Functional model of energy consumption for mixing with a vertical paddle mixer

Alexey Chupshev¹, Vyacheslav Teryushkov¹, Vladimir Konovalov¹², Alexander Mishanin³, Vladimir Novikov³ and Maria Fomina¹

¹Penza State Agrarian University, st. Botanical, 30, Penza, 440014, Russia
²Penza State Technological University, travel Baidukova / st. Gagarina, 1a / 11, Penza, 440039, Russia.
³Samara State Agrarian University, st. Training, 2, P.g.t. Ust-Kinelsky, Samara Region, 446442, Russia.

E-mail: konovalov-penza@rambler.ru

Abstract. A description is given of a vertical paddle mixer with a batch action of bulk materials. Based on the obtained experimental data, part of the previously published and newly identified equations of regression of mixing unevenness, the functions of the factors of the empirical mixing intensity coefficient are obtained. They take into account the influence of technological (proportion of the control component, volume of a mixing tank and its degree of filling), operating (mixer angle of the blades) and design(number of blades, blade length) mixer parameters. Based on the interconnection of the functions describing the power consumption, the required duration of mixing and the mass of the prepared mixture, a mathematical model of specific energy costs is obtained. Graphic materials are presented that make it possible to evaluate the combined effect of the mixer parameters on the mass of the prepared mixture, the duration of mixing, power consumption, and specific energy consumption. The rational use of the mixer with a share of the control component of at least 10%. With an increase in the stirrer rotation frequency of more than 350min⁻¹, the intensity of the reduction in mixing time slows down. Reducing a portion of the mixture reduces energy costs. In terms of energy consumption, small mixers are more efficient, but they have low productivity.

1. Introduction

In the implementation of production processes, the modern national economy makes extensive use of various composite materials and mixtures in construction [1], engineering [2], mining [3], chemical [4] and food industry [5]. These materials are prepared both in extruders and in a wide variety of mixers. For bulk products, drum [5], paddle [6,7], vibration [8] and other mixers are used.

One of the areas of application of mixtures is agriculture, in which various cereal [10] and fodder [11] mixtures are prepared during the production process. One of the sought-after mixtures is compound feeds and their preliminary derivatives - premixes and protein-vitamin supplements. For the preparation of these bulk mixtures, various paddle mixers are widely used [11, 12].

In the study of mixers, the authors focus most often on the theoretical aspects of the completeness of the mixing process [13, 14] and the energy costs involved [15]. However, from a practical point of view, functional dependencies are also of interest, comprehensively describing the process of mixing a particular mixer design according to the main indicators of the technological process.
A design of a vertical paddle mixer was developed, during the study of which an experimental material was obtained, and based on it, regression expressions of specific performance indicators of the proposed mixer were established: power [16], mixing quality [17]. However, there is no comprehensive energy description of the technological process of the specified mixer based on the results.

Conversion of the regression equations for this mixer design into a functional model was not performed.

The aim of this study is to develop a functional model of the energy consumption of mixing of a vertical mixer with paddle working bodies for implementation in the MathCAD computer algebra system to establish the influence of structural, kinematic and technological parameters on the specific energy consumption of mixture formation.

2. Research methods
The methodology of the studies involved the development of a generalized functional model of specific energy costs for the process of mixture formation. In this case, the regression dependences previously established by the authors [16, 17] was used, which describe individual indicators of the flow of the technological process of mixing in the developed mixer (Figure 1).

The specific energy costs were modeled in the MathCAD computer program. Using the developed program, numerical studies were carried out to establish the nature of the change in specific energy consuming parameters of the mixing process for specific technological tasks. The interval of change in the numerical values of the factors presented in the mathematical model corresponded to the values of the parameters of experimental studies.

In the process of experimental studies, the stirrer rotation frequency varied from 250 to 1000 min⁻¹, the number of blades from 3 to 8 pcs., the angle of installation of the blades from 15 to 60°, the length of the blades superimposed on the blades from 15 to 75 mm, the volume of the tank from 1 up to 30 liters, the degree of filling from 0.2 to 0.7, the proportion of the control component from 5 to 20%. The indicator of mixing quality was the coefficient of variation of the content of the control component in 20 samples.

