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Powder Technology 183 (2008) 224 – 230
POWDER TECHNOLOGY
www.elsevier.com/locate/powtec

Modeling of an industrial double-roll crusher of a urea granulation circuit

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Received 24 April 2007; received in revised form 1 June 2007; accepted 23 July 2007
Available online 1 August 2007

Abstract

Since for granulation processes the crusher operation has a decisive influence on the system stability, a reliable mathematical model to represent an industrial double-roll crusher of a urea granulation circuit is provided in this work. The crusher was described by the model given by Austin et al. [Austin L.G., Van Orden D.R., Perez J.W. A Preliminary Analysis of Smooth Roll Crushers, International Journal of Mineral Processing, 6 (1980), 321–336.] for mineral processing. The breakage parameters estimation was based on industrial data. The experimental particle size distributions of the feed, intermediate and product streams were obtained from large-scale crushers belonging to a urea granulation plant with a nominal capacity of 1 million tons/year. The results indicate that the model reproduces in a very accurate way the performance of this type of crushers, being a useful tool to: a) optimize the gap setting to meet specific crushed particle size distribution requirements and b) be included as a mathematical module in a plant simulator of the whole urea granulation circuit.

Keywords: Double-roll crushers; Industrial granulation circuit; Modeling; Urea

1. Introduction

Granulation converts fine powder and/or sprayable liquids (eg. suspensions, solutions or melts) into granular solid products with more desirable physical and/or chemical properties than the original feed material. This size enlargement technique constitutes a key process in many industries such as the pharmaceutical, food, ore processing and fertilizers ones [1]. Particularly, the granulation process has clear advantages regarding the storage, handling and transportation of the final product [2].

Regarding the fertilizer industry, on a worldwide basis urea is the most popular solid nitrogen fertilizer and its use grows much more rapidly than that of other products. The granulation process is considered as the most important technology for urea production because the product has high resistance, low tendency to caking, and flexibility to be combined with other type of fertilizers. All these features, together with the increasing demand of grains due to the continuous world demographic growth, make necessary to do as much research as possible in this field [3].

The production of urea granules is a complex operation that cannot be carried out in a single process unit; it is rather achieved by a combination of process units with specific functions constituting the granulation circuit (see Fig. 1). The main unit is the granulator, where small particles denoted seeds (generally product out of specification) grow due to deposition of concentrated fertilizer solution droplets on the solids surface followed by water evaporation. There are different types of granulators such as fluidized beds and fluidized drums. The granules that leave the enlargement size unit are classified by two consecutive screens into product, oversize and undersize streams. The product is transported to storage facilities, while the oversize fraction is fed to a crusher for size reduction. The crushed oversize particles are then combined with the undersize granules and returned to the granulator as seeds [1].

The operation of granulation plants is difficult, often a relative small fraction of the granules that leave the size enlargement unit are in the required size range. Therefore high recycle ratios are commonly found [1]. The recycle stream can be reduced to some extent by technology improvements; however any process disturbance may affect the performance of the granulation circuits

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doi:10.1016/j.powtec.2007.07.023

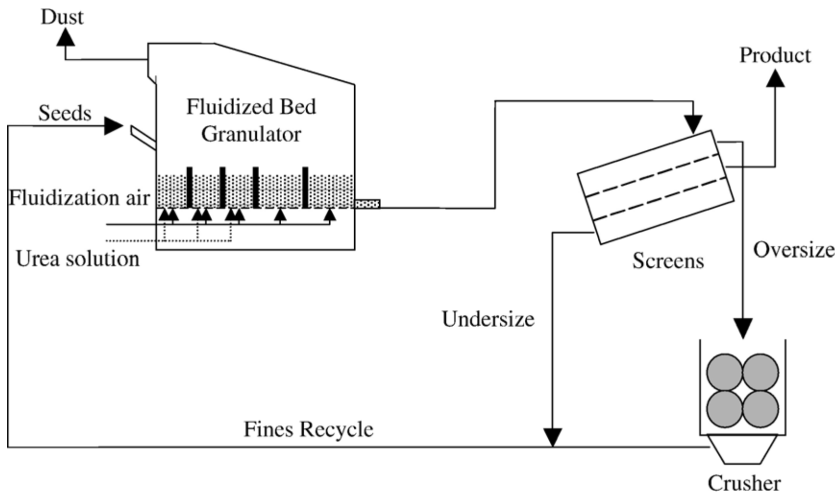

Fig. 1. Typical urea granulation circuit.

strongly. Many authors found that granulation processes might not always operate at steady state (among others, [4–7]) and recognize the important role of the plant simulation to predict and optimize the granulation circuit operation [1,8,6].

