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Assessment of classification with variable air flow for inertial classifier in dry grinding circuit with electromagnetic mill using partition curves

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Abstract: In classification one of the methods used to evaluate the effectiveness of classifier's work is to create the partition curve, which determines the size of the classified particles and characterizes the accuracy of the process. The article presents the results of experiments showing the efficiency of classification in the inertial classifier, designed specifically for the electromagnetic mill. The paper presents the results of tests in order to determine the possibility of controlling the classification by changing the transport air stream flow. In order to verify and assess the classifier work, a series of experiments with different opening level of additional air damper was performed. The results allow thorough assessment of the effectiveness and efficiency of the device and facilitate the optimization of the grinding process by establishing an appropriate control algorithm as well as the air flow in classifier.

Keywords: *electromagnetic mill, grinding, classification, material processing, partition curves*

1. Introduction

Comminution of raw materials is an energy intensive operation. Complex description of the process depends on many factors, e.g.: the size and shape of particles, their mutual arrangement in the grinding chamber, technological parameters of the mill, physicochemical properties of material, trajectory and speed of the particles (Sztaba, 2000; Drzymala, 2007; Gawenda, 2010). It can be represented as effects of pressure exerted by the grinding element on material or particle, which will lead to cracks and degradation into smaller components (Fuerstenau and Han, 2003; Gawenda, 2009). The grain size composition of the comminution product depends on the minerals. Therefore, it should be emphasized that the maximum size of particles and particle size distribution depends on the performance and efficiency of the process (Lynch, 1977; Drzymala, 2007). Performance is also dependent on the particle size of the desired product (finer product, lower performance).

Comminution of raw materials is widely used in many industries starting from mineral processing to the chemical, construction, food, cosmetic and pharmaceutical industries (Gawenda, 2009; Tumidajski et al., 2010.) Selection of the mill and its technical parameters determines the fineness that can be delivered. Technological requirements determine fineness of the ground product. For instance, for copper ore the maximum size is below 75 μm, zinc ore below 100 μm, raw materials for cement production below 90 μm and high-quality mineral fertilizers less than 10 μm (Foszcz et al., 2006; Wills and Napier-Munn, 2006; Clermont and Haas, 2010; Gawenda, 2015; Sidor et al., 2015). Furthermore, grinding is only one of the elements of material comminution process and prepares material for further chemical processes. Conventional grinding of mineral raw materials is carried out by crashing of the material by the grinding media. There is no control over the shape of the obtained particles,

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often resulting in low technological value of the product.

Mineral processing facilities, and device manufacturers constantly strive to develop less energy-intensive, more efficient solutions, with the possibility to precisely define the product properties such as shape and particle size (Horst and Freeh, 1970; Wills and Napier-Munn, 2006; Garg et al., 2015). In the case of the hard-to-enrich non-ferrous ores, one of the most important directions for modern technologies are new solutions designed for ore grinding to obtain grain sizes in the range of µm and development of conditions for effective beneficiation within such grain size (Napier-Munn et al., 1996; Mular et al., 2002).

The electromagnetic mill provides such an opportunity having the ability to adjust the various parameters which will affect the particle properties. Specified requirements for grinding and classification systems regarding the reduction of energy consumption, the optimal particle size and shape as well as surface properties force a need to design a modern system with recirculation of particles which do not meet quality requirements. To make this solution competitive, the system should be as universal as possible for all kinds of raw materials, configurable and equipped with a measuring and control systems (Mular et al., 2002; Subba, 2016; Wolosiewicz-Glab et al., 2016a).

This article presents the effect of changes in the degree of opening of the additional air dampers on the classification in dry grinding circuit with electromagnetic mill. Assessment of those changes is performed by using partition curves. Different parameters of the system during tests, allow to determine the impact of the additional air stream on the classification efficiency that determines the efficiency of the whole grinding and classification system. Relations between classification parameters and different control signals will be considered in future investigation. Electromagnetic mill has an impact on the quality of the obtained material, improving the beneficiation of fine particles, which often are re-milled during the conventional grinding procedure what causes its lower performance during beneficiation processes.

