

## RESEARCH AND MODELING OF PROCESSES IN THE FLUIDIZED BED OPPOSED JET MILL

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Received 5 October 2014, accepted 7 November 2014, available on line 11 November 2014.

**Key words:** fluidized bed opposed jet mill, grinding, classification, matrix model, selection function, cut size, Tromp curve.

### Abstract

A model of the grinding and classification processes in the fluidized bed opposed jet mill based on the Markov chains approach was proposed. The methodology of modelling was elaborated and experimental research of the combined processes of grinding and classification was carried out.

### Introduction

Currently, the fluidized bed opposed jet mills are widely used in many industries for preparation of pure fine powders (OGURTZOV et al. 2004, p. 122–124.). Many publications are devoted to the studies of the grinding process in these mills (PALANIANDY et al. 2008, p. 380–388, FUKUNAKA et al. 2006, p. 89–96, BERTHIAUX, DODDS 1999, p. 78–87, MIZONOV et al. 1997), while the process of classification in the mills is rarely discussed. Description of classification of granular materials in the operating volume of such mills is rather complicated because several processes go simultaneously. In this paper the methodology of decomposition of the total process in a fluidized bed opposed jet

mill is proposed as well as a model of each sub-process inside it. Description of separated processes and their synthesis was carried out with the use of the theory of Markov chains, which is often used to model various processes in powder technology (BERTHIAUX et al. 2005, p. 128–137, MIZONOV et al. 2008, p. 335–340, OTWINOWSKI 2014, p. 399–403).

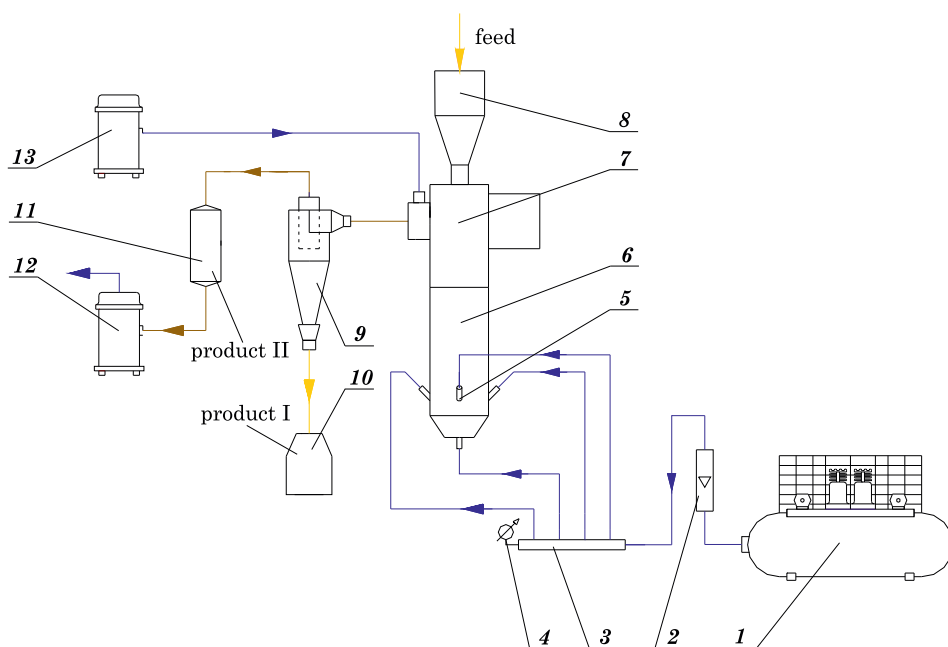
### Experimental set-up

The investigation of comminution was carried out at the experimental set-up schematically presented in Figure 1. A laboratory fluidized bed opposed jet mill, which is designed for fine grinding of granular materials, is the basic element of the set-up. The experimental set-up was equipped with the following systems ensuring the correct work of the mill:

- the material feed system to the mill (charging container, conveyer),
- the air feed system to the mill (compressor, pressure fan, vacuum cleaner),
- the separation system of fine product and the system of cleaning the coming out air (flow classifier, separation cyclone and cloth filter).