The proposed mixer of bulk materials of periodic action (Figure 1) consists of a container 4, inside of which a vertical shaft 3 is installed in the upper bearing support 1 and a similar lower support in the bottom 10 of the mixer tank, driven by a V-belt pulley 9. With a gap from the bottom 10, a stirrer is installed on the shaft 3, consisting of a hub 6 with inclined blades attached to it 7. At the edges of the blades, blades 5 are attached.

Figure 1. Mixer of periodic action for bulk materials: 1 – upper bearing support; 2 – loading funnel; 3 – drive shaft; 4 – capacity of the mixer; 5 – blades; 6 – nave; 7 – blades; 8 – unloading tray; 9 – a pulley of a mixer drive; 10 – bottom of the tank.
The components of the mixture are loaded through the loading funnel 2 with the shutter closed at the unloading tray 8. When the drive is turned on, the mixer rotates, providing both the circumferential movement of the mixed mass and the movement in the vertical plane. After preparing the primary mixture, it is possible to reload the remaining components of the mixture and mix them to obtain the finished mixture. When the shutter is opened, the finished mixture leaves the mixer through the unloading tray 8.

3. Results of the research

Evaluation criteria for the effectiveness of the mechanization of technological lines for the preparation of mixtures are the energy consumption for preparing a portion of the mixture and specific - per kilogram of the mixture. There are a number of restrictions on the use of technological machines. In case of non-compliance with technological requirements for quality indicators of the operation of devices, use is prohibited. Productivity of machines should correspond to productivity of a technological line. The power consumption of electric motors of the machines should not exceed the installed power of the engine for the implementation of technological process, taking into account the necessary margin.

Specific energy consumption in the preparation of the mixture [18], J/kg:

\[ A_y = \frac{P \cdot T_c}{M}, \]  

(1)

where \( P \) – power consumption of the drive of working bodies, \( W \); \( T_c \) – the duration of mixing, providing technological requirements for the quality of the mixture, s; \( M \) – the mass of the prepared portion of the mixture, kg

The mass of the prepared portion of the mixture [18], kg:

\[ M = V_o \cdot E \cdot \rho. \]  

(2)

where \( V_o \) – mixer tank volume; \( E \) – the degree of filling the tank with material; \( \rho \) – filling density of the mixture, kg/m³.

For the design of the mixer under consideration, the power consumption is determined [16], W:

\[ P = 3.680412 \cdot M \cdot n^{0.814137} \cdot (l_s^{0.543368} + l^{0.962341}) \cdot (\sin \alpha)^{0.346369} \cdot Z^{0.393481}, \]  

(3)

where \( n \) – rotational speed, min⁻¹; \( l_s = D/6 \) – blade width, m; \( l = (l_p - l_s) \) – blade length not overlapping the blade width \( l_s \), m; \( l_p \) – full blade length, m; \( Z \) – number of blades, pcs.

The duration of the mixing cycle is defined as the combination of the durations of several measures (c): loading \( T_Z \), mixing \( T_S \), unloading \( T_B \), preparatory and final works \( T_{PB} \) for the technological cycle.

The duration of component loading (s) for the j-th mixing stage in the mixer tank depends on the performance of the particular metering devices used. For multi-component dispenser:

\[ T_Z = K_Z \cdot \max \left( \frac{M_j}{Q_k} \right), \]  

(4)

where \( K_Z \) – coefficient taking into account preparatory and final actions during the operation; \( Q_k \) – productivity of the dosing device of the k-th component, kg / s; \( M_k \) – the mass of the k-th component according to the recipe of the mixture, kg;

\[ M_k = M \cdot D_k \]  

(5)

where \( D_k \) – fraction of the k-th component according to the recipe of the mixture.

