Determining the efficiency of centrifugal counterflow mills

I A Semikopenko¹, D V Vavilov¹ and D V Smirnov¹

¹ Belgorod State Technological University named after V.G. Shukhov, 308012, Kostukov St., 46, Belgorod, Russia

E-mail: semickopenko.i@yandex.ru

Abstract. The article introduces derivation of analytical equation for determining the efficiency of centrifugal counterflow mills with selective grinding. Throughput capacity of the centrifugal counterflow mill is one of the main factors influencing concentration of the mill material in counterflows of the discharge. Particles density in the air dynamic environment must provide collision of particles in the central zone of the discharge. If particles density is not sufficient, then particles arriving into the central zone will interact with accelerating elements of the opposing rotor. It may result in high wear of the accelerating elements and getting of the metallic dust into the prepared material. Increased material concentration in the air flow can lead to multiple interactions and buffering the particles, that will impact the grinding efficiency and result in grinding material coarsening.

1. Introduction

The efficiency of a centrifugal counterflow mill is connected with the work of two vertical quill cylinder rigidly fixed on the case and determines material concentration in counterflows of the discharge. Particles density in the biphasic medium should provide their rational interaction in the center of the discharge. If particles concentration is not sufficient then particles lose velocity in the zone of their supposed interaction and can collide with the accelerating elements of the opposite rotor. It may result in high wear of the accelerating elements and getting of the metallic dust into the prepared material. Increased material concentration in the air flow can lead to multiple interactions and buffering the particles, that will impact the grinding efficiency and result in grinding material coarsening [1].

According to the literature on the subject it is known that the most effective way of striking grinding coarse particles is their head-on collision in counter two-phase flows. Here fine particles interact effectively mutually abrasing in cross trajectories.

To provide selective impact on particles in their interaction zone depending on their size and mass the improved design of the mill under consideration has been suggested (figure 1). It has structural differences which enhance the finery of the grinded material in comparison with the existing mills. The internal effective capacity of the mill has a discharge with additional zones for under-size particles interaction in cross sections of the two-phase flows. The mill contains rotors 1 with rounded accelerating elements 2 and rectilinear accelerating elements 3, vertical quill cylinders 4, discharge 5, which is equidistant from the rotor centers 1. Rotors 1 rotate in the opposite direction. The location of quill cylinders 4 above provide counter flow of two-phase streams with coarse particles, which are accelerated with rounded accelerating elements 2 and cross trajectories of two-phase fine-grain streams, which are accelerated with rectilinear accelerating elements 3.
Figure 1. Calculating scheme for determining centrifugal counterflow mill efficiency: 1 – rotor; 2 – rounded accelerating element; 3 – rectilinear rotor element; 4 – vertical quill cylinder, 5 – discharge $\rho_1$ – the distance from the rotor center to the vertical quill cylinder axis; $R$ – rotor radius; $\beta_1$ is deviation angle of curvilinear accelerating element from radial direction.

The mill operates as follows. Mill material, for example, lime stone is evenly fed through vertical quill cylinders 4 (for example, with the help of screw drives) into the internal part of the mill, where coarse material is trapped by the rounded accelerating elements 2, located higher, past rectilinear accelerating elements 3, and fine grains are trapped with accelerating elements 3, located lower, then the particles move along the accelerating elements 2 and 3 and acquiring velocity sufficient for grinding particles to fly into the discharger. As the rounded accelerating elements 2 are longer than rectilinear accelerating ones 3, then fine fractions pass rectilinear accelerating elements 3 faster than coarse fractions pass rounded accelerating elements 2. So, the take-off time from accelerating elements 2 and 3 is different. Vertical quill cylinders 4 location on the view from above is the same for all fractions of the mill material. Due to this under-size particles take-off from accelerating elements and fly in cross trajectories that are angular to the coarse particles trajectories. The construction of each vertical quill cylinder 4 and its location provide counter interaction of the coarse particles and interaction of fine particles in cross trajectories. Mill material is led by the air flow into the discharger 5 and separated from the air flow in the cyclone.

Thus, grinding efficiency in the suggested mill increases by separating different material fractions before their interaction in the discharger and selective impact on the particles depending on their size and mass. It specifies the problem to determine maximal throughput capacity of the mill.

Mass flow of the granular material through the vertical quill cylinder is determined by the equation:

$$Q = \gamma_0 \frac{dV}{dt}$$  

(1)

where $\gamma_0$ is bulk density of the granular material inside the vertical quill cylinder, kg/m$^3$; $V$ the volume of the granular material, m$^3$, enclosed in the vertical quill cylinder with height “$z$” and internal diameter “$D$”.

This volume is determined as follows (figure 1):

$$V = \frac{\pi D^2}{4} \ z$$  

(2)

where $z$ is running coordinate “$z$” of the vertical hollow cylinder.