2. Material and methods

2.1 Grinding system

The system consists of electromagnetic mill and two classifiers. The electromagnetic mill design concept assumes a vertical position of the working chamber. The material is transported by a screw feeder and is loaded from the top of the mill. Properly moistened stream of transport air is provided from the bottom side of the working chamber (Pawelczyk et al., 2015). Above the working chamber, integrated with the mill, a preliminary classifier is located, which forms the inner recycle stream (Pawelczyk et al., 2015; Wolosiewicz-Glab and Foszcz, 2015). The material is received from the working chamber of the mill from the top and goes to the pre-classifier. The remaining material returns, along with the feed from the top, to the working chamber and material of suitable particle size distribution is entrained upwards towards the classifier, which is designed as an inertial-impingement classifier. The description of the technology is presented in Fig. 1, that shows the schematic diagram of the milling system with classification (Sidor et al., 2015) while detailed description of the electromagnetic mill can be found in the paper of Wolosiewicz-Glab et al. (2016a).

To ensure classification, there is an adjustable additional air intake between the internal and inertial-impingement classifier. The classifier separates the stream of ground material to the end product and the recycle stream provides the closed loop cycle of the mill operation (Wolosiewicz-Glab et al., 2016b). As the pneumatic conveying system is implemented by using vacuum with a single vacuum source, the air speed in the respective parts of the system is regulated by varying the opening of the damping flaps. Due to the single source of vacuum, a change in the position of one flap affects the flows in all parts of the system. This results in a significant complication from the control point of view, which requires multi-level control system supported by mathematical modelling. The whole grinding and classification circuit is a nonlinear, multidimensional dynamic system with cross-couplings, that needs a stabilizing control. Operational points of the installation follow from the technological requirements, especially concerning quality of the milling product. However, the control system however cannot directly measure quality parameters. Only the indirect measurement is possible. Thus, modeling and parameters identification is required. On the other hand, the whole control system needs to be decomposed into several hierarchical layers, i.e. production management, optimization, supervisory and direct control layers (Wolosiewicz-Glab, 2016a). The results presented in the paper allows for parameterization of the classification control algorithm in the supervisory layer. The algorithm calculates the set points for the air flaps to maximizes the imperfection while satisfying the air flow constraints according to the technological requirements. This is described in detail in another paper (Ogonowski et al., 2016).

A properly chosen classifying device should provide a sharp partition curve, which means that larger particles should not pass into fine particle product, and recycled material from classifier should has as little of fine particles as possible (Gawenda, 2015). The recycling ratio is defined as the ratio of the amount of recycled material to the quantity of the newly loaded feed. The recycle ratio is high in the milling process. In practice, grinding of cement or limestone provides size reduction degree equal to 2–2,6, while for wet ore grinding it can be up to 3.5 and for the crushing of the material in crushers it is much lower and does not exceed 1.8 (Gawenda, 2015).

In case of classification of small (approximately <1 mm) and very small (<0.1 mm) particles mixtures, the classification is carried out in an aqueous or air medium. Different forces operate in classification including centrifugal, stream or resistance of the medium, Coriolis, gravity, buoyancy, gradient resulting from changes in concentration of grains (Horst and Freeh, 1970; Cullinan et al., 1999; Gawenda, 2015). As a result, during comminution and other physical and chemical processes, what one generally obtains is a Fig. mixture of particles with different sizes and shapes (Kelly and Spottiswood, 1982; Warach, 1996).

As already mentioned, the electromagnetic mill includes inertial-impingement classifier. Its technological structure is presented in Fig. 2.

