

# CHEMICAL ENGINEERING, HEAT ENGINEERING AND ENERGY-SAVING

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## MATHEMATICAL DESCRIPTION OF THE CARRY-OVER OF THE GROUND MATERIAL INTO THE SEPARATION SPACE OF ROLLER MILLS

Developed a mathematical description of the ash particulate material in the separation space roller mills. A mathematical model of the motion of particles in a swirling upward gas flow, for the first time takes into account the concentration of the solid phase. The dependence of the axial velocity of the particle on the velocity of the carrier medium at different concentrations of the solid phase. It is shown that at low solids content (1–5%) relative to the carrier gas environment with unrestricted conditions, the influence of neighboring particles on the trajectory can be neglected.

**Introduction.** Specific of roller mills is as follows: all the material exiting from the rotating grinding table, regardless of the particles size should be blown off into the separation zone and then into the separator. In gravity separation zone larger particles are deposited and returned for re-grinding. The middle class and fine commodity product are carried away in a separator where they are divided: the commodity product is taken away from a mill, and the middle class comes back in the center of a plate for re-grinding. Thus closed circuit of mill operation is carried out. Therefore, in these grinding aggregates a mill and a separator are a single unit and respectively, the movement of material flows in them should be interlinked.

In scientific literature there isn't much data on the movement of the particles after entering the annular space formed by the end face of the grinding table and the body of the mill. In the publication [1], the movement of particles in the separation area is regarded in the axial flow. However under such gas supply it is very difficult to distribute it by regular intervals. As a result zones with retarded speed of gas are formed in which the material isn't blown up, but falls down, disrupting the normal operation of the mill. Recently various ways of alignment of structure of a gas stream are offered, one of which is the tangential supply of the bearing environment.

Movement of particles in the twirled stream was widely studied in cyclonic processes, vortical mass exchanged devices, vortical and centrifugal mills [2–3]. We have previously carried out theoretical studies of single particles in the swirling gas stream in the separation space of roller mills [4]. As a result particle flight path in separation space

is received, as well as components of full speed and height at which there is its contact with a wall of a body. The final parameter is necessary for structural improvement of the mill as a separation zone should be made in such a way that particles couldn't reach a mill wall above an annular space. In contact with a wall particles slide down the body of the mill under the grinding table, i.e. downfall of the grinded material takes place.

In the process of the development of the above-mentioned model [4] we admitted absence of interaction between the particles, as some sources [5] suggested that when considering the motion of the solid particles in gas suspensions at concentrations of less than 0.02 the influence of the channel walls or neighboring particles on the terminal velocity can be neglected. At the same time, in the annular space and above the grinding table concentration of the solid phase can reach  $\beta = 0.05$  in connection with the peculiarity of the mill operation in a closed circuit and arising circulation of the part of the material. Thus, the aim of the work was to assess the impact of constraint motion of particles in carrier flow onto a flight path of their movement.

**Main part.** As it is known, in case of a particle entering into the swirling gas flow the particle is affected by a complex of external forces. Determining forces affecting the movement of the particles in a gas environment are the aerodynamic resistance  $F_b$  and gravity ( $G$ ) (fig. 1).

In general, formula of a particle motion of the material in a swirling air stream can be represented as follows:

$$m \frac{d\vec{u}}{dt} = \sum_{i=1}^k \vec{F}_i, \quad (1)$$

where  $u$  – motion speed of a particle in a swirling air stream, m/s;  $t$  – travelling time of a particle, s;  $k$  – number of external force, affecting a particle of the material during its movement;  $F_i$  – active force, N.

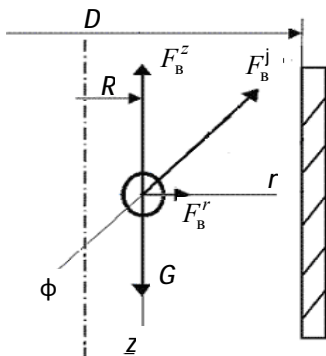


Fig. 1. Computational scheme

Force of aerodynamic influence of air has the main effect on a particle movement of the material in the swirling flow and in this case is defined as follows:

$$\begin{aligned}\bar{F}_B &= \frac{1}{2} k c r S |\bar{w}_i - \bar{u}| (\bar{w}_i - \bar{u}) = \\ &= \frac{1}{8} k c r \rho d^2 |\bar{w}_i - \bar{u}| (\bar{w}_i - \bar{u}),\end{aligned}\quad (2)$$

where  $k$  – particle drag coefficient;  $c$  – aerodynamic drag coefficient;  $\rho$  – air density, kg/m<sup>3</sup>;  $S$  – section area of a particle, m<sup>2</sup>;  $w_i$  – airspeed in the given point of the device, m/s;  $d$  – particle diameter, m.

Module of speed differential of air stream and a particle (relative speed) is possible to present in the form of:

$$|\bar{w}_i - \bar{u}| = \sqrt{(w_r - u_r)^2 + (w_\phi - u_\phi)^2 + (w_z - u_z)^2}, \quad (3)$$

where  $w_r$ ,  $w_\phi$ ,  $w_z$  – constituents of full speed of air stream, m/s.

