Justification of the movement and displacement of the product inside the drum dryer with a paddle agitator

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Abstract. The technique and technology of movement and displacement of the powder product inside the drum dryer with a paddle agitator have been developed. Theoretical studies were carried out to assess the effect of the system of forces on the product inside the rotating drum when the agitator rotating in the opposite direction is exposed to it, which allowed estimating the throughput capability of the drying unit. It is established that, with an increase in the speed of movement and mixing of the product, the drying speed increases. The results of these studies can be used in the future when designing drying units and improving the drying technology.

1. Introduction

The improvement of drying technology is possible only through the development of modern methods of intensifying the drying speed and the development of new machines and apparatuses. To determine the technological and energy parameters of drum dryers, it is necessary to justify the movement and displacement of the product inside the dryer [1, 2, 4-7]. The drying speed is seriously affected by the following factors: how the product is mixed and how it moves inside the drum.

In most cases, drum dryers are installed, not horizontally, but at a slope in the direction of product movement or the opposite direction [2-5, 7]. Depending on the installation of the drum, the movement of the product along it depends on the action of a different set of forces:
- horizontal installation of the drum involves the promotion of the product under the action of hydrodynamic flow forces; therefore, this installation method is better used for a batch drum dryer;
- the installation with a slope involves the movement of the product under the action of the same hydrodynamic forces, together with the axial component due to the gravity of the particles of the dried product.

2. Materials and methods

The studied drying device with an angle of inclination in the direction of product movement (Figure 1) is a batch drum dryer equipped with a paddle agitator [3, 4, 5, 7].

The product to be dried is located inside a cylindrical perforated drying drum 1, the air supply is carried out by branch tubes 12 on both sides. A special feature of the device is the presence of a paddle mixing device 2, which rotates in the opposite direction of rotation of the drum. The product enters the...
drum during loading, then due to the angle of inclination it rolls down to the place of unloading, but the mixing device redirects it in the opposite direction (thereby loosening, tossing and washing with a drying agent).

**Figure 1.** Main view of the drum dryer: 1 - drying perforated drum; 2 - lobed mixing device; 3 - drive mixing device; 4 - nozzles; 5 - driven pulley; 6 - belt drive; 7 - tensioning device for the belt; 8 - drive drum; 9 - remote control; 10 - loading hatch; 11 - insulation jacket; 12 - branch tubes; 13 - heating chamber; 14 - tubular heaters; 15 - fan 16 - unloading hatch; 17 - output slot of the spent drying agent; 18 - adjusting screws; 19 - the frame of the dryer; 20 - damper for measuring and control operations

When loading, the product, under the action of the hydrodynamic force of the flow and the axial component due to the gravity of the particles, moves towards the unloading hatch 16 (Figure 1). The cross-section of the drum is shown in Figure 2.

When the dryer is turned on, the drum begins to rotate in one direction with an angular velocity $w_1$, and the paddle mixing device in the opposite direction with a speed $w_2$. The centrifugal force generated by the rotation of the drum presses part of the dried product against the walls of the drum, where it is carried away by the drum blades and moves with it, the other part of the product is delayed by the blades of the mixing device and moves with them in the opposite direction, at a speed equal to the speed of the agitator. Thus, inside the drum, there are two multidirectional flows of the dried product.

Two approaches are currently used to characterize the movement of the product in a rotating drum.

The first approach involves modelling the movement of a powder product by drawing up and describing a model of the movement of a single particle – the “single-particle” approach.

The second approach involves the use of such a phenomenon as “viscous flow”. The second method is more universal, since it allows considering the processes occurring under the action of stimulated forces,
while the first method is preferable only when describing free motion, but the use of the viscoplastic medium method is accompanied by the need to determine a large number of empirical dependencies, which can be established with more or less sufficient reproducibility only through numerous laboratory tests.

![Diagram of a drum dryer](image)

**Figure 2.** Cross-section of the drum: 1 - nozzles inside the perforated drum; 2 - agitator blades

3. Results and Discussion
In a drum dryer with a paddle agitator, the dried product will move through the volume of the drum in three directions:
- movement under the action of centrifugal force in the direction of movement of the drum;
- movement of the product along the axis of rotation of the agitator;
- the boundary region that occurs between two rotating flows, for which the motion of the particles is described by the equations below.

Figure 3 shows the longitudinal section of the drum with the angle of inclination coinciding with the direction of movement of the dried product. A diagram of the forces acting on a particle of a powder product in a drum with an angle of inclination in the direction of movement of the product is shown (Figure 3).
Figure 3. Movement of the particles of the powder product in the drum with an angle of inclination in the direction of its displacement: \( v \) - air velocity, m/s; \( F \) - the pressure of the airflow, N; \( \phi \) - the angle of rotation of the nozzle, degrees; \( y_1 \) - the magnitude of the displacement of the particle, m; \( g \) - gravitational acceleration, m/s\(^2\); \( m \) - the mass of the particle, kg; A, B - the points of the position of particles; \( h \) – the height of fall of the particles with the nozzles installed in the drum, m; \( a \) - the size of the blade in the radial direction, m

The particle, separated from the nozzle, moves under the influence of the following forces:
- the component of gravity relative to the x-axis (\( F_x \));
- the component of gravity relative to the y-axis (\( F_y \)).

\[
F_x = m \frac{d^2 x}{dt^2} = mg \cos \phi. \tag{1}
\]

where \( d \) - the equivalent particle size, m; \( m \); \( t \) – time, s.

