Modeling of the power of the drive of the spiral mixer

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Abstract. The goal of the paper is on the basis of the power analysis of revealing the expressions allowing to simulate by numerical methods the power of the drive of the mixer with a spiral stirrer. Expressions of effective forces are determined as a result of force analysis of spiral blade movement in the casing filled with material segment. The calculation model implemented in the Mathcad program allows to calculate the operating forces, torque and power consumption by numerical methods. The error of calculation, taking into account the correction factor that takes into account the material spillage when changing the spiral blade pitch, relative to the experimental power data does not exceed 5%.

1 Introduction
Modern economy provides for the use of various mixtures and composites with different properties [1–3]. Liquid [4], powdered [5] and lumpy mixtures of different granulometric composition are prepared [6, 7]. In the process of preparation of the mixture the energy consumption of mixture formation is reduced [8–10] and the quality of the mixture is improved [10, 11].

The most common types of mixers have various working bodies [12–14]. Recently, mixer mixers with screws [15, 16] and spiral elements [17] have been spread.

The use of a screw with a remote central part (belt spiral) allows to combine the mixing efficiency of components with a decrease in the resistance of the material to the movement of the working body. The use of such tools increases the efficiency of mixing [18].

2 Materials and methods

2.1 Object of study

The purpose of this work was to identify expressions on the basis of power analysis, which allow to simulate by numerical methods the power of the drive of the mixer with a spiral mixer, using the known positions of theoretical mechanics to determine the power consumption for the rotation of the working body - the vane mixer.

According to the results of the calculations, the expressions of normal reaction of the mixer casing to the material N, the average power on the rotation of the mixer blade spiral $P_{kr1}$, the power spent on...
the movement of the material from a single coil of $P_{dv1}$ were obtained, of power on a drive of one coil of a spiral $P_1$, power spent on rotation of a spiral $P$ and the histogram of convergence of rated $N_t$ (W) and experimental $N_o$ (W) power is constructed accordingly at various pitch of a screw (m) taking into account correction factor.

2.2 Research tools

As the main modeling tool, a modern computer based on the Microsoft Windows 8 platform was used. The work of the working body of the mixer was theoretically described and the calculation was made in the computer program Mathcad.

3 Results

Continuous mixer (Figure 1) is a spiral-screw conveyor [18], in which the working body serves as a mixer for transportation and simultaneous mixing of the loaded receiving neck of 3 components of the mixture. Mixer 5 is executed in the form of a shaft 6 on which two sites of spiral blades are established: with the big step 2 and small step 7. The finished mixture is unloaded on the discharge chute 4. In the process of rotation the spiral blade will capture the material and direct it up along the walls of the tank (Figure 2).

The research technique provided the analysis of forces acting on spiral blades of the mixer 5 mixer (Figure 1) at its rotation. On the basis of equilibrium equations the effective torque, and taking into account the angular velocity of the shaft - the power consumption for the stirrer rotation.

When climbing some angle (Figure 2), the material particles are poured down, forming the surface of the material ($A_0A_1$) at an angle - the dynamic angle of collapse of the material relative to the horizontal, Rad.

When performing the force analysis (Figure 1) we assume that the material in the cross-section of the mixer casing is located at a specified angle relative to the horizontal. There is an offset in the direction of the spiral movement, and thus before the spiral there is a build-up of the wedge shape, which makes the layers of material move along the surface of the specified build-up.

![Figure 1. Spiral mixer mixer: (a) - general view; (b) - complete working organ; 1 - electric motor; 2 - spiral blades with a large spiral pitch; 3 - receiving neck; 4 - discharge chute; 5 - stirrer; 6 - stirrer shaft; 7 - spiral blades with a small spiral pitch](image)
Having made an equation of the force balance knowing the value of the acting forces (Figure 2) per particle M. This equation is the following, H:

\[ \begin{aligned} \sum F_x &= F_{tr} + G \cdot \sin \beta - F \cdot \sin \theta + F_{tc} \cdot \cos \alpha = 0 \\ \sum F_y &= F_a + F_{tg} + F_c + G \cdot \cos \beta - N + F \cdot \cos \theta - F_{tc} \cdot \sin \alpha = 0 \end{aligned} \]  \tag{1}