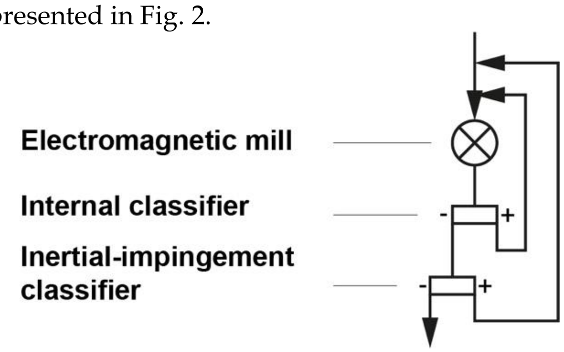

Fig. 1. Grinding system consisting of two classifiers and an electromagnetic mill

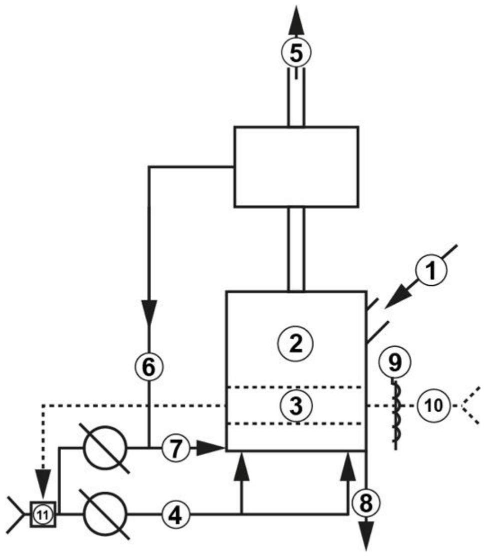

Fig. 2. Dry grinding in electromagnetic mill: 1 – Feed stream, 2 – Vertically aligned working chamber, 3 – Workspace with grinding media, 4 – Main stream of gaseous medium, 5 – Final product, 6 – Recycle stream, 7 – Additional stream of gaseous medium, 8 – Stream of not milled material, 9 – Inductor winding, 10 – Cooling stream, 11 – Air intake (based on patent no. P413041 of July 6, 2015)

Inertial-impingement classifier and cyclone were designed utilizing flow simulations conducted by using computational fluid dynamics (CFD). The performance parameters and particle size of individual streams were calculated. The classifier was designed in a way to enable change of the separated particles size by varying the position (mounting height) of the impingement element or its replacement with another one with different opening angle (Pawelczyk et al., 2015). Fig. 3 shows the design, fabrication and impingement element of this type of classifier.

In the case of an ideal material classification using sieves or classifiers, particles which are smaller in size than predetermined size or weight, form the first product and the others the second one. The classified particles d_{50} is the particle diameter for which the probability of being in the top or bottom product is equal to 50% (Gaudin and Hukki, 1946; Jankovic et al., 2003; Gawenda, 2015).

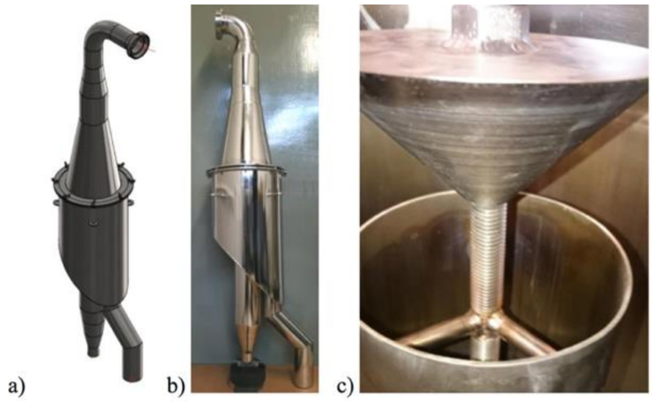

Fig. 3. Inertial-impingement classifier: design (a), fabrication (b), impingement element (c) (courtesy of Promill – cyclone contractor)

Classification is never perfect. Each classifier has a specific classification ability. Classification ability of a classifier and its partition curve are a function of the degree of classification depending on the diameter of the particle. It is most commonly presented in the form of a partition curve in a system in which the abscissa indicates the average particle size and the ordinate indicates recovery of each size fraction in [%]. The partition curve is not a curve of particle size distribution, only a set of points representing the extent to which the infinitely narrow particle size fractions with an average particle size splits into upper and lower product (Lynch, 1977; King et al., 2001; Mular et al., 2002).