The working air is supplied to the mill by the compressor 1 and the sealing air is supplied by the vacuum cleaner 13. The granular feed material with known particle size distribution is fed to the cylindrical milling chamber 6 gravitationally from the charging container 8. The feed material undergoes an extensive fluidization by means of the air jets from the nozzles 5. The nozzles inject air concentrically with the controlled flow rate  $\dot{V}$  and overpressure  $p$  with the flow velocity  $u$ . The mass flow rate of working air is measured by the rotameter 2, while the overpressure – by the elastic pressure gauge 4. Symmetrical design of the air collector 3 ensures homogeneous air distribution over individual jets and its dehydration and de-oiling. The collision of opposed air jets and turbulent fluidization state in the grinding chamber makes it possible to obtain a high-energy fluidization layer. This layer, in turn, ensures effective grinding of granular material. The rotor classifier 7 is installed above the grinding chamber 6 in the range of fountain flow of ground particles. The classifier separates the ground material into the fine fraction directed to the cyclone 9 and the coarse fraction directed to the milling chamber for repeated grinding. The cut size of classification can be controlled by regulation of angular speed of the rotor. The classifier makes it possible to obtain very fine milling product without the so-called mesh fraction (presence of coarse particles in a fine-ground product). Separation of the fine particles from the air after classification occurs in the cyclone 9. The air-particle mixture is separated into the flow dusted working air that is directed to the cloth filter 11 and

the flow of milling product I that is directed to the container 10. The solid particles in air, which was not captured in the cyclone, are captured in the cloth filter. These particles as the milling product II together with milling product I are the total product of fluidized-jet grinding. A negative pressure is assured by a vacuum cleaner 12.



1 – compressor, 2 – rotameter, 3 – collector of working air, 4 – elastic pressure gauge, 5 – air nozzles, 6 – grinding chamber, 7 – rotational flow classifier with electric motor, 8 – filling container of feed material, 9 – cyclone, 10 – container of milling product I, 11 – cloth filter (milling product II), 12 – vacuum cleaner of exhaust air, 13 – vacuum cleaner of seal air

Fig. 1. Schematic diagram of the experimental set-up

## Modeling and identification of processes in the fluidized bed opposed jet mill

The grinding of material in the fluidized bed opposed jet mill is primarily due to abrasion of the grains. During the grinding the fine particles detached from the feed particles. After grinding, the feed particles pass into two classes: fine and the neighboring to the feed one. On the basis of the mass balance of the particles population the grinding process can be described by the following matrix equation (BERTHIAUX et al. 2005, p. 128–137):

$$\mathbf{F}^{k+1} = \mathbf{G} \mathbf{F}^k \quad (1)$$

where:

$\mathbf{F}$  – the particle size distribution of the material expressed by the column vector,

$\mathbf{G}$  – the grinding matrix,

$k$  is the discrete time of the process (the number of time transition).

The discrete time step of the process is equal to:

$$k = \frac{t}{\Delta t} \quad (2)$$

where:

$t$  – the total duration of experiment of the batch grinding,

$\Delta t$  – the dimensional time step.

The matrix  $\mathbf{G}$  of grinding has the following form:

$$\mathbf{G} = \begin{bmatrix} g_{11} & 0 & \dots & 0 & 0 \\ g_{21} & g_{22} & \dots & 0 & 0 \\ 0 & g_{32} & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & g_{m-1m-1} & 0 \\ g_{m1} & g_{m2} & \dots & g_{mm-1} & g_{mm} \end{bmatrix} \quad (3)$$

where:

$g_{ij}$  – the part of the fraction  $j$  that transits into the fraction  $i$  during  $\Delta t$  due to grinding,  $m$  – the total number of fractions under observation.