where \( \beta = \beta_j \) – is the current angle of the spiral bar position relative to the vertical, deg.;

\[ G = m \cdot g = (\rho \cdot \Delta S \cdot h_1) \cdot g, \]  \tag{2}

where \( G \) – gravity force, H; \( m \) – mass of material above the reference particle, kg; \( g \) – acceleration of free fall, km/s²; \( \rho \) – bulk density of material, kg/m³; \( h_1 \) – material height, m; \( \Delta S \) – area of the elementary section on the surface of the mixer shell (m²), corresponds to the angle \( \varphi = 1^\circ \) and width (s/360°), at s, the step of the spiral, m.

Centrifugal force (H) is in expression:

\[ F_c = m \cdot \omega^2 \cdot R' = (\rho \cdot \Delta S \cdot h_1) \cdot \omega^2 \cdot R, \]  \tag{3}

where \( \omega \) – shaft angular velocity, rad/s; \( R' \) – the radius of the centre of gravity of the elementary sector of the material above particle M in the direction of the axis of rotation, \( R = \frac{2}{3}(R^2 - h_2^2)\sin(\varphi) \); \( h_2 \) – height of radial column of wedge-shaped material, m; \( \varphi \) – central corner of the elemental sector of the material, \( \varphi = 1^\circ \).

Normal mixer shell response to material N (H) will be:

\[ N = -\frac{G \sin \beta - F \sin \theta + F_{tc} \cos \alpha}{f_a}, \]  \tag{4}

where \( F_a = N f_a \) – friction force of the material against the mixer shell, H;

Force of inertia when lifting material, H:

\[ F_a = (\rho \cdot \Delta S \cdot (h_0 - h_2)) \cdot \frac{2 \cdot (\omega \cdot R_0)^2}{(R_1)^2}, \]  \tag{5}

Where \( h_2 \) – height of material layer in the growth of wedge shape in the direction of rotation axis, m.

The force of Coriolis is, H:

\[ F_k = (\rho \cdot \Delta S \cdot (h_0 - h_2)) \cdot 2 \cdot \omega \cdot \delta = (\rho \cdot \Delta S \cdot (h_0 - h_2)) \cdot 2 \cdot \omega \cdot \frac{R_x}{R^2}, \]  \tag{6}

**Figure 2.** Calculated diagram of spiral blades operation when filling the intertidal space of the mixer with material: (a) - scheme of forces action; 1 - mixer casing; 2 - outer edge of the material's heap; 3 - material particle; 4 - cross-section of the bar spiral; (b) - scheme of geometrical parameters arrangement.
where \( R_x = 2r + r_\Delta \) – wedge height, \( m \); \( r \) – spiral radius, \( m \); \( r_\Delta \) – gap between mixer casing and spiral blade, \( m \).

Friction force of the material on the growth of the wedge-shaped material, \( H \):
\[
F_{tc} = (\rho \cdot \Delta S \cdot (h_1 - h_2)) \cdot g \cdot f_0,
\]
where \( h_3 \) – height of material layer in the growth of wedge shape, \( m \).

