Study of efficiency of using vibration to improve the process of loose raw material classification

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Abstract. The paper presents the results of a study dedicated to assessment of the effectiveness of vibration use to intensify the process of classification of loose mediums at arch screens. In the laboratory, the experiment was based on the separation of bulk material flow at the arch screen. The frequency and amplitude of oscillations of the screening surface were taken as variable parameters, while the response function was the fraction of take-off product in the total volume of the sifted mass of bulk material. According to the experiment data processing using the method of mathematical planning, the feasibility of vibrations application was confirmed, providing a reduction of energy consumption up to 14%.

1. Introduction

Application of vibration in technological processes associated with the processing of bulk materials for the intensification of production is quite widespread. The efficiency of using superimposed vibration fields, if it is understood simply as an increase in the productivity of the main technological equipment, is confirmed by a large number of actually existing production systems. However, with a broader interpretation of the term “efficiency” as a category and taking into account qualitative changes in the correlation of prices for raw materials and especially for energy resources over the years of reforms, the question of whether it’s reasonable to use vibration as a catalyst for any technological process can be studied in a slightly different aspect than before. As it is known, one of the integral technical characteristics of any production is its energy saturation. Therefore, it is rational to carry out a comparative analysis of various variants of the technological process from the position of estimating energy cost required for their implementation [1].

In this paper, the results of the energy analysis of two technological options are presented on the example of bulk materials classification process. Modification of such screens are represented by devices in which the screening surface vibrates involuntarily. The intensification of the classification process from the action of vibration is achieved by improving material layer moving conditions: by reducing the values of the coefficient of friction between the material and the screening surface, as well as the internal coefficient of friction between the particles of the material. In addition to the constructive complication of the screen, which requires additional material costs itself, the costs associated with the implementation of the vibrating drive of the screening surface significantly reduce the effectiveness of vibrating arch screens usage. Following the energy approach towards estimating the process of dividing solid particles stream, the aim of this study was formulated as follows. With
The equality of the parameters characterizing the classification process, in cases with application of vibration and without it, it was necessary to establish in which one energy expenditure is greater.

2. Setting laboratory experiment
Development of an experimental setup. According to the problem mentioned above, it became necessary to implement two processes with predetermined equal output parameters. For example, it can be achieved in the case when the fraction of take-off product in the total volume of the sifted mass of the bulk raw material \( k \) and the productivity \( P \) are also equal in each process presented for studying [2]. The stated requirement is easier to satisfy when conducting experimental work in the laboratory. For this purpose an experimental setup was already designed and manufactured, its scheme is shown in fig. 1. The installation includes an arch screen model 1 with a cell size of the screening surface with a clearance of \( 5 \times 10^{-3} \) m, a hopper 2 movably mounted on a tripod 3. Screen 1 is mounted on a vibrating table 4 created on the basis of a 30 W sound speaker. Vibrating table 4 is connected to the low-frequency signal generator 5 GZ-106. The amplitude \( a_0 \) of the oscillations was determined by the vibrometer 6 VIP-2 type, supplied from the power unit 7 of IEPP-2 type with a constant voltage of 6 V, using an induction vibration measuring transducer 9 of D21A type mounted on a vibrating table 4.

The whole experiment was divided into two stages. At first, the vibrating table was turned off, the arch screen model was used according to the gravitational type. At the same time, \( V = 2.5 \times 10^{-3} \) m\(^3\) of classified material was passed through its working space. Crushing screenings received in the production of crushed stone were taken as such a material, particles with a maximum transverse size of less than and more than \( 5 \times 10^{-3} \) m were contained in equal proportions in a specified volume. An equal ratio of particles volumes was provided by preliminary material screening through a sieve with a cell size of \( 5 \times 10^{-3} \) m. The rational parameters of the considered screen operation mode were \( k = 0.53 \) and \( P = 3.110^{-1} \) m\(^3\)/h, while the process time \( t = 29 \) s was provided by the corresponding slot width \( \delta \) of the bunker gate. Among the factors that have a significant impact on the results of the process we should mention the distance \( h \) from the gate of the bunker to the entrance into the arch screen working space. The initial velocity of the particles on the screening surface depends on this distance. At the first stage of the experiment, \( h \) was taken equal to \( 7.5 \times 10^{-3} \) m. For these experimental conditions, the specified value of \( h \) was optimal. Changing it up or down had a negative effect on the coefficient \( k \). At the same time, the part of the work performed by external forces is connected precisely with the value of \( h \):

\[
A_h = \rho \cdot V \cdot g \cdot h,
\]

where \( g = 9.81 \) m/s\(^2\) is the free fall acceleration, \( \rho = 3 \times 10^7 \) MPa is density of crushed stone.