Substituting (2) into (1) results in the following equation:
\[ Q = \frac{\pi \rho_0 D^2}{4} \cdot \mathcal{G} \]  

(3)

where \( \mathcal{G} \) is the velocity of grain material particles movement inside the vertical quill cylinder, m/s. The value of this velocity can be received from the equation:

\[ \mathcal{G} = \frac{\sqrt{2gH}}{\mathcal{G}} \]  

(4)

where \( g \) is gravity acceleration, m/s^2; \( H \) is the height where grain material particles fall inside the vertical quill cylinder, m.

Suppose, the particles are trapped with accelerating elements of one rotor per time “\( t \)” equal to the time of vertical displacement of the particles inside the vertical quill cylinder to the distance equal their half-diameter “\( d \)”:

\[ t = \frac{d_H}{2 \cdot \mathcal{G}} = \frac{d_H}{2 \sqrt{2gH}} \]  

(5)

If particles fall onto the operational surface of the rounded accelerating rotor element the material moves along this surface with velocity “\( \beta l \)” equal [2], [3]:

\[ \beta_1 = \frac{\omega \cdot \rho_1}{2 \cdot f} \left( \cos \beta_1 - f \sin \beta_1 \right) \]  

(6)

where \( \rho_1 \) is the distance from rotor rotation axis to the center of the vertical quill cylinder, m; \( f \) is friction coefficient of the material particle on the surface of the accelerating element; \( \beta_1 \) is deviation angle of the tangent line to the operating surface of the rounded accelerating element surface from radial segment, degrees.

In their turn when particles get onto the working surface of the radially located accelerating element the material starts to move along its working surface with the velocity “\( \beta r \)” , which according to (6) will be determined as:

\[ \beta_r = \frac{\omega \cdot \rho_1}{2 \cdot f} \]  

(7)

Onto the working surface of every rectilinear accelerating element “\( l_r \)” long, during time “\( t \)” a bulk of material is directed from the vertical quill cylinder:

\[ l_r = t \cdot \beta_r = \frac{\omega \cdot d_H \cdot \rho_1}{4 \sqrt{2} \cdot f \sqrt{g} \cdot H} \]  

(8)

And onto every rounded accelerating element during “\( t \)” a bulk of material “\( l_k \)” is directed equal to:

\[ l_k = t \cdot \beta_1 = \frac{\omega \cdot d_H \cdot \rho_1}{4 \sqrt{2} \cdot f \sqrt{g} \cdot H} \left( \cos \beta_1 - f \sin \beta_1 \right) \]  

(9)

If the time of 360° rotor rotation with the cyclic frequency of its rotation “\( \omega \)” is related by:

\[ T = \frac{2 \cdot \pi}{\omega} \]  

(10)

And mass \( M_1 \) of the material passing through one rotor during its complete rotation equals to:

\[ M_1 = \gamma_1 \cdot (S_k \cdot l_k \cdot n_k + S_r \cdot l_r \cdot n_r) \]  

(11)

where \( \gamma_1 \) is bulk density of the material on the operating areas of the accelerating elements, kg/m³; \( S_k \) and \( S_r \) are respectively working surfaces areas of the rounded and rectilinear accelerating elements, loaded with material, m²; \( n_k \) and \( n_r \) are correspondingly the number of the rounded and rectilinear accelerating elements on one rotor.

These working surfaces areas are equal:

– for the rounded accelerating element:
\[ S_k = d \cdot n_k \quad (12) \]
\[ S_r = d \cdot n_r \quad (13) \]

Here \( h_k \) and \( h_r \) are correspondingly vertical size of the rounded and rectilinear accelerating element, m.

Determining maximal throughput capacity of the mill we take into account that during the time period from the load moment of the accelerating element with the bulk of material to the moment of its take–off from the accelerating element not all accelerating elements are envolved along the rotor periphery, but only half of them.

Basing on the received equations (8)–(13) efficiency \( Q_m \) of the studied centrifugal counterflow mill will be determined by the following equation:

\[ Q_m = 2Q_r = 2 \frac{M_i}{T} = \frac{\gamma_r \cdot \omega^2 \cdot d_r^2 \cdot \rho_v}{2 \cdot \pi \cdot h_r (\cos \beta_r - f \cdot \sin \beta_r) + h_r \cdot n_r} \quad (14) \]

where \( Q_r \) is one rotor efficiency of the studied mill, kg/s.

The equation (14) determines the efficiency of the centrifugal counterflow mill.

To provide the efficiency (14) it is necessary for the internal diameter of the vertical quill cylinder to be equal: \( Q_m = Q \).