It should be noted that when considering any tasks of the movement of biphase streams finding of constituents of full speed of the gas flow is a certain difficulty.

Until recently the most simple and reliable method of speed and pressure calculation was pneumatic based on pressure detection in certain points of the surface by measuring devices (probes) brought in a stream. Besides, the measurements were carried out mainly using three-channel probes due to their simplicity and availability. But apart from the low accuracy of the measurements, the use of three-channel probes meant the inability to obtain data for the radial component of the gas velocity. In some sources it is recommended to ignore this component due to its insignificance when considering the motion of particles in a steady swirling gas flow. We have previously also used

this approach and the above-mentioned assumption when developing the model of motion of a single particle [4]. However, the air flow in the separation space of roller mills is not steady due to the presence of a number of elements that violate the flow pattern (rollers and the grinding table, etc.). Besides, at the present stage of development of computing technologies and computers, new methods of obtaining velocity profiles based on computer modeling of aerodynamics gas environments using specialized mathematical packages such as Solid Works Flow Simulation, Ansys, etc appeared. Earlier we have carried out research of aerodynamics of the roller mill separation zone with the help of applied package Solid Works Cosmos Flo Works [6]. As a result of modeling distribution profiles of the three components of air speed were obtained, besides a significant impact of the radial velocity on the motion state was shown. Data processing has provided an opportunity to make experimental and analytical model [4], characterizing change of gas velocity components  $w_r$ ,  $w_\phi$ ,  $w_z$  on section of the mill, which we used in further calculations (4).

$$\begin{aligned}w_r &= 14.4\% - 31.3\% + 18.2\% - 1.3\% + 0.1; \\ w_\phi &= 7.9\% - 41.1\% + 49.5\% - 16.7\% - 0.1; \\ w_z &= -19.1\% + 37.4\% - 20.8\% + 4.2\%\end{aligned}\quad (4)$$

where  $w_r$ ,  $w_\phi$  – respectively relative flow velocity components and the relative radius.

In literature there are many empirical formulas for the calculation of aerodynamic drag coefficient  $C$ , depending on the Reynolds number  $Re$  [5]. For analytical studies the following functional connection is favourable:

$$C = A Re^{-n}, \quad (5)$$

where  $A$  and  $n$  – empirical coefficients depending on the value of  $Re$ , ie, the mode of motion.

However, the overall lack of formulas of this type is that their application is limited by a small range of values  $Re$ .

In many cases it is advisable to use the binomial formulae, the most famous of which is the formula of L. S. Klyachko [5]:

$$c = 24 Re^{-1} + 4 Re^{-1/3}. \quad (6)$$

It is considered that in the laminar flow of a gas suspension with strictly monodisperse spherical particles collisions between them does not occur. If one of these conditions is not satisfied, the trajectory of the different particles may overlap, which leads to more or less intense interaction between them. Such a situation occurs when the chaotic motion of particles during their removal to the separation zone of roller mills takes place.

Particle terminal velocity (removal rate) testing with the help of known functional connection  $c = f(\text{Re})$  requires iterations which are also slow to converge. Therefore it is more convenient to express dependence  $c = f(\text{Re})$  as  $c = f(\text{Ar})$  because Archimedes criterion does not obviously depend on terminal velocity.

In many cases presence of neighboring particles significantly affects the flow phenomena of the particle by gas and, consequently, terminal velocity rate, which is smaller than it should be. From numerous sources the following correlation of Reynolds number for recording of influence of concentration of a firm phase in a gas stream is considered to be the most reliable [5]:

$$\text{Re} = \text{Ar}(1 - b)^{4.75} \frac{\rho_m}{\rho} \left( \frac{g}{\nu} \right)^{-1} + 0.61 \sqrt{\text{Ar}(1 - b)^{4.75} \frac{\rho_m}{\rho}} \quad (7)$$

where  $\text{Ar}$  – Archimedes number.

Archimedes number can be determined by the classical formula:

$$\text{Ar} = \frac{g d^3 \rho_m}{\nu^2 \rho} \quad (8)$$

where  $g$  – gravity factor,  $\text{m/s}^2$ ;  $\nu$  – kinematic viscosity of the environment,  $\text{m}^2/\text{s}$ ;  $\rho_m$  – particle density of the mill material,  $\text{kg/m}^3$ .

Movement of the twirled gas stream has a complex spatial character. Solid particles, trapped in such a stream are taken away by the gas and begin to move along the spiraling path. Movement along such paths is usually considered in a cylindrical coordinate system. Center of the coordinate system is compatible with the center of the mill.  $r$ ,  $\varphi$ ,  $z$  will be current coordinates in this case. Full particle velocity in this case is characterized by three components:  $u_r$ ,  $u_j$ ,  $u_z$ .