It was recently reported that the crushing of the screen oversize material has a decisive influence on the circuit stability and duration of the unsteady start-up stage. In fact, a very slight variation in the average diameter of the stream that leaves the crusher may cause the instability of the system [5–7]. In view of the importance of the simulation tools to predict the granulation circuit performance, which cannot be done intuitively, reliable models for all the circuit units should be available. Unfortunately, the crusher model requires the knowledge of some parameters that have to be determined from experimental data.

There are many size reduction equipment that find applicability in a wide variety of industries, especially in the mineral processing one. Among others the ball, hammer and autogenous mills as well as the jaw, gyratory and roll crushers can be mentioned. Usually the double-roll type of crusher is used as the size reduction unit in urea granulation circuits. This device is constituted by two pairs of rolls that rotate in opposite directions at different speeds. The rolls can be smooth, corrugated or toothed and the distance between them (gap) is a key variable parameter. In the breakage of urea, the double-roll crusher is preferred over other comminuting equipment because narrow size distributions, low dust and limited noise generation are expected [9].

In this work, a model for a large-scale crusher of an industrial urea granulation plant is presented. The breakage parameters needed for the complete representation of the crusher are fitted using industrial data from a plant of high capacity (1 million tons of granulated urea/year). In order to predict the performance of the crusher, the particle size distribution of the feed (oversize fraction) and the gaps settings are the only required inputs. The model reported in this contribution is a useful tool to: a) understand the influence of the crusher operating variables (i.e., gaps of the upper and lower pairs of rolls) on the crushed particle size distributions and b) develop reliable simulators of industrial urea plants, which are essential to improve the granulation circuits performance.

2. The double-roll crusher model

Most of the actual size reduction devices have been widely studied because of their applicability in the well-known mineral processing industry. Many of them, like the ball and hammer mills, are represented by mathematical models that accurately describe their performances [10,11,1,12–14]. The double-roll crusher has less applicability in the mineral plants and consequently few researchers have studied its modeling.

As it was aforementioned, the fertilizer industry also requires comminution equipment. Many authors have developed entire granulation circuit simulations, modeling in all cases a hammer mill as the size reduction device [1,2]. To our best knowledge, the double-roll crusher model for urea production has not been reported in the open literature.

The crusher model here presented is the one developed by Austin et al. [15] for the mineral processing industry. It is important to note that the well-known ball mill model cannot be directly used for the roll crusher. In fact, the double-roll crusher operates in a different way than reservoir type of mills and therefore must receive a different treatment. In ball mills the particles have a residence time during which they suffer repeatedly breaks. Breakage in double-roll crushers (‘once-through’ equipment) occurs instantaneously while the material is pulled into the rolls, thus all the particles pass through the set gap [10].

The double-roll crusher model, first proposed by Austin et al. [15] and lately refined by Austin et al. [16], is based on the following assumptions: a) breakage of each size particle occurs independently of the other sizes, b) provided the roll diameter is large enough compared with the feed size and gap, the product size distribution depends on the feed size to gap ratio and c) a single product size gets constituted by unbroken material and particles generated by different breakage stages. To model the crusher, the particle size intervals are expressed on a geometric grid (i.e., the ratio between two contiguous size intervals is for example: $\sqrt{2}, \sqrt[4]{2}$, etc.) and numbered 1 for the largest size, 2 for the second size, down to nth for the sink class which contains the material smaller than the smallest sieve size. Austin et al. [16] adopted the convention of denoting each interval by the biggest size of the passing material and indexing it with the integer i. According to the model hypotheses, when material of size x_i is pulled through the gap of dimension x_g, a fraction a_i is selected for primary breakage and therefore a fraction $(1-a_i)$ of size x_i passes through the rolls unbroken. If the fed material is much bigger than the gap, the probability of selection for breakage is high and a_i tends to 1. This probability is small (a_i approaches 0) when the opposite occurs and breakage takes place just because the particle gets nipped between two bigger lumps, but most of the material remains unbroken [15].