The estimated value of work \( A_h \) turned out to be 0.552 J. The rise of the processed material above the screen to an additional height equal to the distance \( h \) only leads to an increase in the potential energy per unit volume of material, therefore, the work associated with this rise can be attributed to wasteful energy. Under real production conditions, transport equipment such as conveyors, elevators, and so on is created to fill the bunkers with material and to accomplish this work. That’s why the distance \( h \) is made as small as possible in industrial designs of screens. It was possible to reduce the value of \( h \) at the first stage of considered experiment while maintaining the value \( k = 0.53 \) only with a certain decrease in the performance \( P \) [3].

Based on the information mentioned above, the tasks of the second stage of the experiment were determined as follows:

- to investigate the possibility of preserving the values of the parameters \( k \) and \( P \) with a structurally minimal surface of the screen \( h = 0.53 \times 10^{-3} \) m due to the vibration of the screening;
- to determine the magnitude of the amplitude \( a_0 \) and the frequency of the oscillations \( \nu \) that satisfy the latter condition;
• compare the energy savings from reducing the value of \( h \) with its consumption for the implementation of screening surface oscillations of the screen when the flow of material passes through it.

![Figure 1. Scheme of laboratory installation of a vibration arch screen](image)

3. Processing of experimental results

All the tasks mentioned above could be solved after determining the dependence of the parameter \( k \) on the amplitude \( a_0 \) and oscillation frequency \( \nu \) as a function of the form [4]:

\[
k = F(\nu, a_0)
\]

The construction of such a function in this paper was carried out using experimental planning methods [5]. The levels of experimental factors variation are presented in (Table 1). The choice of star points was determined by technologically acceptable intervals of variation of the oscillation frequency \( \nu \) and amplitude \( a_0 \). The experiment was conducted taking into account the possibility of transition to quadratic planning. In the matrix of a symmetric composite rotatable plan (Table 1), values that characterize the energy supplied to the layer of moving material were entered:

- \( U \), \( I \) – voltage and current in the vibrating table, respectively;
- \( \nu \) – vibration velocity.

Variance valuation of experimental results performed on four experiments is represented in the center of the plan. The variance consisted \( S_\nu = 1.29\cdot10^{-2} \) with the number of degrees of freedom \( f_i = 3 \).

The root-mean-square error was \( S_\nu = 0.645 \cdot 10^{-2} \). With a \( t \)-criterion equal to 3.18 out of three factors, only two were considered statistically significant: \( 0 = 25.75\cdot10^{-2} \) and \( b_2 = 3.75\cdot10^{-2} \). Therefore, the regression equation is represented:

\[
k = 0.2575 + 0.0375 \cdot x_2
\]  

Checking the equation adequacy according to Fisher criterion showed the need for a transition to a quadratic model.

The construction of such a function in this paper was carried out using experimental planning methods.
The levels of experimental factors variation are presented in Table 1, the choice of star points was determined by technologically acceptable intervals of variation of the oscillation frequency $\nu$ and amplitude $a_0$.

**Table 1. Levels of factors variation**

| The factors          | Oscillation frequency $\nu$, Hz | Vibration amplitude $2a_0\times10^{-3}$ |
|----------------------|---------------------------------|----------------------------------------|
| Ground level $x_0$   | 19.5                            | 0.235                                  |
| Variation interval $\Delta x$ | 1.061                         | 0.095                                  |
| The top level        | 20.561                          | 0.33                                   |
| The lower level      | 18.439                          | 0.14                                   |
| Star-shaped point “+”| 21.000                          | 0.37                                   |
| Star-shaped point “-”| 18.000                          | 0.1                                    |

Planning an experiment using a quadratic regression equation. At this stage of the study the experiment consisted of 12: four experiments of the full factorial experiment $2^2$, four at the center of the plan for obtaining variance estimate, and four more at the star points (Table 2).

