The rotating layer mechanics of polydisperse particles in the continuous action pneumatic mixers

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Abstract. The article presents the dry construction mixtures various components polydisperse flow with light and heavy particles rotating layer mechanics numerical and experimental study results. The obtained results allow to control the polydisperse flow layer rotation while it is mixing in the pneumatic mixer chamber working volume. The conditions for estimating the braking parameter of a rotating layer with polydisperse particles on the basis of which the working mixing chamber necessary dimensions can be effectively selected were analytically obtained.

Introduction

In the building materials industry, as well as in related industries: chemical, medical, metallurgical, etc., various pneumatic units are used for the polydisperse mixtures transportation and homogenization for a long time. For example, the continuous-flow pneumatic mixers modern designs are widely used for the various dispersed components effective mixing in the dry construction mixtures production [1, 2, 3].

In the works of a number of Russian [4,5] and foreign [6,7] authors in recent years, great attention is paid to the development of mathematical models describing the polydisperse systems motion in the various designs mixing chambers volume. At the same time, the behavior experimental modeling issue of the of polydisperse systems with the presence of light and heavy particles of different activity is still important.

We consider the rotating layer mechanics of an air-material flow with particles of different size and density in the working volume in a pneumatic mixer with continuous action [1]. In this process we use the probabilistic-analytical method described in [8].

Main part

It is known [8] that when the removal rate ratio to the weighing speed is:

\[ \frac{u_r}{u_w} \leq 78, \]  

The layer will be in the pneumatic mixing chamber main mixing zone, shown in Figure 1, in a suspended state and for \( \frac{u_r}{u_w} > 78 \) particles are not weighed with the flow. This condition is taken as the mathematical model initial condition.
In the analytical studies process and on the experimental and numerical values basis, an expression for the maximum separation coefficient at the periphery of the chamber was obtained:

$$K_{s \text{ max}} < \frac{8.8}{\sqrt{s}}$$  \hspace{1cm} (2)

where $K_{s \text{ max}}$ is determined from the expression proposed in [4]:

$$K_{s \text{ max}} = \sqrt{\frac{K^2(1-\bar{\rho})\rho d_{\text{max}}^2(u_k)}{18δ R_k}}.$$  \hspace{1cm} (3)

$K$ – is the degree of flow swirling with particles with respect to the radial velocity at the periphery of the mixing chamber (or at the radius of the outlet), determined according to the method in [8];

$s$ – is the parameter of deceleration of flow by a layer of particles, defined as in [8];

$\bar{\rho}$ - is a porosity coefficient.

$\rho_p$ – is a particle density, kg/m$^3$;

$d_{\text{max}}$ – is a maximum particle diameter, m;

$u_k$ - is the calculated radial velocity at the periphery of the chamber, m/s;

$\mu$ - is dynamic viscosity of the polydisperse flow, m$^2$/s;

$R_k$ – is the mixing chamber radius, m.

Expression (3) obtained by empirical and analytical methods determines the condition for the partially suspended layer existence of particles with a diameter $d < d_{\text{max}}$ in the mixing chamber volume. In the example with a layer of mass $M_0 = 151$ g, the deceleration parameter is $s = 0.08$. Then $K_{s \text{ max}} = 3.39$. To find a single particle on the equilibrium orbit, it suffices that $K_s = 1$. For a suspended layer in the mixing chamber volume the separation coefficient (3) calculated from the undisturbed flow parameters must be much higher. This is a condition for the rotating layer formation in the vortex flow formed in the mixing chamber, which also shows that in this case the centrifugal acceleration along the unperturbed flow must be much larger than is required for the equilibrium trajectory of a single particle. A single particle motion simulation in the mixing chamber volume is shown on Figure 2.

The particles for which the weighting rate $u_w$ is directed toward the center will exceed the value of the ablation rate $u_a$ will move into orbits (radial trajectories) with a smaller radius. If for particles of a certain diameter the weighing rate $u_w$ reaches the ablation rate $u_y$ on the radius of the outlet $R_1$, then a further increase in $u_w$ will lead to the removal of particles from the chamber and the homogenization process will not be effective. Then the minimum separation factor can be subtracted from the relation:

$$K_{s \text{ min}} > \frac{1}{\sqrt{s}} \left(\frac{R_1}{R_k}\right)^n,$$  \hspace{1cm} (4)

where $n$ – is an indicator of the absolute particle velocity.