When a fed particle of size x_j passes through the rolls, it generates a set of smaller particles defined by the $B_{i,j}$ cumulative mass function, that is the amount of particles smaller than size x_i generated by breakage of a fed x_j size. Hence, the fraction belonging to size x_i is determined by the difference of two consecutive cumulative mass fractions $b_{i,j}=B_{i,j}-B_{i+1,j}$. These new particles, generated by primary breakage, continue their way through the rolls; breaking again with an a_j' probability if they are bigger than the distance between rolls or bypassing through the gap. The $(1-a_j')$ fraction represents the material that leaves the crusher without further breakage [15].

The mass balance for the crushed product of size x_i can be expressed as follows:

$$p_i = f_i(1-a_i) + p_i'(1-a_i'). \tag{1}$$

The first term of the right hand side of Eq. (1) represents the contribution to the product class i (p_i) of the fed mass of size x_i (f_i) that is not primarily broken, and the second term is the mass fraction of primary fragments that bypasses the gap. The mass of p_i' is given by Eq. (2):

$$p_i' = \sum_{j=1}^{i-1} b_{i,j}(a_j' p_j' + f_j a_j) \tag{2}$$

which describes the sum of the contributions to the product formation of size x_i, from every material of class j either coming from primary or further breakage. It is worth to note that p_1' is equal to 0 because it is not possible to have breakage of particles towards the largest size 1 [15].

Both expressions (1) and (2) can be combined to give the following expression:

$$p_i = f_i(1-a_i) + (1-a_i')\sum_{j=1}^{i-1} b_{i,j}\left[a_j'\left(\frac{p_j - f_j(1-a_j)}{(1-a_j')}\right) + f_j a_j\right]. \tag{3}$$

The crushed mass of each size x_i (p_i) is calculated sequentially through Eq. (3) starting with $i=1$, since by definition $b_{1,1}=0$, $f_0=0$ and $p_0=0$ [15]. This equation can be used to compute the crushed product size distribution if the feed is known and the expressions for the a_i, a_i' and $b_{i,j}$ parameters are provided. [17] found that the $B_{i,j}$ function (i.e., the cumulative form of the $b_{i,j}$) can be fitted by the following expression:

$$B_{i,j} = \begin{cases} 1 & 1\le i\le j \\ \phi\left(\frac{x_{i-1}}{x_j}\right)^{\gamma} + (1-\phi)\left(\frac{x_{i-1}}{x_j}\right)^{\beta} & n\ge i>j\ge 1 \end{cases}. \tag{4}$$

According to the geometric sequence chosen to represent the size intervals, the quotient x_{i+1}/x_i corresponds to a constant relation R. Then, Eq. (4) can be rewritten as:

$$B_{i,j} = \begin{cases} 1 & 1\le i\le j \\ \phi(R^{\gamma})^{i-j-1} + (1-\phi)(R^{\beta})^{i-j-1} & n\ge i>j\ge 1 \end{cases} \tag{5}$$

where γ, β, and ϕ are parameters that have to be fitted from experimental data, subjected to the following constraints $\beta\ge\gamma\ge 0$ and $0\le\phi\le 1$. Expression (5) is constituted by the sum of two power functions; the first term is dominant at small values of (x_{i+1}/x_i) [18]. As it can be clearly seen, this $B_{i,j}$ function is normalized and satisfies the assumption of breakage being independent of the size that is broken. In fact, $B_{2,1}=B_{3,2}$, $B_{4,2}=B_{5,3}$, etc.

Austin et al. [16] also found that a_i can be expressed as:

$$a_i = \frac{1}{1+\left(\frac{x_i/x_g}{\mu}\right)^{-\lambda}} \tag{6}$$

where λ and μ are adjustable parameters higher than zero.

According to Austin et al. [16], the a_i' values can be empirically related to the a_i ones as follows:

$$a_i' = \begin{cases} a_{i-1} & i<i_g-1 \\ \dfrac{a_{i_g-1}+a_{i_g-2}}{2} & i=i_g-1 \\ a_i & i\ge i_g \end{cases} \tag{7}$$

being i_g the size interval number corresponding to x_g.