Internal friction force of the material, \( N \):
\[
F_{tg} = (\rho \cdot \Delta S \cdot (h_0 - h_2)) \cdot g \cdot f_0.
\]
Spiral blade force in the section, \( N \):
\[
F = \frac{P_a + F_{tg} + F_{c} + g}{\omega f_1} \left[ F_{tg} \sin \alpha \right] = \frac{(h_0 - h_2) \left( a + g \cdot f_0 + 2 \omega R_2 \right) + h_2 \cdot 2 \omega^2 R + g \cdot h_1 \left( \cos \beta \sin \beta_1 \right) + g \cdot f_0 \cdot (h_1 - h_2) \cdot [1 + \sin(\alpha)/f_1]}{(\sin(\beta)/f_1)}.
\]
For elementary sectors along the length of the wedge-shaped growth:
\[
F_i = \rho \cdot \Delta S \times (h_0 - h_2) \left( a + g \cdot f_0 + 2 \omega R_2 \right) + h_2 \cdot 2 \omega^2 R + g \cdot h_1 \left( \cos \beta \sin \beta_1 \right) + g \cdot f_0 \cdot (h_1 - h_2) \cdot [1 + \sin(\alpha)/f_1] \cdot \frac{(\sin(\beta_i)-\cos(\beta_i))}{(f_1)}.
\]
By summing up the power segments of the wedge-shaped node, we obtain the torque for a specific position of the spiral rod, \( N \cdot m \):
\[
M_{kr} = \sum_{i=0}^{\gamma_1} F_i \cdot \sin \theta_i \cdot (R - r - r_\Delta)
\]
Average power per spiral rotation, \( W \):
\[
P_{kr} = \sum_{j=0}^{\gamma_2} M_{kr} \cdot \frac{\omega}{2 \pi} = \sum_{j=0}^{\gamma_2} \left( \frac{\sum_{i=0}^{\gamma_1} F_i \cdot \sin \theta_i}{f_1} \right) \cdot \frac{\omega (R - r - r_\Delta)}{2 \pi}.
\]
For progressive motion for a specific elementary \( i \)-th segment of the nostaclin shape of the friction force of the material on the shell of the container, \( N \):
\[
F_{tr} = N_1 \cdot f_1 = f_1 \cdot \frac{G \cdot \sin \beta - F \cdot \sin \theta_1 + F_{c} \cdot \cos \alpha}{f_1}.
\]
Power consumption per revolution, \( W \):
\[
P_{d} = F_{tr} \cdot \omega = \sum_{i=0}^{\gamma_0} \left[ \frac{G \cdot r \cdot (\sin(\beta + i) - F_1 \cdot \sin \theta_1 + F_{c} \cdot \cos \alpha)}{2 \pi} \right] \cdot \omega \cdot s.
\]
The power to drive a single coil of coil (\( W \)) is defined by:
\[
P_1 = \left( P_{kr} + P_{d} \right) \cdot k_p.
\]
where \( k_p \) – pilot ratio.
Spiral power consumption (\( W \)):
\[
P = \sum_{j=1}^{L \cdot s} \left( P_{kr1} + P_{d} \right) \cdot k_p.
\]
Spiral screw capacity will be, kg/s:
\[
Q = 15 \cdot \omega \cdot [(R - r_\Delta)^2 - (R - 2r - r_\Delta)^2] \cdot s \cdot z \cdot k_q \cdot \frac{y}{\pi},
\]
where \( k_q \) – pilot ratio; \( z \) – number of spiral blades, pcs.

A normal reaction to the frictional force may be directed towards, towards or across the material movement direction. At a certain pitch of the coil, the possibility of the material moving forward is eliminated. Mixing of the material is facilitated by the absence of the condition of pushing the material forward, i.e. the pitch of the screw should be greater than the minimum pitch. Therefore, the critical tangent of the screw spiral angle during transport must be slightly less than the friction tangent of the material
\[
tg(\phi) = \frac{s}{(\pi (R - r - r_\Delta))}, \text{or } s = tg(\phi_{\text{mat}}) \pi (R - r - r_\Delta).
\]

The central angle of \( \gamma \) is determined by numerical methods from the segment equation: \( \gamma - \sin \gamma = \frac{2s}{R^2} \).
The angles of the material segment will be determined by degrees:
\[ \gamma = 5.047 + 789.744 \cdot S_2 - 1264 \cdot S_2^2 + 794.723 \cdot S_2^3, \]
\[ \beta_0 = \alpha - \frac{\gamma}{2}, \quad \beta_1 = \alpha + \frac{\gamma}{2}, \quad \beta_2 = \beta_1 - 2 \left( \beta_1 - \frac{\pi}{2} \right). \]  
(19)

For the current (i-th) values of angle \( \beta = \beta_i \), in the range of angles \((\beta_0; \beta_1)\), the height (i-th) of the material layer for the filling level \( S_2 < 0.5 \) is the following, \( m \) [19]:
\[ h_{0i} = R - \frac{R \cos(0.5 \gamma)}{\cos(\alpha - \beta_i)}; \quad \text{at } S_2 \geq 0.5 \text{ the height is the following } h_{0i} = R. \]  
(20)