The dependence of the mixing duration, which provides technological requirements for the quality of the mixture, remains unknown. Moreover, the dependence of the quality of the mixture on a number of parameters is known [17], including taking into account the duration of mixing of the components. The model function of the relative uniformity of the mixture \((V_p, \%)\) is an exponential expression:

\[ V_p = 100 - e^{-k \cdot T} \]  

(6)
where $k'$ – empirical components mixing intensity coefficient. Empirical components mixing intensity coefficients expressed by the function [17]:

$$k' = K_e \cdot K_{V_0} \cdot K_{Dk},$$

(7)

where $K_e$ – empirical coefficient of influence of the degree of the tank filling; $K_{V_0}$ – empirical coefficient of the mixing tank volume; $K_{Dk}$ – empirical ratio of the share of the control component.

The indicated empirical coefficients are described by the expressions:

$$K_{Dk} = -0.04 \cdot (0.176 \cdot T_s) \cdot (0.099) \cdot 2.038523 \cdot (0.0676) \cdot 1.85623,$$

(8)

$$K_e = \frac{-1.9822 - 6.2676 \cdot 10^{-4} \cdot T_s}{1.98226 \cdot 0.462945 \cdot 1.85623},$$

$$K_{V_0} = 1.20813 \cdot \left(\frac{1}{T_s}\right) \cdot \frac{V_0}{(V_0)^{0.7429}}.$$

Using the indicated expression (7), it was substantially refined by introducing additional coefficients that take into account the design of the mixer. The empirical coefficient of mixing intensity is described by the expression:

$$k' = K_T \cdot K_K = (K_{Dk} \cdot K_e) \cdot (K_{V_0} \cdot K_{\alpha} \cdot K_{nl} \cdot K_{nz}),$$

(9)

where $K_T$ – empirical coefficient of influence of technological parameters; $K_K$ – empirical coefficient of influence of design and operating parameters of the mixer; $K_{Dk}$ – empirical ratio of the share of the control component; $K_e$ – empirical coefficient of influence of the degree of the tank filling; $K_{V_0}$ – empirical coefficient of the mixing tank volume; $K_{\alpha}$ – empirical coefficient of influence of the blade angle; $K_{nl}$ – empirical coefficient of influence of blades length; $K_{nz}$ – empirical coefficient of influence of the number of blades.

Additional empirical mixing intensity coefficients (factors) are expressed by functions (Figure 2):

$$K_{\alpha} = \frac{3.0105819}{n^{0.194652(\sin \alpha)0.153251}},$$

$$K_{nl} = \frac{0.1542453}{(n)^{0.0261775(0.815979\alpha)^{28.13775}}},$$

$$K_{nz} = \frac{3.75988}{(n)^{0.18758(2)^{0.12892}}},$$

(10)

The indicated empirical coefficients are obtained on the basis of the transformation of the below, obtained on the basis of experimental data, expressions of the unevenness of mixing.

The expression of uneven mixing $v_t$ taking into account the stirrer rotation speed n and the installation angle of its blades $\alpha$, 0.01%:

$$v_t = 0.01 \cdot e^{2.2247(0.0297-n)^{-0.194652(\sin \alpha)}-0.153251},$$

(11)

where $n$ – mixer rotation speed, min$^{-1}$; $\alpha$ – blades installation angle, degrees. In this case, the correlation coefficient R=0.95211.

The expression of uneven mixing $v_{nl}$ taking into account the speed $n$ of the mixer and the length of the blades $L$ outside the blades, 0.01%:

$$v_{nl} = 0.01 \cdot e^{115618(n)^{0.0373-26.1775(0.815979\alpha)^{28.13775}},}$$

(12)

where $L$ is the length of the blades outside the blades, m. The correlation coefficient R=0.96709.