The probability of particles transition from class  $j$  to class  $i$  as a result of grinding during  $\Delta t$  can be determined from the following relationship:

$$g_{ij} = \begin{cases} 1 - S_j \Delta t, & i = j \\ \frac{S_j x_{j+1}^v}{x_{j+1}^v + x_m^v} \Delta t, & i = j + 1 \\ \frac{S_j x_m^v}{x_{j+1}^v + x_m^v} \Delta t, & i = m \\ 0, & i \neq j, j + 1, m \end{cases} \quad (4)$$

where:

$S$  – the selection function,

$\nu$  – the particle shape parameter and  $\nu = 1$  for needle particles,  $\nu = 2$  for flat particles,  $\nu = 3$  for the three-dimensional particles.

It is assumed that the selection function has the exponential form

$$S_j = \alpha x_j^r \quad (5)$$

where:

$\alpha$  and  $r$  are the constant coefficients (identification parameters).

The experimental identification of the grinding model was performed with the described above laboratory set-up for three durations of the grinding test: 20, 40 and 60 minutes. Samples of limestone with the particles size range 0–2 mm from „Czatkowice” Mine in Krzeszowice near Cracow were used in the tests. Milling product I (from the cyclone) and milling product II (from the filter) were mixed to represent the ground material. Then representative samples of the feed and total ground product were taken to determine the particle size distribution with the use of the Infrared Particle Sizer (IPS) analyser manufactured by Kamika Instruments. The results are shown in Figure 2.

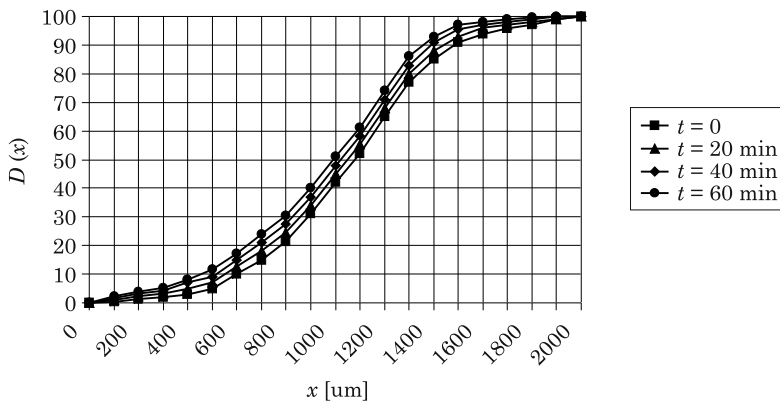


Fig.2. Particle size distribution in the feed ( $t = 0$ ) and total ground product after various durations of grinding test

Particle size distribution in the ground product depends significantly on the material mass in the fluidized bed. In order to determine the dependence of the parameter  $\alpha$  on the mass of the material in the bed the series of

experimental tests for various value of the mass in the range 0.5–3.5 kg were performed. Theoretical analysis of the test results allowed obtaining the following correlation:

$$\alpha = 0.0116 + 0.0084 \cdot M - 0.0021 \cdot M^2 \quad (6)$$

Figure 3 shows comparison of experimental and computational data for the cumulative undersize distribution  $D_j$  (points correspond to various particle size  $x_j$ ). The comparison looks rather satisfactory excepting small deviation in the range of very fine particles.

It is interesting to note that, due to Eq. (6), there exists the optimum value of the hold-up ( $M = 2$  kg) that corresponds to the maximum rate of grinding. The following explanation of the fact can be suggested. At small hold-up the air jets penetrate deeply into the bed and transfer to particles high kinetic energy but because of small particle concentration the probability of inter-particle collision is small and the rate of grinding is small. On the opposite, at high hold-up this probability is high but the depth of jets penetration is small and particle kinetic energy is small. It leads to the optimum hold-up at which these opposite tendencies are combined in the rational way.