The obtained relations (2) - (4) depending on the mixing chamber design parameters, the energy carrier properties and the unloaded mixing chamber gas-dynamic characteristics, allow to calculate the spectrum of particle diameters that will be in the rotating vortex layer. The solid particles that are in the energy carrier flow interact most intensively with the mixing chamber walls. Therefore, it is advisable to consider the tangential flow velocity inhibition in the parabolic cone volume.

The forces moment due to the energy outflow from the loading pipe, taking into account the tangential turbulence:

$$\Omega_{ip} = \rho Q \cdot \nu_{ip} R_k = G \cdot \Gamma_k,$$  \hspace{1cm} (5)

where $\rho$ – is the density of a single-phase medium or the density of the carrier phase (air), kg/m$^3$;

$Q$ – is the volume flow rate of a single-phase medium or carrier phase, kg/m$^3$;

$\nu_{ip}$ – is the tangential velocity at the outlet of the pipes of the inflation, m/s;

$G$ – is the mass flow rate of a single-phase medium or carrier phase, kg/m$^3$;

$\Gamma_k$ – is the estimated circulation [9].

This forces moment on one hand is applied to the tangential flow of a polydisperse system with air, and on the other hand creates a flow momentum moment. The input moment is counteracted by the friction moment $\Omega_f$ of the layer against the walls of the mixing chamber. The rest of the moment $\Omega_{ip}$ in creates a stream of angular momentum of the medium $\Omega$ passing through the layer, i.e.:
The moment of friction $\Omega_1$ from the pressing force $F$ of particles to the walls of the mixing chamber taking into account the friction coefficient of the $f_f$ layer with its surface is equal to:

$$\Omega_1 = F \cdot R_k \cdot f_f.$$  

The pressing force $F$ of particles in the radial direction is determined in accordance with the Stokes law:

$$F = \frac{m_p \cdot du_p}{dt}.$$  

Here $m_p$ is the particle mass, kg; $\frac{du_p}{dt}$ is the radial acceleration of a particle in the flow Stokes law around a particle, m/s.

Taking into account the expressions obtained in [8] we conclude that the expression for the force at radial velocity $u_p = 0$:

$$F = - \frac{m_p \cdot u_k^2}{R_k} \cdot S_p [1 - K_f^2].$$  

Where $u_k^2$ is the calculated radial velocity at the camera periphery, m/s; $S_p$ is the flow impact parameter on the particle.

In this expression $K_f^2$ depends on the twist degree

$$K_f^2 = K_f$$

in the loaded mixing chamber. From expression (9) it follows that when the separation coefficient is less than 1, the force is negative, i.e. it is directed toward the center, and when $K_f > 1$, it is positive and presses the particle to the side surface of the mixing chamber. Then the frictional moment created by one particle is following:

$$\Omega_1 = - \frac{m_p \cdot u_k^2}{R_k} \cdot S_p [1 - K_f^2] \cdot f_f.$$  

Summing up (11) over all particles, for $S_p$ and $K_f$, the frictional moment of the layer can be written as follow:

$$\Omega_f = - \frac{u_k^2}{f_f} \cdot \sum_{d_{kp}} d = \left[\frac{3\pi \mu R_k}{6(1 - \dot{\rho})} \cdot \frac{\pi d^2}{6} \cdot \rho_p K_f^2 (1 - \dot{\rho})\right].$$

where $d_{kp}$ is determined from the condition 1 and in the Stokes mode it will be as follows:

$$d_{kp} = \frac{18\pi \mu R_k}{\sqrt{K_f^2(1 - \dot{\rho})(1 - \dot{\rho})}}.$$  

Here $d_{max}$ is the diameter of the largest particle in the layer, m.

Since, for $d_{e} > d_{max}$ the first term in (12) is significantly less than the second and can be neglected when summed up, we have the moment in the form:

$$\Omega_f \approx \frac{\nu_{pk}^2}{R_k} \cdot \frac{d_{e}}{d_{c}} \cdot \frac{d_e}{\rho_p} \cdot (1 - \dot{\rho}) \cdot \sum_{d_{kp}} d_{max} m_p,$$

where $d_{c}$ is the diameter of a spherical particle with a volume of $V_p$.

