Algorithm for calculating the power factor of a rotary mixer drive

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Abstract. The purpose of the research was to develop a methodology for calculating the power factor of the rotary agitator unit drive with its components and an algorithm for their determination, implemented in the form of a computer program. The structural scheme of the bulk material mixer with the developed agitator unit is given. The definition of the required parameters is realized on the base of the known expressions and operating parameters of the mixer. The developed technique and calculation algorithm, which is realized in the MathCAD mathematical package, allow determining the peripheral velocity profile parameter of the material and the hydraulic resistance coefficient of the working body, the power factor and the mixing capacity factor, which allows calculating the torque and power required for material mixing by a rotary mixer with a vertical shaft of the developed design.

1. Introduction

Modern production requires materials with a variety of properties. In order to obtain different properties in materials, mixtures of several components are prepared. Such mixtures are used in the construction, mechanical engineering and chemical industries to produce composite materials [1, 2]. In the food industry or agriculture, mixtures are also required to produce efficient feed or original food products [3,4]. Particulate mixtures are also often used in the form of particles encapsulated with a different composition [5]. To maintain the formulation of the mixture, it is necessary to dose the components [6], and then distribute them evenly over the entire volume of the mixture being prepared [7]. This is most often realised in mixers - devices for mixing such materials. In addition to mixing of particles of materials, some designs are used for their post-mixing [8], or for thermal treatment [9].

In the development of mixers both the results of experimental studies and the implementation of theoretical developments are used [10]. In the above article two methods for assessing the mixing efficiency are given. A numerical model of the device operation is considered and an experimental model is presented. The use of the two methods for the calculation of mixing improves the reliability of the result.

Probabilistic methods of mixer loading are considered in [11]. The authors modelled the mixing process. Data on the effect of random mixture loading on the mixing drum and parts are revealed. The law of variation of random load with regard to probability distribution is obtained.

Statsenko V. and other authors [12] built a mathematical model of bulk materials particle motion in the rotor of a continuous-acting centrifugal mixer, taking into account geometrical and physical-mechanical parameters, based on the method of discrete elements.
In the work [8] the mixers for thin chemical products are investigated. The influence of structural and kinematic parameters of high shear toothed mixers on the performance of micro-mixing is shown. Computational fluid dynamics calculations were carried out to investigate the flow structure and turbulent energy dissipation rate.

In the work [3] the influence of mixer design features, mixing speed and properties of the materials to be mixed were revealed. Theoretical calculations of power from material properties and device parameters and operating modes were obtained. The dependencies between the power of the mixer screw and the degree of grinding of the product were obtained.

Unfortunately, it was not possible to find a method of determining the coefficients establishing the influence of the rotary mixer parameters on the resistance to the movement of the agitator in the material and the value of the consumed power. The aim of the research is to develop a methodology for calculating the power factor of the rotary mixer drive with its components, and an algorithm for their determination, implemented in the form of a computer program.

2. Research methodology

The research methodology involved a theoretical justification of expressions based on known scientific provisions with the justification of the relationship between the torque of the rotating agitator and the empirical resistance coefficient of the tank walls to calculate the power taking into account the parameters of the circumferential velocity profile of the material. Based on the theoretical justification performed, an algorithm for determining the coefficients of power calculation was developed. To estimate the reliability of the obtained result, a graphic check of the equilibrium of the rotating moments from the agitator and the tank (their balance is zero) and determination of the consumed power was made. For mixing the ingredients of the mixture it is proposed to use a mixer [13] with rotary agitators (Figure 1). The mixer uses several vessels, each of which has its own rotary agitator with paddles. Considering the similarity of the agitators of the different tanks, the calculation of the drive power of any of their agitators has a similar methodology.

![Figure 1. Structural and technological diagram of the micro-additive mixer:](image)

1. frame; 2 – body; 3, 4, 5 – mixing vessels; 6 – central shaft; 7 – agitator; 8 – vessel flap; 9 – handle; 10 – body discharge flap; 11 – tray; 12 – bunker; 13 – bunker flaps; 14 - flexible hose; 15 – V-belt transmission; 16 – electric motor.

Based on the provisions of mechanics, the condition of equilibrium of the acting forces and moments is observed in the case of steady-state motion. That is, the sum of forces and the sum of moments of the system must be zero. In such a case, it is known that the torque on the shaft of the agitator, transmitted from its paddles through the material to be agitated to the tank walls, will be balanced by the friction...
moment of the material against the tank walls. These moments and their components, as well as the expression of power are determined by the known [14,15] expressions.