2.2 Experimental

A 2 kg sample of copper ore obtained from the deposit operated by KGHM at Legnica-Glogow Copper District having 1-2 mm particles in size was used in the study. It was divided into four test samples. Ten sieves were used for the size analysis. There were four experiments performed in a row plus additional two preliminary tests which were performed in order to confirm reproducibility of the classification in the inertial-impingement classifier for the same parameters of the feed (particle size and flow) and transport streams. The frequency of the electromagnetic field in the mill was unchanged during the tests. However, an opening of the additional air damping flaps was changing, except the first two preliminary tests. The randomness of the process results from the fact that in addition to effects which guarantee classification into products having different properties, there are effects that disturb the classification, the magnitude of which may vary from one point to another. Partition curves presented in Fig. 4 show the recovery (which is equal to probability) of each size fraction of the feed reporting to the upper product as a function of mean size of each fraction. It was assumed that comparable density can be taken into consideration with respect to the fine mineralization of the ore and the fact that only small particles below 0.045 mm are expected to have higher density differences, therefore particle size was chosen as a separation feature. Fig. 4 shows a comparison of the partition curves obtained in preliminary experiments.

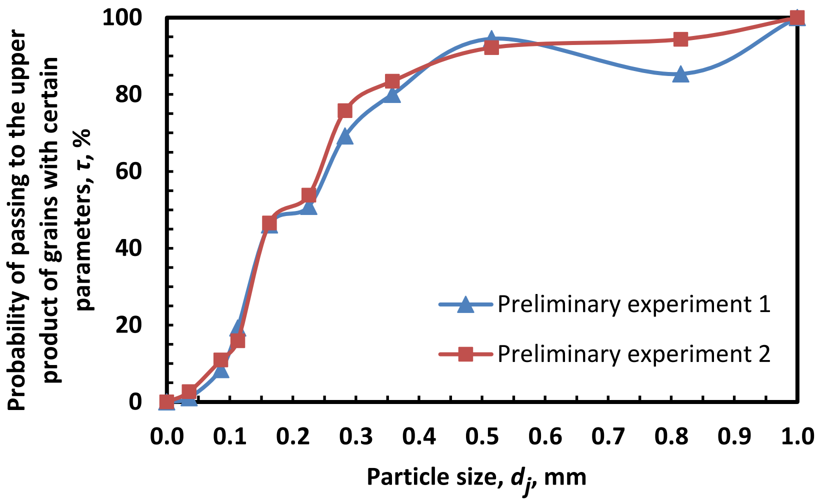

Fig. 4. Partition curves for preliminary experiments

In subsequent studies, a series of four experiments was performed with different arrangements of the additional air damping flap. Changing the position of the flap did not significantly alter the flow of transporting air through the electromagnetic mill, especially when the flap control system is fitted with an adequate system of compensation, even though the stream of transporting air in the classifier changes. The experiments were aimed to determine whether or not there is a possibility to influence classification by changing the flow of the transporting air. As a result, this relationship can be used in the future to control the flow of recycle material in a closed loop system within the operating point determined by the physical parameterization of the classifier (Fig. 3c). The aim of the study was also to verify the functioning of the classifier and the assessment of the effectiveness of its operation and to show that not only the parameters of generated electromagnetic fields affect the recycle of the material, but also it is very important to control the air flow and the damping flaps including main air stream damping flap, recycle air stream damping flap, additional air damping flap, efficiency of the feed auger conveyor. For each experiment, partition curves were plotted and the relationship between the opening of the flaps, and the efficiency of the classification was described. Opening of main air flap K_G and recycle air flap K_R were constant during the experiment and set to 100% while K_D (opening of additional air flap) was 5,10, 20 and 30%. The control algorithm calculates the set-points for the flap openings and not for air flows. The airflow in the separator changes according to some additional parameters (e.g. other flaps positions) which were constant in the presented experiment. Moreover, the air flow in the classifier itself cannot be measured and is only modelled as precisely described by Ogonowski (2017). For the constant position of the recycle and main air flap, the airflow in the separator rises with wider opening of the additional air flap. This relation is not linear due to different pneumatic resistances in the particular elements of the plant and some minor, uncontrolled air leaks in the system. In the presented experiments, the air flow through the separator was changing in the range from 210 m^3/h to 260 m^3/h.