In (13), the degree of twist $K_f = \frac{\nu_{pk}^2}{u_k}$ depends on the tangential velocity $\nu_{pk}$ of the energy carrier and the layer on the periphery of the mixing chamber. Moving from summation (14) to integrating the mass of particles expressed through the distribution function $dM = M \frac{dd}{dd}$ (where $M$ is the mass of all particles in the layer), we finally get:

$$\Omega_f = q \cdot \left(\frac{d_e}{d_{c}}\right) M \cdot (1 - \dot{\rho}) \cdot [1 - D(\tau_{kp})] v_{pk}^2 \cdot f_f,$$

where $\tau_{kp} = \frac{d_{kp}}{d_{c}}$ - defines an argument of the particle distribution function.

In the steady state, the tangential velocity of the medium passing through the suspended layer is equal to the tangential velocity $\nu_{pk}^2$. Therefore, the flow of angular momentum is equal to:

$$\Omega = \rho \cdot Q \cdot v_p \cdot R_k.$$
After substituting the moments in (10) and performing the transformation, we find the relation for the parameter \( s \):

\[
\frac{1}{s} = \frac{M(1-\bar{\rho})[1-D(\tau_{kp})]d_3f_f\sin\phi ip}{\rho R_k f_{ip} d_c} + \frac{1}{\sqrt{s}}.
\]  
(17)

This layer braking parameter \( s \) dependence on \( M \) is similar to the experimental one that we have made for conducting a full-scale experiment:

\[
\frac{1}{s} = 0.09M + 1.25.
\]  
(18)

Under experimental conditions \( D(\tau_{kp}) = 0.5; f_f = 0.01 \) coefficient for \( M \) in (17) is \( 0.12r^{-1} \) and is close to the value of the experimental coefficient. In this comparison, the value of \( f_f = 0.01 \) is assumed to be lower than with sliding friction, due to the fact that the particles have the ability to roll. Taking into account the theoretical coefficient in (17) the experimental dependence in a generalized form is written as:

\[
\frac{1}{s} = \bar{M} \cdot (1 - \bar{\rho})[1 - D(\tau_{kp})] \cdot f_f + 1,
\]  
(19)

where \( \bar{M} = M \cdot d_e \cdot s \cdot \sin\phi ip / \rho \cdot R_k \cdot f_{ip} \cdot d_c \) – relative mass of the layer.

The ratio \( \frac{d_e}{d_c} \) will be defined as:

\[
\frac{d_e}{d_c} = \sqrt{\frac{1}{1 + 0862 \ln(q)}} \quad \text{if} \ S_p > 10; \quad \text{(20)}
\]

\[
\frac{d_e}{d_c} = \frac{q}{\sqrt{12.4q - 11.4}} \quad \text{if} \ \frac{K_{s2}(S_{p2}^{1.5})}{\sqrt{1-\rho}} < 1 \quad \text{(21)}
\]

In case (20), the critical particle diameter is calculated from the condition \( \eta_{d2} = 1 \) for \( S_{p2} \cdot K_{s2} < 3 \) and for \( S_{p2} \cdot K_{s2} > 3 \) from the condition \( K_{s2} = 1 \). The parameters \( S_{p2} \) and \( K_{s2} \) are the flow effect parameter on a particle with a quadratic flow law and the separation coefficient with a quadratic flow law of particles, respectively. Expression (19) allows to estimate the braking parameter \( s \) and close the equations system (2) - (4) by the rotating layer mechanics. When considering \( s \) in (19) it is necessary to take into account that the critical diameter \( d_{kp} \) through \( K_{kp} \) depends on \( s \), therefore \( s \) is calculated by the method of successive approximations.

In accordance with the objectives of this study, a situational model of the process of homogenization of particles in the working volume of the mixing chamber of a pneumatic mixer was made. The simulation results of a rotating layer in the SolidWorks2014 software package, using the example of a particle, are correlated with the results of a mathematical model (Figure 1).

As can be seen from Figure 2, when an axial flow enters the mixing chamber under the action of a tangential inflow, the material layer rotates in the air at the maximum radius of the chamber and its rotation continues through the reverse flow zone shown in Figure 1. There is a stationary vortex motion of particles in the energy flow the components of the velocity of the particles can be determined in accordance with [4,5].

\[ \text{a)} \quad \text{b)} \]
Summary
The obtained analytical expressions establish the rotating layer braking parameters mathematical dependence on the mixing chamber dimensions and allow to effectively manage the polydisperse systems homogenization process in the pneumatic mixer working volume.

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