**Table 2. The plan of experiment of the second order**

| The number of experiment | The number of experiment | $x_0$ | $x_1$ | $x_2$ | $x_1x_2$ | $x_1^2$ | $x_2^2$ | $k$  | $U$, (V) | $I$, (A) | $V$, ($10^{-3}$m) |
|--------------------------|--------------------------|-------|-------|-------|----------|--------|--------|-----|--------|--------|-------------------|
| 1                        | 1                        | +1    | +1    | +1    | +1       | +1     | +1     | 0.23| 0.239  | 55.8   | 14.5              |
| 2                        | 2                        | +1    | -1    | +1    | -1       | +1     | +1     | 0.36| 0.174  | 34.5   | 13                |
| 3                        | 3                        | +1    | +1    | -1    | -1       | +1     | +1     | 0.29| 0.089  | 19.9   | 19.8              |
| 4                        | 4                        | +1    | -1    | -1    | +1       | +1     | +1     | 0.15| 0.070  | 13.5   | 5.4               |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |
|                          |                          |       |       |       |          |        |        |     |        |        |                   |

Completesthe factor experiment

| 5                        | 5                        | +1    | +1.414 | 0 | 0 | +2 | 0 | 0.68 | 0.162 | 38.5 | 10 |
| 6                        | 6                        | +1    | -1.414 | 0 | 0 | +2 | 0 | 0.25 | 0.108 | 19.7 | 9.1 |
| 7                        | 7                        | +1    | 0 | +1.414 | 0 | 0 | +2 | 0.19 | 0.236 | 54.5 | 15.8 |
| 8                        | 8                        | +1    | 0 | -1.414 | 0 | 0 | +2 | 0.4  | 0.061 | 12.9 | 4.4 |

Star-shaped point

| 9                        | 9                        | +1    | 0 | 0 | 0 | 0 | 0 | 0.37 | 0.136 | 29.7 | 9.8 |
| 10                       | 10                       | +1    | 0 | 0 | 0 | 0 | 0 | 0.35 | 0.138 | 29.6 | 9.6 |
| 11                       | 11                       | +1    | 0 | 0 | 0 | 0 | 0 | 0.36 | 0.139 | 29.9 | 10 |
| 12                       | 12                       | +1    | 0 | 0 | 0 | 0 | 0 | 0.38 | 0.137 | 29.8 | 9.7 |

Centre of the plan
By processing the results of experimental data, a quadratic model of the unknown function was obtained:

$$k = 0.365 + 0.0773x_1 - 0.0184x_2 - 0.0675x_1x_2 - 0.656x_2^2,$$  \hspace{1cm} (2)

where $x_1$ and $x_2$ are the values of the experiment factors in a coded scale, associated with the values of the frequency $\nu$ and the amplitude $a_0$ of oscillations in the natural scale dependencies of the form:

$$x_1 = \frac{\nu - 19.5}{1.061}, \quad x_2 = \frac{2a_0 - 0.235}{0.095}.$$

The absolute value of the regression coefficients, signs at the beginning of the resulting equation, indicate that only the frequency of oscillations of the screening surface of screen contributes to an increase in the completeness coefficient of the classified material flow division. The latter is explained by the fact that it is the best conditions for the rotation of particles around their own axis as they pass through the flow of material are created due to vibrations. And, on the contrary, an increase in the amplitude of oscillations reduces the magnitude of the studied function, and when the amplitude of oscillations reaches a threshold value corresponding to the separation of particles from the screening surface, the ratio of division completeness takes the minimum value. Ridge analysis using the Lagrange multipliers method of the obtained quadratic model of the studied function allowed us to establish the values of the vibration frequency factors $\nu = 21.137$ Hz and the amplitude $a_0 = 0.6894 \times 10^{-3}$ m, corresponding to the value given by the experimental conditions, $k = 0.53$. Checking the results of the solution in the course of additional experiments showed good convergence of the calculated and experimental data. The obtained quadratic model, written in the form of equation (2) by the Fisher criterion at 5% significance level of the coefficients, is adequate for the conditions and results of experiments.

In canonical form, equation (2) has the form:

$$k = 0.2579 = -0.07986X_2^2 + 0.01426X_2^2.$$  \hspace{1cm} (3)

The signs of the coefficients of the equation show that the surface of the response function is a hyperbolic paraboloid, its new coordinates are expressed through the old equations:

$$\tilde{X}_1 = 0.3893 \cdot (x_1 + 2.4985) + 0.9211 \cdot (x_2 - 1.1452)$$

$$\tilde{X}_2 = -0.9211 \cdot (x_1 + 2.4985) + 0.3893 \cdot (x_2 - 1.1452)$$  \hspace{1cm} (4)

and, accordingly, the old coordinates are interlinked with new ones by expressions:

$$x_1 = 0.3893\tilde{X}_1 - 0.9211\tilde{X}_2$$

$$x_2 = 0.9211\tilde{X}_1 + 0.3892\tilde{X}_2$$  \hspace{1cm} (5)

The coordinates of tracks projections from cutting plates on the response surface corresponding to five ranks are calculated by the formula (3) and are given in Table. 3

| $\tilde{X}_1$ | $\tilde{X}_2$ |
|-------------|-------------|
| 0.2579      | 0.3         |
| 0.3         | 0.4         |
| 0.5         | 0.5         |