3. Results

The only parameter which was changing through all the tests was the percentage of additional air damper opening ratio. Table 1 presents the data obtained from the experiments and partition curves. In each case, the probable error values and imperfection values were calculated. The range and interval of the additional air flap opening was defined according to previous experimentations results. Due to the physical structure of the plant, opening of this flap above the 30% led to the air flow drops in the recycle stream and working chamber stream below the correct values from the technological point of view. The maximum possible air flow through the separator is achieved for all flaps open to 100% and is equal to 320 m^3/h.

Fig. 5 presents partition curves for all the experiments in a single plot. One can observe the changes in shape of the curves depending on the additional air damper opening value. Relation between increased opening of the damper and the imperfection through the experiments is presented in Table

1. In order to compare different settings of air damping flaps, let us introduce the concept of imperfection. The smaller value of imperfection (and *Ep* as well), the more accurate classification. For the air classification, one can expect an imperfection value above 0.3. The upper limit of acceptable value depends on the selected optimization criteria of classification. It is related to the value of recycle flow from classifier back to the mill, its efficiency and energy consumption. In addition, we must take into account the impact of changes in the flow parameters on classified particles indexing. Summing up it is important to establish the relations which enable control as the optimal values may vary. The greater opening of the air flap, the higher air flow in the classifier can be observed. It can be seen that the higher flow of the additional air, the higher imperfection value as well. Thus, the accuracy of the classification and the d_{50} value decrease (Table 2).

Table 1. Parameters of the classification process

Exp. #	Opening of additional air flap K_D [%]	d_{50} [mm]	Probable error *Ep* [mm]	Imperfection *I* [-]
1	5	0.17	0.049	0.29
2	10	0.145	0.044	0.30
3	20	0.132	0.055	0.45
4	30	0.125	0.068	0.54

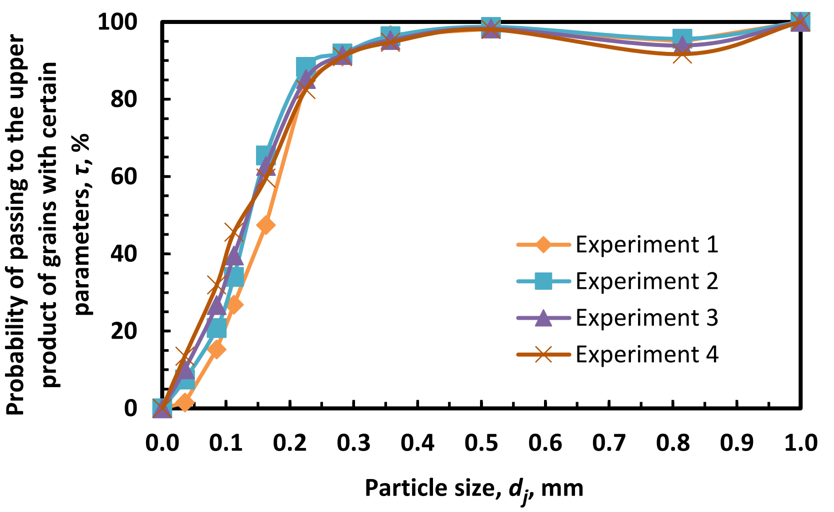

Fig. 5. Partition curves of classification tests for different values of opening of additional air flap K_D