Taking into account (14) and (3) and admitting (4) we can write:

\[ D = D_{vq} = \frac{\omega \cdot d_m}{\pi} \cdot \sqrt{\frac{\rho_v \cdot \gamma_0}{2gH}} (h_k \cdot n_k (\cos \beta_k - f \cdot \sin \beta_k) + h_r \cdot n_r) \quad (15) \]

If the diameter of the vertical quill cylinder is \( D = D_{vq} \) the centrifugal counterflow mill efficiency is maximal. In its turn, value \( \gamma_0 \) can be determined basing on the equality of the throughput capacity of the vertical quill cylinder and the conic clipped batch bin [4, 5].

Basing on the said above we receive the following equation:

\[ \frac{\pi \cdot \gamma_0 \cdot D^2}{4} \cdot \sqrt{\frac{2}{g \cdot H}} = \frac{\pi \cdot D^2}{4} \cdot \gamma_1 \cdot \sqrt{\frac{gHD}{4R_u^2 - 2D}} \quad (16) \]

where \( R_u \) is the radius of the upper base of the conic batch bin, m.

Basing on (16) we find that:

\[ \gamma_0 = \gamma_1 \cdot \sqrt{\frac{D}{8R_u^2 - 4D}} \quad (17) \]

According to the relation (17) \( \gamma_0 = \gamma_1 \), if:

\[ R_u = \frac{5}{8} D \quad (18) \]

The received equation (18) determines interconnection between the radius \( R_u \) of the conic batch bin upper base and diameter \( D \) of the vertical quill cylinder. Basing on the equation (14) graph dependancies \( Q_m = f(n) \) are drawn with the account that \( \omega = 2\pi m \).

Line 1 corresponds to the value \( \beta_1 = \pi/6 \), line 2 – \( \beta_1 = \pi/12 \) at constant values \( \gamma_1 = 250 \text{ kg/m}^3; \rho_v = 0.025 \text{ m}; \gamma_1 = 4; n_r = 4; f = 0.3; h_k = 0.007 \text{ m}; h_r = 0.002 \text{ m}; d = 0.001 \text{ m}; H = 0.03 \text{ m} \).

Analyzing these graphs (figure 2), we can draw a conclusion that the mill efficiency increases with rotor rotation frequency increase and radial distance from the vertical quill cylinder to the center of rotor rotation, along with this, the increase is similar to linear.
Figure 2. Efficiency dependance $Q$ of the centrifugal counterflow mill on rotor rotation frequency $n$:

1 – $Q = f(n)$ with $\beta_1 = \pi/6$; 2 – $Q = f(n)$ with $\beta_1 = \pi/12$

If analyze the efficiency of the centrifugal counterflow mill then it decreases with the angle increase. This angle determines deviation of the tangential line to the operating surface of the rounded accelerating element from radial direction, it is notable that this change in the determined range of the angle variation is similar to linear. For example, at rotor rotation frequency 120 s$^{-1}$ and angle $\beta_1 = \pi/6$ mill efficiency is equal 0.053 kg/s, and at rotor frequency 200 s$^{-1}$ the efficiency is 0.15 kg/s. If angle $\beta_1$ decreases to $\pi/12$ at the same values of rotor frequency, then mill efficiency increases correspondingly till 0.07 kg/s and 0.19 kg/s.

2. Conclusion

The article introduces the result of mathematical transformations – an analytical equation for determining the efficiency value of the centrifugal counterflow mill. This efficiency increase is caused by installing upgraded rotors with accelerating elements of different geometry, rotating in opposite directions. Rotors with accelerating elements of rectilinear and rounded form provide selective impact on the material depending on the size and mass of the grinded particles. When determining the efficiency of the centrifugal counterflow mill the throughput capacity of two vertical quill cylinders has been taken into account. They are rigidly fixed on the mill case and provide continuous and even feed of the mill material onto the horizontal rotors with screw drives.

3. Summary

The received formulas allow to interconnect structural, engineering, technological and energetic parameters of the centrifugal counterflow mill operation with selective impact on the material particles depending on their size and mass.

Acknowledgments

The work is realized in the framework of the Program of flagship university development on the base of the Belgorod State Technological University named after V.G. Shoukhov, using equipment of High Technology Center at BSTU named after V.G. Shoukhov

References

[1] Smirnov N M 1990 Development of designs of centrifugal counterflow mills and the method of calculating their main dimensions. Intensive mechanical technology of bulk materials.
Interuniversity collection of scientific papers 60-69

[2] Voronov V P, Semikopenko I A, Penzev P P 2008 Theoretical studies of the speed of movement of particles of a material along the surface of a percussion element of a disintegrator-type mill. Izvestiya VUZ. Building. 11–12 93-96

[3] Semikopenko I A, Voronov V P, Gorban T L 2015 Motion of a particle along the surface of a curvilinear rotor blade. Bulletin of the BSTU named after V G Shukhov. 3 103-105

[4] Kuhling H 1982 Handbook of Physics (Moscow: Mir) p 520

[5] Uvarov V A 2006 Calculation of the effective interaction area of the material being milled in the grinding chamber of a countercurrent jet mill. Construction and road machines. 2 39-41