Then projected on the axis of the cylindrical coordinate system the equations of motion of a solid particle in a swirling flow will be as follows:

$$\begin{aligned} m \frac{du_r}{dt} - \frac{u_j^2}{R} &= F_B^r, \\ m \frac{du_j}{dt} + \frac{2u_r u_j}{R} &= F_B^j, \\ m \frac{du_z}{dt} &= F_B^z - G, \end{aligned} \quad (9)$$

where  $R$  – current radius of movement of a particle of the material and airflow,  $\text{m}$  (Fig. 1).

Substituting in the system of differential equations (9) expressions (2), (3) and (6) – (8) and carrying out appropriate transformations, we finally receive

$$\begin{aligned} \frac{du_r}{dt} &= \frac{3kcr(w_r - u_r)}{4dr_m}, \\ \sqrt{(w_r - u_r)^2 + (w_j - u_j)^2 + (w_z - u_z)^2} &+ \frac{u_j^2}{R}, \\ \frac{du_j}{dt} &= \frac{3kcr(w_j - u_j)}{4dr_m}, \\ \sqrt{(w_r - u_r)^2 + (w_j - u_j)^2 + (w_z - u_z)^2} &- \frac{2u_r u_j}{R}, \\ \frac{du_z}{dt} &= \frac{3kcr(w_z - u_z)}{4dr_m}, \\ \sqrt{(w_r - u_r)^2 + (w_j - u_j)^2 + (w_z - u_z)^2} &- g. \end{aligned} \quad (10)$$

Thus, solving the system of differential equations and taking into account the above-mentioned initial conditions, we receive numerical values of tangential, radial and axial speeds of movement of a single particle in a ring clearance of a roller mill.

Taking into account the size of separate components it is possible to calculate the value of full speed of a particle when contacting with a wall of a mill:

$$u = \sqrt{u_r^2 + u_j^2 + u_z^2}. \quad (11)$$

Fig. 2 shows the dependence of the axial velocity of the particle movement in the annular gap on average consumable gas velocity at various concentrations of a solid phase in a carrier stream, resulting at the calculation of a roller mill with an internal diameter of 250 mm and a diameter of a grinding table of 214 mm. The initial values of the components of velocity of particles from the grinding table were defined earlier [7].

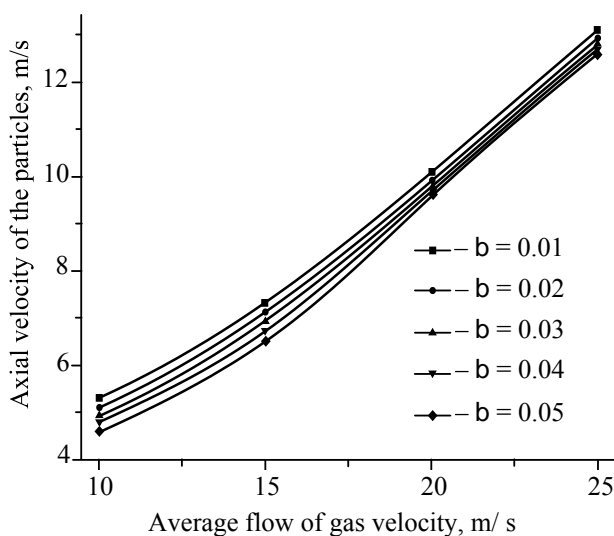


Fig. 2. Dependence of axial speed of a particle on speed of a bearing stream at various concentration of a firm phase

The dependence shows that the axial velocity of the particle changes almost linearly. The analysis of the received data shows, that even at a fivefold increase of concentration of a firm phase in a gas stream (in a range from 1 up to 5 %) speed of movement of particles changes no more than by 4 %.

On the received dependence, having calculated speed витания particles, it is possible to define speed of a bearing stream at which the particle will start to fall by gravity. These data are important to determine the conditions that prevent the failure of the material.

Also, according to the proposed mathematical model of particle movement its flight trajectory is built after descending from the grinding table and falling into the bearing gas flow (Fig. 3).

According to the trajectory it is easy to establish the height ( $H$ ) at which the particle will rise before contacting with an internal wall of the mill and the direction of movement of a particle. For the effective separation particles should not get on a wall of a mill, therefore it is necessary to direct the gas flow from periphery to the center under the angle, larger than the angle of a particle flight.

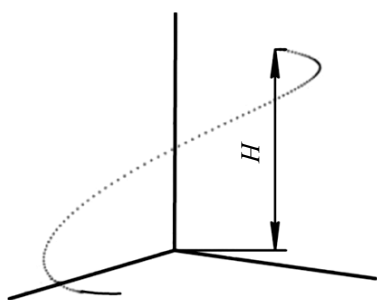


Fig. 3. Particle flight trajectory

It should be mentioned that under the development of the proposed mathematical model assumptions about the homogeneity on particle size of the ground product were accepted, that is far from being so, therefore while applying it in the design of a roller mill it is necessary to conduct calculation on the top border of a disperse structure of the product after its grinding.

**Conclusion.** The received model may be used at the development of constructional execution of

a ring clearance and separation space of roller mills. And when designing aggregates with a low concentration of the solid phase relatively to the bearing gas environment at unrestricted conditions (which are the traffic conditions in the mills operating in closed mode) the influence of neighboring particles on the trajectory of motion can be neglected.

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