The power required for mixing the materials with the rotary agitator:

\[ N_n = K_N \cdot \rho \cdot n^3 \cdot d_m^5, \]  

where \( \rho \) – the medium density, kg/m\(^3\); \( n \) – the agitator speed, c\(^{-1}\); \( d_m \) – the outside diameter of the agitator, m.

In this case, the power indicator:

\[ K_N = 3.87 \cdot Z \cdot \zeta \cdot K_1, \]  

where \( Z \) – the number of paddles, pcs.; \( \zeta \) – the hydraulic resistance coefficient determined empirically; \( K_1 \) – the mixing power factor, depending on the design of the paddles.

The torque on the agitator shaft, N·m

\[ M_m = Z \cdot \zeta \cdot K_1, \]  

The torque of friction of the material against the vessel walls, N·m

\[ M_p = \frac{\pi \cdot \gamma \cdot \nu}{2 \cdot R e^{0.25}} \cdot \Gamma^{2.75} \cdot V_a^{1.75}, \]  

The circulatory Reynolds criterion is determined by

\[ R_e = n \cdot d_m^2 / \nu, \]  

where \( \nu \) – the kinematic viscosity of the medium to be mixed, m\(^2\)/s.

The resistance coefficient of the vessel walls.

\[ \lambda = \frac{R e}{(20.35 \cdot R e^{-1.91})}, \]  

where \( \gamma \) – the device filling height parameter, \( \Gamma_D = D / d_m \) – the hydrodynamic similarity simplex (the ratio of vessel diameter \( D \) to the agitator diameter \( d_m \)); \( V_a \) – the relative average circumferential velocity of the material in the vessel:

\[ V_a = \frac{1 + 0.4 + \psi_1 + 0.5 \cdot \psi_2 + 1.75 \cdot (1 + \psi_1 + \psi_2) \cdot (\Gamma_D - 1)}{2 \cdot \Gamma_D}. \]  

At this \( \psi_1 \) and \( \psi_2 \) – the parameters of the circumferential velocity profile of the material.

The values \( \psi_1 \) and \( \psi_2 \) are connected by the relationship:

\[ \psi_2 = -s_1 - s_2 \cdot \psi_1, \]  

where \( s_1 = \frac{7 \cdot \Gamma_D - 6}{21 \cdot \Gamma_D - 20} \) and \( s_2 = \frac{28 \cdot \Gamma_D - 27}{21 \cdot \Gamma_D - 20} \).

The empirical expressions used for the previously mentioned indicators may vary, however, the dependencies used for our design have the specified form.

The mixing power factor:

\[ K_1 = (\psi_1 + \psi_2)^2. \]  

Given the large number of empirical interdependent expressions, it is necessary to express the main force values through the circumferential velocity profile parameters of the material. Once the material circumferential velocity profile parameters are determined, it will be possible to find the numerical value of the tank wall resistance coefficient and consequently calculate the torque value of the mixing unit and its power consumption: \( N = N_n \).

3. Research results.

Given the lack of known numerical values of the parameters of the circumferential velocity profile of the material in the studied mixer, it is not possible to calculate the remaining above-mentioned
indicators, including the torque and power of the agitator drive. Therefore, it is necessary to develop a calculation method for the indicators used and to implement an algorithm for their calculation in the form of a computer program.

From the experimental values of the power consumption of the mixer drive $N_n$ and f.1, it is possible to identify the value of the power index $K_N$. At the same time, the product of the coefficient of hydraulic resistance $\zeta$ to the mixing power factor $K_1$ can be expressed from f.2. In this case, the mixing power factor $K_1$ is (f.9) a function of the parameters of the circumferential velocity profile of the material $\psi_1$ and $\psi_2$.

To determine the torque on the agitator shaft (f.3) it is necessary to determine the peripheral velocity profile parameters $\psi_1$ and $\psi_2$. In this case $\psi_2$ is defined by the parameter $\psi_1$. On the other hand, the friction torque of the material against the vessel walls (f.4) depends on the resistance coefficient of the vessel walls $\lambda$ and the relative average circumferential velocity of the material in the vessel $V_a$. The latter figure (f.7) also includes parameters for the circumferential velocity profile of material $\psi_1$ and $\psi_2$.