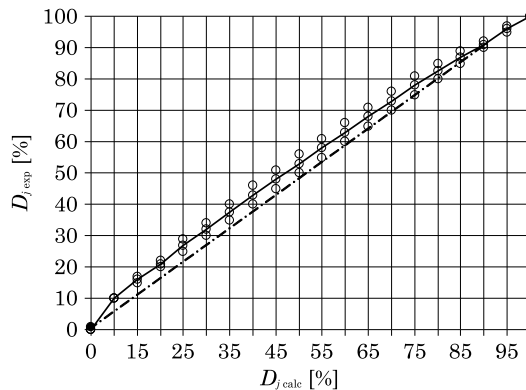


Fig. 3. Comparison of experimental and calculated data according to the proposed grinding model

In modeling the classification process two stages of it were taken into consideration: the gravitational stage and centrifugal stage. In the two-stage classifier the feed material to the classifier is separated into two products: fine and coarse-ground. A commonly used characteristic of such classifier is the Tromp curve  $C(x)$ , which shows the part of a fraction that goes to the fine product as a function of the fraction size. The discrete analogue of the Tromp curve is the matrix of classification  $\mathbf{C}$ :

$$\mathbf{C} = \begin{bmatrix} c_{11} & 0 & 0 & \dots & 0 \\ 0 & c_{22} & 0 & \dots & 0 \\ 0 & 0 & c_{33} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & c_{mm} \end{bmatrix} \quad (7)$$

Very often the Molerus's formula is used to describe the Tromp curve (MIZONOV et al. 1997):

$$C(x_j) = \frac{1}{1 + \exp(E[x_j/x_c]^2 - 1)} \quad (8)$$

where:

- $E$  – the particle separation efficiency parameter to be determined experimentally,
- $x_c$  – the cut size, for which the particle has the equal probability 0.5 to appear in the both products.

Particle size distribution in the fine product  $\mathbf{F}_3$  and in the coarse product  $\mathbf{F}_2$  of classification can be calculated from the following equations (MIZONOV et al. 1997):

$$\begin{aligned} \mathbf{F}_3 &= \mathbf{C}\mathbf{F}_1 \\ \mathbf{F}_2 &= (\mathbf{I} - \mathbf{C})\mathbf{F}_1 \end{aligned} \quad (9)$$

where:

- $\mathbf{F}_1$  – the particle size distribution in the feed material,
- $\mathbf{I}$  – the identity matrix.

The particle size distributions  $\mathbf{F}_3$  and  $\mathbf{F}_2$  are normalized to the unit mass portion of the feed.

The complex nature of particles motion in the fluidized bed makes the study of classification process difficult. Due to the fact that the processes of grinding and classification go simultaneously in order to study pure classification in the mill the quartz sand was used in these experiments, which is practically not being ground in the grinding zone. The specificity of the experimental identification of the classification model is that the process takes place in the two stages of classification simultaneously. The efficiency of the gravitational stage strongly depends on the air flow rate through the milling chamber and on the hold-up. The centrifugal stage mainly depends on the

rotor speed and air flow rate. Identification of the gravitational stage was based on experimental results for the grinding chamber without the centrifugal stage (at zero angular speed of the classifier rotor). During the study the following process parameters were measured in the experiments: the atmospheric pressure  $p_a$ , the pressure of working air at the mill inlet  $p$ , the rotational speed of the classifier rotor  $n$ , the duration of the experiment  $\tau$ , the mass of the feed material  $m_N$ , the mass of material in the chamber  $m_K$ , the mass of material from the cyclone  $m_c$ , the volumetric flow rate of air  $Q$ . The particle size distribution in the loose materials was measured with the electronic analyzer IPS Kamika Instruments. The particle size distribution in the fine product of the gravitational stage, determined for different values of the air flow rate, is the particle size distribution in the feed material to the centrifugal stage. The centrifugal classification process was tested for the angular speed of the rotor within the range 0–25 1/s.