The expression of uneven mixing $v_{nz}$ taking into account the speed $n$ of the mixer and the number of blades $Z$, 0.01%:

$$v_{nz} = 0.01 \cdot e^{2.850856(0.055241-n)^{-0.18758(0.001289Z)^{0.12892}},}$$

(13)

where $L$ is the length of the blades outside the blades, m. The correlation coefficient R=0.98023.
From the expression (6), the mixing time is determined by the dependence, c:

\[ T_s = \frac{-\ln(v_{\text{tech}})}{k} \]  

(14)

where \( v_{\text{tech}} \) – mixture unevenness (variation coefficient control component content in the samples taken) according to technological (or livestock farming – zootechnical) requirements.

It is impossible to express the duration of mixing from expressions (6), (9), (10), (14). However, using the capabilities of a computer program by the method of selecting values with an acceptable error, it was possible to establish the duration of mixing to achieve a given quality of the mixture. Factor analysis (according one factor) made it possible to graphically establish the effect of part of specific factors on the duration of mixing (Figure 2).

\[ T_s = \frac{-\ln(v_{\text{tech}})}{k} \]  

The proportion of the control component in the mixture is most intensively affected - the smaller the value, the more intensive the increase in the duration of mixing. An increase in the rotation speed, the number of blades and the angle of installation of the mixing blades of the mixer reduce the duration of mixing. The increase in the mass of the feed portion (including the volume of the mixer and the degree of filling) require an increase in the duration of mixing.

Based on the expressions (1,2,3,15), using factor analysis (one factor each), the effect of technological and operating parameters on the combined effect can be established for the mass of the prepared portion of the mixture \( M \) (kg), power consumption \( P \) (W), mixing duration \( T_s \) (s) and specific energy consumption \( A_y \) (J / kg), shown in Figure 3.
Figure 3. The influence of the design, operating and technological parameters of the mixer on the required duration of mixing (c): (a) – stirrer rotation speed \( n \), min\(^{-1}\); (b) – number of blades \( Z \), pcs.; (c) – blades installation angle \( \alpha \), degrees; (d) – proportion of the control component \( D_k \), %; (e) – degree of filling of the mixing tank \( \varepsilon \), 0,01%; (f) – mixing tank volume \( V_0 \), m\(^3\).

An increase in the degree of filling the tank increases the mass of the mixture being prepared (Figure 3.a), this leads to an increase in the power consumption of the drive and the required mixing time. Accordingly, energy costs are growing. Reducing a portion of the mixture reduces energy costs.

An increase in the volume of the mixing tank increases the mass of the mixture being prepared (Figure 3.b), this leads to an increase in the power consumption of the drive. However, with increasing volume, the increase in mixing time slows down. Accordingly, energy costs are growing, but the increase in their intensity is slightly reduced. That is, small mixers are more efficient in terms of energy consumption, but they have low productivity.

When the proportion of the control component changes (Figure 3.c), the mixture mass and power consumption are constant. As the proportion of the control component increases, the mixing time decreases. The rational use of the mixer with a share of the control component of at least 10%. The change in energy consumption corresponds to the duration of mixing.
Figure 4. The effect on the mass of the prepared portion of the mixture $M$ (kg), power consumption $P$ (W), mixing duration $T_s$ (s) and specific energy consumption $A_y$ (J/kg) technological and operational parameters of the mixer: (a) – degree of filling of the mixing tank $\varepsilon$, 0.01%; (b) – mixing tank volume $V_o$, m$^3$; (c) – proportion of the control component $D_k$, %; (d) – stirrer rotation speed $n$, min$^{-1}$.

An increase in the rotation speed leads to an increase in power consumption and energy costs (Figure 3.d). In this case, the duration of mixing is reduced. With a stirrer speed of more than 350 min$^{-1}$, the intensity of the reduction in mixing time slows down.