Taking into account the condition of equality (modulo) of the torque on the agitator shaft (f.3) to the friction torque of the material against the vessel wall, and substituting the values from f.5-8, this condition is:

$$M_m = M_v; \quad (10)$$

whence:

$$Z \cdot \zeta \cdot K_1 = \frac{\pi \lambda \gamma}{2.2 R_e^{2/5}} \cdot \frac{V_d^{2.75}}{D} \cdot V_d^{1.75}. \quad (11)$$

From f.1 we express the power indicator:

$$K_N = \frac{N_n}{\rho n^3 d_m \zeta} \quad (12)$$

From f.2 we express the mixing power factor:

$$K_1 = \frac{K_N}{3.87 Z \cdot \zeta} = \frac{N_n}{\rho n^3 d_m \zeta (3.87 Z \cdot \zeta)}. \quad (13)$$

Substituting the mixing power factor in f.11, we obtain an expression for the torque on the agitator shaft (f.3)

$$M_m = Z \cdot \zeta \cdot K_1 = Z \cdot \zeta \cdot \frac{N_n}{\rho n^3 d_m ^2 (3.87 Z \cdot \zeta)} = \frac{N_n}{3.87 \rho n^3 d_m ^3}. \quad (14)$$

Then: $|M_m - M_v| = |B_m| \rightarrow 0$. Or

$$\frac{N_n}{3.87 \rho n^3 d_m ^3} - \frac{\pi \lambda \gamma}{2.2 R_e^{2/5}} \frac{V_d^{2.75}}{D} \left(\frac{1+0.4 \psi_1+0.5 \psi_2+1.75 (1+\psi_4+\psi_2) \cdot (1+\psi_4+\psi_2) \cdot (1+\psi_4+\psi_2)}{2 \Gamma D}ight)^{1.75} = 0. \quad (15)$$

An attempt was made to express the circumferential velocity profile parameter $\psi_1$ from f.15. However, it was not possible to express it symbolically.

It remained possible to solve the expression numerically.

In that case, the algorithm for calculating the indices was as follows (Figure 2). Based on the initial conditions (numerical values of the parameters during the experiments), we preliminarily determined all possible values of the used indicators.

And using the numerical values of the parameters in f.15, the values satisfying the condition of equality were selected (i.e. a value of $\psi_1$ was found).

Using the set value of $\psi_1$, we determined the value of the hydraulic resistance coefficient $\zeta$ for the power factor (f.2) and the mixing power factor (f.12).

The hydraulic resistance coefficient

$$\zeta = \frac{N_n}{3.87 Z \left(\psi_1+(-S_1-S_2 \psi_1)^2 \cdot \rho n^3 d_m \zeta \right)} \quad (16)$$
Figure 2. Algorithm for calculating the mixer agitator indicators and coefficients
The above algorithm was implemented in the Mathcad mathematical package. The circumferential velocity profile parameter of the material $\varphi_1$ was determined from the solution of the expression f.15 using the built-in functions "Given"-"Find", essentially implementing a cyclic calculation of the algorithm section (in the dotted frame in Figure 2), but with slightly different methods.

In order to check the correctness of calculations a graphic analysis of moment balance (F.10,11) was carried out. For this purpose the calculated value of the circumferential velocity profile parameter $\varphi_1$ with the factor 0.4 was taken and numerical values of the left part of f.15 (momentum balance mismatch index - $Bm_1$) on some interval of the values $\varphi_1$ were calculated. At the calculated value of the material circumferential velocity profile parameter $\varphi_1$, the momentum balance mismatch $Bm_1$ must intersect with the zero balance line. If the condition is fulfilled, then the calculation of coefficients and indicators is correct. In the above case, the condition was fulfilled (Figure 3), i.e., the problem was solved correctly.

![Figure 3. Momentum balance test results $Bm_1$ at the calculated values of the material circumferential velocity profile parameter $\varphi_1$](image)

4. Conclusion

The developed method and calculation algorithm realized in the mathematical package MathCAD allows to determine the values of profile parameter of circumferential velocity of material and subsequently the hydraulic resistance coefficient of the working body, power factor and power factor of mixing necessary for the calculation of torque and power of material mixing by rotor agitator with a vertical shaft of the developed design.

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