression (9).

According to the data of [2], the total energy consumption of this type of devices is spent on overcoming the hydraulic resistance of the structural elements of the apparatus and the resistances created by the downward flow of the product from the blades, mechanical costs associated with transferring the product along the axis of the device, lifting and tipping, creating a segregated flow and friction losses in mechanical transmissions, energy spent on removing moisture from the material.

$$N = N_{AP} + N_{M} + N_{T},$$  \hspace{1cm} (10)

where $N_{AP}$ are specific energy costs for overcoming the hydraulic resistance of the structural elements of the device and created by the product; $N_{T}$ is specific heat energy costs for removing one kg
of moisture from the product; $N_M$ is specific energy costs for performing mechanical work and “useful consumption” (energy losses for lifting and tipping granules, creating a segregated flow, transferring the product along the axis of the device).

To compare the energy consumption for performing mechanical work and overcoming hydraulic resistance, the calculation was made in conventional units (kJ/1000 m$^3$), then the calculation was made in (kJ/kg moisture) for the purpose of comparative analysis with the cost of removing moisture from the material. Mechanical energy costs are defined by the following expression:

$$N_M = N_E + N_U,$$

where $N_E$ are energy costs for overcoming friction forces in mechanisms; $N_U$ are “useful energy consumption” for transporting, lifting and tipping the product, as well as creating segregated flows.

Figure 4 shows the research results of mechanical energy consumption in BVO-C. Analysis of the data allows to conclude that the “useful energy consumption” is relatively small, they make up no more than 30% of the mechanical costs, therefore, in this case, the improvement of the design is not required.

When analyzing the energy consumption (figure 5) for mechanical, hydraulic and moisture evaporation costs, it can be concluded that the prevailing consumption is, of course, the consumption of liquid evaporation, which is from 80 to 88% of the total energy consumption.

![Figure 4](image1.png)  
**Figure 4.** Dependence of “useful energy consumption” on the belt mixer speed: 1 - $A=1$ mm, $\nu=30$ Hz; 2 - $A=1$ mm, $\nu=50$ Hz; 3 - $A=3$ mm, $\nu=20$ Hz.

![Figure 5](image2.png)  
**Figure 5.** Dependences of total energy consumption on the gas speed: 1 - $A=1$ mm, $V=30$ Hz, $n=5$ rpm; 2 - $A=3$ mm, $V=20$ Hz, $n=9$ rpm.

In order to determine the degree of influence of each factor on the total energy consumption, a correlation analysis of experimental data was performed:

$$Y_5 = 3126 + 53,28 \cdot X_6 + 18,17 \cdot X_5 + 1,73 \cdot X_6 \cdot X_5 - 0,75 \cdot X_1 \cdot X_2 + 0,1 \cdot X_5 \cdot X_3$$  

(12)

The correlation coefficient for equation (12) is $R=0.98$.

The search for rational process parameters with the imposition of boundary conditions in the new BVO-C design was performed in the Microsoft Excel system. As a result of processing the obtained data, the following rational values were obtained: $A = 1$, mm; $\nu = 30$, Hz; $n = 9$, rpm; $\alpha = 1^\circ$; $V = 3$ m/s; $t = 60$, °C.

6. **Conclusion**

The use of phase volume characteristics of dispersed systems allows to improve the method for determining the thermal characteristics of dry and wet dispersed systems. It will increase the reliability of the results obtained. The results of the study of specific energy consumption for the drying process allowed to determine the percentage ratio between the values of energy consumption from each
component of the process, as well as the coefficient of accounting for the conditional moisture vapour \( K_{CM} \) evaporated from the granules, which in turn allowed to establish rational parameters of the process.

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