Figure 4 shows the experimental dependence of the mass fraction of the coarse product of the centrifugal stage on the volumetric air flow rate at various values of rotational speed of the classifier rotor. The experimental results allowed determining the cut size for the gravitational and centrifugal stage. The procedure is based on the equations (9) with the use of the method of least squares. Theoretical foundations of modelling the multi-stage classification are described in the paper OTWINOWSKI (2014, p. 399–403). The results are shown in Figure 5.

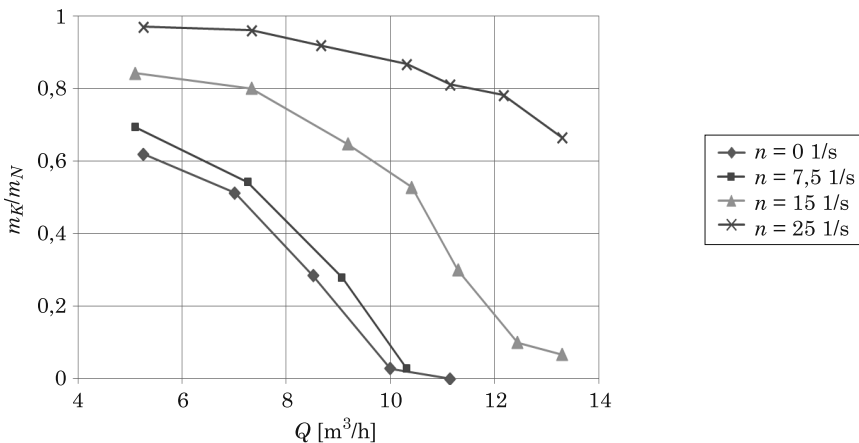


Fig. 4. Influence of the air flow rate  $Q$  on the mass fraction of coarse product at different angular speed of the classifier rotor



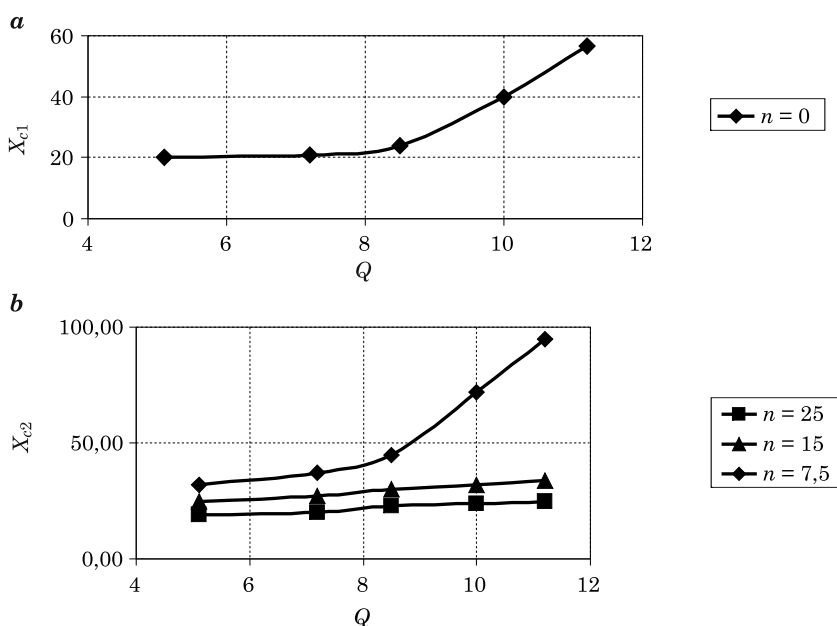


Fig. 5. Particle cut size of the gravitational and centrifugal classification as the function of the air flow rate  $Q$  [m<sup>3</sup>/h] at different rotational speed  $n$  [1/s] of the classifier rotor

## Summary

The proposed models of grinding and classification of granular material in the opposed fluidized bed jet mill makes it possible to describe the particle size distribution after any stage of the combined process grinding plus classification. Results of numerical experiments with the model can be used in the design and optimization of equipment for grinding and classification.

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