In the beginning, the product is affected by the airflow \( F_1 \) on one side and \( F_2 \) on the other side. The resulting force will be the flow \( F \):

\[
F = (F_1 - F_2) \tag{2}
\]

At the point of contact with the drum nozzle, the particle will appear after a time equal to:

\[
t_1 = \frac{\sqrt{2h_{av}}}{g \cos \phi}. \tag{3}
\]

The average height of the falling particles can be represented as the height of a rectangle whose area is equal to the area of the figure bounded by the sinusoid and the abscissa axis:

\[
h_{av} = \frac{\int_0^{\pi} 2(R - a) \sin \phi d\phi}{\pi} = \frac{4(R - a)}{\pi}. \tag{4}
\]

where \( R \) - the inner radius of the drum, m.

The motion of the particle along the axis (y) occurs under the action of a force:
\[ F_y = m \frac{d^2 y}{dt^2} = F + mg \sin \phi. \]  

Accordingly, at the point of contact with the drum nozzle, the particle along the axis (y) will shift by a distance:

\[ y_1 = \left( \frac{F}{mg \cos \phi} + tg \phi \right) h_{av}. \]  

The pressure force of the airflow \( F \) and the mass \( m \) are expressed in terms of the parameters of the particle and the airflow:

\[ F = \left( \frac{\pi d^2}{4} \right) \rho g \frac{v^2}{k}. \]  

\[ m = \frac{\pi d^3}{6} \rho \]  

where \( \rho_g \) - the air density, kg/m\(^3\); \( k \) - the coefficient that takes into account the shape of the product; \( \rho \) - the particle density, kg/m\(^3\).

Concerning the design of the studied device, the formula (6) substituting the values of \( F \) and \( m \) from equation (7) and (8) can be presented in the following form:

\[ y_1 = \left( \frac{3v^2 \rho g k}{4d \rho g \cos \phi} + tg \phi \right) h_{av}. \]  

The particle fallen to the point B for some time \( t_2 \) will be mixed only in the vertical plane passing through the axis of the drum:

\[ t_2 = \frac{\phi_{av}}{\omega} \]  

where \( \phi_{av} \) - the average angle of rotation of the particle, which is found as the arithmetic means between the minimum and maximum angles of rotation; \( \omega \) - the angular velocity of the drum, c\(^{-1}\).

Figure 3 shows that \( \phi_{min} = 0 \),

\[ \phi_{max} = 2\pi - y = 2\pi - \arccos\left( \frac{R - a}{R} \right). \]

Substituting the values of \( \phi_{av} \) in equation (10), we get:

\[ t_2 = \frac{2\pi - \arccos((R - a) / R)}{2\omega}. \]  

The equation for the average velocity of the product moving in the axial direction will be as follows:

\[ V_{av} = \frac{y_1}{t_1 + t_2} = \frac{3v^2 \rho g (R - a)}{\pi d \rho g \cos \phi} + \frac{4(R - a)tg \phi}{\pi} + \frac{2\pi - \arccos\left( \frac{R - a}{R} \right)}{2\omega}. \]
To determine the volumetric throughput capability $Q$ of the dryer, we assume that a certain volume of product is poured from the nozzles per unit of time, which in cross-section occupies an area of:

$$S = S_l z_h n_b,$$

(13)

where $S_l$ - the cross-sectional area of the product layer captured by a single nozzle, $m^2$; $z_h$ - number of nozzles, pcs; $n_b$ - speed of rotation of the drum, rpm. When calculating $S_l$, we select an elementary area with coordinates $r$, $\varphi$, dimensions $dr$, $d\varphi$, and area $rdrdrd\varphi$, and represent it as

$$S_l = \int_0^\pi a^2 \sin \varphi d\varphi = \frac{a^2}{2} \int_0^\pi \sin \varphi d\varphi \approx a^2.$$

(14)

where $r$ - the radius of the nozzle, m.

Then the volumetric throughput capability of the dryer can be represented as:

$$Q = S \gamma_1 = \left(\frac{3v^2k\rho_s(R-a)}{\pi gd\rho \cos \phi} + \frac{4}{\pi}(R-a)\tan \phi \right)a^2 z_h n_b$$

(15)

In the case of using a single-blade device inside the drum, from the throughput capability $Q$ the capacity of the single-blade agitator $Q_2$ must be subtracted, since it rotates in the opposite direction to the drum.

According to sources [8, 9], $Q_2$ is assumed to be equal to:

$$Q_2 = 60 z_h \pi D^2 H \eta_\gamma \gamma n_m$$

(16)

where $z_b$ - the number of shafts, pcs; $D$ - the outer diameter of the blades, m; $H$ - the pitch of the blades, m; $\gamma$ - product weight, $kg/m^3$; $\eta_\gamma$ - filling factor, equal to 0.25; $n_m$ - the average number of rotations of the agitator, rpm; $T$ - the duration of the drying process, min.

Substituting values $Q$ and $Q_2$, we can determine the throughput capability of a drum dryer with a paddle agitator $Q_l$:

$$Q_l = Q - Q_2 = \left(\frac{3v^2k\rho_s(R-a)}{\pi gd\rho \cos \phi} + \frac{4}{\pi}(R-a)\tan \phi \right)a^2 z_h n_b - 60 z_h \pi D^2 H \eta_\gamma \gamma n_m$$

(17)

4. Conclusion

1. Analyzing the above equations (1-17), it can be concluded that the drying speed in a drum dryer with a paddle agitator can be intensified by increasing the speed of movement and mixing of the powder product, while it is important to optimally select the speed of the heated air supply to increase the amount of moisture that will eventually lead to a reduction in the time to achieve the final result.

2. The technique and technology of movement and displacement of the powder product inside the drum dryer with a paddle agitator have been developed. Theoretical studies were carried out to assess the effect of the system of forces on the product inside the rotating drum when the agitator rotating in the opposite direction is exposed to it, which allowed estimating the throughput capability of the drying unit. The results of these studies can be used in the future when designing drying units and improving the drying technology.
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