Table 3. Coordinates of tracks projections of response surface

The remoteness of the surface center from the experimental area makes it necessary to execute the search for a conditional extremum lying on the surface of a certain hypersphere with its center in the center of the plan, and not in the center of the response function surface. To determine the points of conditional extremum, we compose the following system of equations:

$$\begin{cases}
(b_{11} - \lambda) \cdot x_1 + 0.5 \cdot b_{12} \cdot x_2 + 0.5 \cdot b_1 = 0 \\
0.5 \cdot b_{21} \cdot x_1 + (b_{22} - \lambda) \cdot x_2 + 0.5 \cdot b_2 = 0
\end{cases}$$
Where $\lambda$ is uncertain Lagrangian factor, $b_1, b_{12}, b_{21}, b_{22}$ are coefficients of the equation (2).

After substituting the values of the coefficients in (6), we obtain the following system of equations:

$$
\begin{align*}
(0 - \lambda) x_1 + 0.5(-0.0675)x_2 + 0.5 \cdot 0.0773 &= 0, \\
0.5(-0.0675)x_1 + (-0.0656 - \lambda)x_2 + 0.5(-0.08184) &= 0
\end{align*}
$$

which is given in an aspect after simplification:

$$
\begin{align*}
-\lambda x_1 - 0.03375x_2 + 0.03865 &= 0, \\
-0.03375x_1 - 0.0656x_2 - \lambda x_2 - 0.0092 &= 0
\end{align*}
$$

The value of the multiplier when searching for the maximum must be greater than the maximum positive coefficient in the regression equation (3) reduced to the canonical form. In this case, the multiplier should be greater than 0.01426.

The sequence of computational operations during the search of conditional extremum points is as follows. Initially, we specify several values and solve the system of equations (7), as a result of which we determine the values of factors at these points on a code scale. Then we calculate the magnitude of the response by substituting the found values into equation (2). After determining the conditions of experiments in full scale, we find the value of the sphere radius by the formula:

$$\tilde{R} = \sqrt{\sum_{i=1}^{n} x_i^2}$$

The calculation results are summarized in Table 4. The coordinates of the conditional extremum point of the eighth experiment are closest to the optimal value of the parameters of the screen operation mode, which represents a confirmation of its rationality.

**Table 4.** Coordinates of conditional extremums

| Thenumber ofexperie | $\lambda$  | $R$   | $x_1$ | $x_2$ | $v_\nu$ (Hz) | $2a_\nu$ (10^{-3}m) | $k$ |
|---------------------|------------|-------|-------|-------|---------------|----------------------|-----|
| Codegauge           | Naturalgauge|
| 1                   | 0.02       | 6.824 | 6.31  | -2.548 |               |                      |     |
| 2                   | 0.025      | 3.65  | 3.3858| -1.3628| 0.8269        |                      |     |
| 3                   | 0.03       | 2.4904| 2.3166| -0.9141| 0.6490        |                      |     |
| 4                   | 0.035      | 1.8910| 1.7633| -0.6830| 0.5645        |                      |     |
| 5                   | 0.04       | 1.5224| 1.4227| -0.5418| 0.5176        |                      |     |
| 6                   | 0.045      | 1.2753| 1.1942| -0.4476| -             |                      |     |
| 7                   | 0.05       | 1.0979| 1.03  | -0.3802| -             |                      |     |
| 8                   | 0.038      | 1.6525| 1.543 | -0.5915| 21.137        | 0.1788               | 0.525 |

Let us compare the energy savings from a decrease in the value of $h$ with its expenditures on the implementation of oscillations of the screening surface of the screen when the material flow passes through it without taking into account the energy costs of the forced oscillations of the surface itself. Then, following the energy analysis of the classification process, we point out that part of the work of all external forces in the presence of oscillations of the screening surface corresponds to the expression:

$$A' = A_h + A_\nu,$$

where $A_\nu$ is work performed by an external force equal to the gravity $G_\theta$ of the second volume of the classified material on the screening surface of the screen related to the frequency and amplitude of oscillations by the ratio [4]
The calculated values of $A_h$ and $A_\nu$ turned out to be 0.0368 J and 0.433 J, respectively, with a total value of work $A^* = 0.4696$ J.

4. Conclusion
Thus, the energy savings from the use of vibration in the second of the considered classification processes amounted to 0.0822 J in absolute terms, or 14% of the amount of energy given to the material flow by lifting it over the screening media. That confirms the feasibility of using vibration to intensify the process of classification of bulk materials.

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