For the arc \( A_0 \overline{A_i} \) – \( h_{1i} = h_{0i} \cdot \frac{\cos(\alpha - \beta_i)}{\cos \alpha} \); for the arc \( \overline{A_i} \overline{A_0} \) – \( h_{1i} = 2R \cdot \cos(\beta_i) \); for the arc \( \overline{A} \overline{A_1} \) – \( h_{1i} = 0 \).

The central angle \( \gamma_0 \) of the growth is determined by the expression [19]:
\[ \cos \gamma_0 = \frac{R \cos \beta \cdot X_{\beta_i} + R \sin \beta \cdot Y_{\beta_i}}{R \cdot \sqrt{X_{\beta_i}^2 + Y_{\beta_i}^2}}. \]  
(21)

Estimated value \([Rx^*] = R - \frac{R \cos(\alpha + \gamma_0)}{\cos(\alpha)}\).

Angle \( \theta \) between the force line \( F \) and the pipe radius is determined by:
\[ \theta = 180^{\circ} - \gamma_0 - \arcsin \left( \frac{R \sin \gamma_0}{\sqrt{(R - r - r_\Delta)^2 + R^2 - 2 \cdot (R - r - r_\Delta) \cdot R \cdot \cos \gamma_0}} \right). \]  
(22)

Angle \( \gamma_0 \) can be determined by numerical methods from the expression:
\[ [R - r - r_\Delta] \cos \gamma_0 - \cos \left( \gamma_0 + \arcsin \left( \frac{R \sin \gamma_0}{\sqrt{(R - r - r_\Delta)^2 + R^2 - 2 \cdot (R - r - r_\Delta) \cdot R \cdot \cos \gamma_0}} \right) \right) \times \]
\[ \sqrt{(R - r - r_\Delta)^2 + R^2 - 2 \cdot (R - r - r_\Delta) \cdot R \cdot \cos \gamma_0} - R = 0. \]

Height of current i-th value of wedge-shaped growth [19], \( m \):
\[ h_{3i} = R \cdot \frac{\sin ((\beta_j + \gamma_0) - (\beta_j + i))}{\sin ((\beta_j + \gamma_0) + (\beta_j + i))} = -R \cdot \frac{\sin(\gamma_0 - i)}{\sin(2\beta_j + \gamma_0 + i)} \]  
(23)

Radial height of the current i-value of the node \( h_2 \) at the angle of the spiral section \( \beta_i \) for angles \( \gamma_0 \) (deg.) and \( i \) (deg.), \( m \):
\[ h_{2ji} = h_{0ji} \cdot \frac{\gamma_0 - i}{\gamma_0}. \]  
(24)

Calculation error of up to 5% (Fig. 3) according to the formulas is achieved by using the correction factor, which takes into account the spreading of material when changing the screw pitch.

When the feed is transferred, the energy loss factor is:
\[ k_p = 2.414 - 4.891 \cdot k_s + 4.141 \cdot k_s^2 - 0.898 \cdot k_s^3, \]  
(25)

where \( k_s = \frac{s}{D - 2 \cdot r_\Delta} \) – is the ratio of the screw pitch to screw diameter; \( D \) – casing inner diameter, \( m; s \) – spiral pitch, \( m; r_\Delta \) – the gap between the spiral screw and the casing, \( m \).
Figure 3. Histogram of convergence of the calculated $W_t$ and experimental $W_o$ power (W), respectively, at different screw pitches $S$ (m) with regard to the coefficient $k_p$.

4 Conclusion

The force analysis of the spiral blade movement in the casing filled with a segment of material allowed to establish the expressions of active forces and moments. The calculation model implemented in the Mathcad software allows the calculation of operating forces, torque and power consumption using numerical methods. Error of calculation, taking into account the correction factor that takes into account the spiral blade pitch change; relative to the experimental power data does not exceed 5%.

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