3.1 Mathematical approximation of the partition curve

Classifier outputs can be estimated basing on the partition curves model in the form of non-linear function of the E_p (probable error) and *I* (imperfection) parameters. Values of these parameters can be calculated based on d_{50} (cut point) and d_{25} and d_{75} values:

$$Ep = \frac{d_{25} - d_{75}}{2} \tag{1}$$

$$I = \frac{Ep}{d_{50}} \tag{2}$$

where d_{25}, d_{75}, d_{50} – particle size for which classification value (probability) equals respectively 25, 50 and 75%. The shape of the partition curves was described by the below mathematical equation:

$$\tau_j = \frac{1}{\pi}\left(\text{arctg}\left(\frac{1}{Ep}\cdot d_j - \frac{1}{I}\right)\right) + 0.5 \tag{3}$$

where d_j is the arithmetic mean size of the *j-th* particle size fractions and function arctg is expressed in radians. In the above equation (Eq. 3), the values of τ_j are from 0 to 1, or after multiplication by 100%, in percent. The model was developed by the present authors to model the investigated wet classification. The idea was to design a simple model with a minimum number of parameters. The presented in Fig. 3 model is universal and was also successfully tested in partition curves modelling for hydrocyclones and spiral classifiers in copper enrichment plants. As the studies show (see Fig. 6), the non-linear function approximates the shape of the partition curves with acceptable accuracy from the control point of view. Further studies will focus, among others, on E_p and I replacement with dampers positions in the model presented earlier.

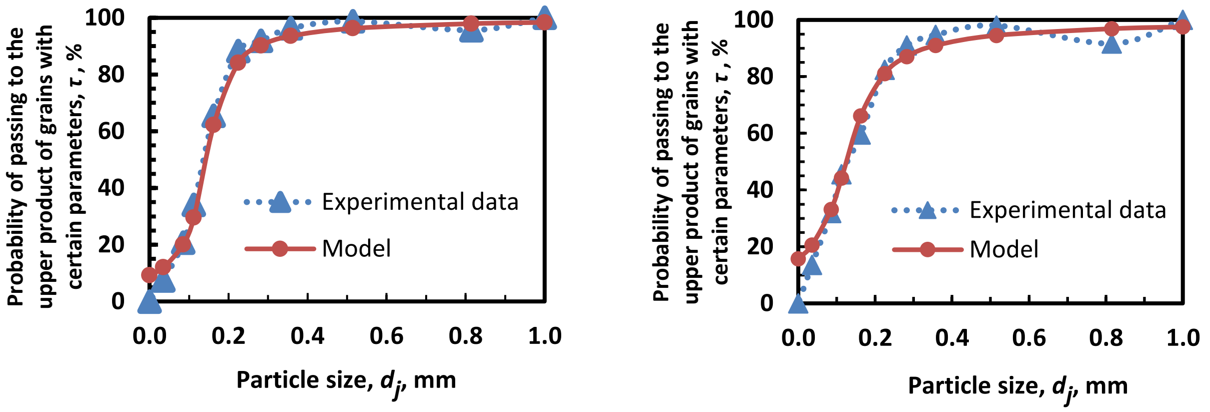

Fig. 6. Examples of partition curves modelling for inertial classifier (data from experiments 2 and 4)

4. Conclusions

When designing a classification system for the electromagnetic mill, the goal is to obtain the most efficient operation of the mill. With a partition effect curves, it is possible to prepare simulation of the grinding and classification and determine the size of recycle flow, that would allow to create appropriate control algorithms which guarantee the correct operation of the mill and the entire system. The characteristics of classification are calculated for different values of additional air damper opening level. In the review of the classification devices for fine-grained products, to predict the final products of the electromagnetic mill, one should use the separation effect curves, which provide opportunities to optimize the operation of the grinding-classification system. One can read from them the classified particles size and get information about the accuracy of the implemented process. Comparisons of the accuracy of the system with different parameters, allows us to determine the impact of the additional air stream on classification efficiency that will determine the efficiency of the whole grinding and classification system. A relation between classification parameters and different control signals will be investigated further. The influence of the additional air stream flow on the classification parameters can be successfully used in the supervisory control. Together with the presented partition curve model, it can be used to modify direct control set points according to the technological requirements of the process.

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