4. Conclusion
The determination of the functional dependences of the empirical mixing intensity coefficients made it possible to obtain the equation for changing the quality of the mixture during mixer operation, taking into account the duration of mixing. This made it possible to determine the required mixing time, which, in combination with the equations of the power consumption of the mixer and the mass of the portion being prepared, made it possible to obtain a functional model of the energy consumption of mixing the vertical mixer with blade working bodies, implemented in the MathCAD computer algebra system. Numerical studies of the obtained model allow us to study the operation of the mixer to establish the influence of structural, kinematic and technological parameters on the specific energy consumption of mixture formation for specific technological problems. The rational use of the mixer with a share of the control component of at least 10%. With an increase in the stirrer rotation frequency of more than 350 min$^{-1}$, the intensity of the reduction in mixing time slows down. Reducing a portion of the mixture reduces energy costs. In terms of energy consumption, small mixers are more efficient, but they have low productivity.
References
[1] Zagorodonjuk L, Lesovik V, Volodchenko A 2015International Journal of Applied Engineering Research 10 24 pp 4484-44847https://elibrary.ru/item.asp?id=26291612
[2] Celik O, BontenC 2019AIP Conference Proceedings 2055 020008 https://doi.org/10.1063/1.5084809
[3] Luo X,Li J , Yang W-L, Wu F-J, Ouyang J-Q 2015Chinese Rare Earths 36 5 pp 146-150https://DOI:10.16533/J.CNKI.15-1099/TF.201505026
[4] Shenoy P, Viau M.Tammel K, Fitzpatrick J, Ahrné L 2015Powder Technology 272 pp165-172https://doi.org/10.1016/j.powtec.2014.11.023
[5] Zhumagalieva G, Pershin V, Tkachev A, Vorobiev A, Pasko A, Galunin E 2018AIP Conference Proceedings 204113 020010 https://doi.org/10.1063/1.5079341
[6] Yaraghi A, Ebrahim M, Ein-Mozaffari F, Lohi A 2018 Advanced Powder Technology 29 11 pp 2693-2706https://DOI:10.1016/j.apt.2018.07.019
[7] Ebrahim M, Yaraghi A, Ein-Mozaffari F, Lohi A 2018Powder Technology 332 pp 158-170https://DOI:10.1016/j.powtec.2018.03.061
[8] Vandenbergh A, Wille K 2018Construction and Building Materials 164 pp 716-730https://doi.org/10.1016/j.conbuildmat.2017.12.217
[9] Kato Y, Yasui N, Furukawa H, Nagumo R 2016Kagaku Kagaku Ronbunshu 42 6 pp 187-191https://doi.org/10.1252/kakoronbunshu.42.187
[10] Mudarisov S, Khasanov E, RakhimovZ and other2017 Journal of Mechanical Engineering Research and Developments 404 pp 706-715 https://DOI: 10.7508/jmerd.2017.04.018
[11] Rocha A, Montanhini R, Dilkin P, Tamiosso C, Mallmann C 2015Animal Feed Science and Technology209 pp 249-256 https://DOI: 10.1016/j.anifeedsct.2015.09.005
[12] Wu M-C, Wu C-S , Liang J-Y, Lei Y-T,YangB 2017 458 pp 68-73 http://en.cnki.com.cn/Article_en/CJFDTOTAL-IMIY201708014.htm
[13] Jin X-L, Jing L, Ma B-J 2013Advanced Materials Research 655-657 pp 257-263https://doi.org/10.4028/www.scientific.net/AMR.655-657.257
[14] Dyomin O, Pershin V, Smolin D 2012 Chemical and Petroleum Engineering 483-4 pp213-216https://doi.org/10.1007/s10556-012-9600-9
[15] Kato Y, Obata A, Kato T, Furukawa H, Tada Y 2012Kagaku Kagaku Ronbunshu 383 pp 139-143https://DOI: 10.1252/kakoronbunshu.38.139
[16] Fomina M, Konovalov V, Cupshev A, Teruskov V 2016Innovative Techniques and Technol.3.08pp 50-56https://elibrary.ru/item.asp?id=27224202
[17] Konovalov V, Cupshev A, Fomina M 2016Innovative Techniques and Technol. 3.08 pp 57-66 https://elibrary.ru/item.asp?id=27224203
[18] Chupshev A, Konovalov V, Fomina M 2018IOP Conf. Series: Journal of Physics: Conf. Series 1084 012010 https://doi:10.1088/1742-6596/1084/1/012010