For a given feed size distribution and a set gap, Eq. (3) can be solved together with the expressions (5), (6), and (7) to predict the particle size distribution of the crusher product, prior estimation of the parameters λ, μ, γ, β, and ϕ.

3. Parameter estimation

Austin et al. [15,16] validated their model with experimental data obtained through the following procedure. Monodisperse feeds of different sizes x_i were crushed in a laboratory-scale smooth double-roll crusher. The samples were carefully fed and the product collected for sieving. This allowed determining the p_i values and finding out the amount of feed of size x_i that remained unbroken. The a_i values were then easily calculated from the following equation:

$$a_i = 1 - p_i. \tag{8}$$

Once all the a_i were calculated, the parameters λ and μ were estimated by expression (6). The a_i' values were determined through Eq. (7) and the $b_{i,j}$ values by rearranging expression (3). The $b_{i,j}$ were then accumulated and the parameters γ, β, and ϕ estimated by means of expression (5). Different coals and rocks were tested and the five corresponding parameters estimated.

Rogers and Shoji [19] investigated the applicability of the model to an industrial-scale crusher. The parameters were estimated in a laboratory-scale crusher breaking single $\sqrt{2}$ feed sizes and then were used to predict product size distributions from industrial crushers. Results of the study showed the validity of the model over a wide range of operating conditions including variations in the sizes of the feed material (nominal single size fractions and distributed feeds), crusher roll speeds, gap settings and roll surface configurations (smooth, corrugated).

The global aim of the present work is to apply the previously described model to the breakage of urea in large-scale double-roll crushers from an industrial granulation plant. To do this, experimental data from an industrial double-roll crusher belonging to a urea granulation circuit under normal operation were used. That is, no laboratory estimations were performed and the parameters were fitted all at once. This implies that the obtained values may not have strictly the intrinsic physical meaning given by Austin et al. [15,16]. Nevertheless, by fitting the parameters all together it is possible to develop a simulator capable of predicting the crusher product size distribution and of determining the influence of the gap setting on it, at least for operating conditions not very far from the ones employed to adjust the crusher parameters.

The parameter estimation was performed by using the Athena Visual Studio Software (www.AthenaVisual.com). The input data, for each pair of rolls, included feed and product size distributions, gap setting and an initial estimation for the parameters λ, μ, γ, β, and ϕ. The selected routine minimizes the difference between experimental and calculated p_i according to the following least-square objective function (F):

$$F = \sum_{i=1}^{n} \left[p_{\mathrm{exp},i} - p_{\mathrm{calc},i}\right]^2 \tag{9}$$

where $p_{\mathrm{exp},i}$ and $p_{\mathrm{calc},i}$ are the experimental and calculated product size distributions, respectively. The calculated p_i are estimated by means of expression (3), previous evaluation of a_i, a'_i, $B_{i,j}$ (through Eqs. (5), (6) and (7)) and $b_{i,j}$ (as the difference of two consecutive $B_{i,j}$) in that order.

4. Experimental data

The experimental data were collected in two large-scale double-roll crushers of identical characteristics belonging to one of the two parallel circuits of an industrial urea plant. As shown in Fig. 2, both crushers include two pairs of rolls, the lower smooth and the upper corrugated.

Samples, by duplicate, of the crusher feed (A), the product of the upper pair of rolls (B) and the product of the lower pair of rolls (C) for both crushers were collected and granulometrically analyzed every 4 and 12 h for two independent experiments (Tests 1 and 2) that lasted 36 and 72 h, respectively. During these plant experiments just the gaps between the rolls were modified, the remaining operating variables of the whole circuit were kept constant. The industrial data were represented on nine size intervals according to a $\sqrt[3]{2}$ geometric sequence.

For Test 1 the gap of the upper pair of rolls was fixed at 2.50 mm while for the lower pair two different settings were imposed: 1.60 and 1.40 mm. Regarding Test 2, the gap between the upper pair of rolls was set firstly at 2.50 and secondly at 2.10 mm while the gap of the lower pair was fixed at 1.40 mm. About 200 samples were collected and analyzed; i.e. 34 samples per sampling point and per crusher.

The feed was sampled from the free falling stream entering to the crushers while the crushed material from the upper and lower pair of rolls were collected, due to safety reasons, through relatively small sampling ports located beneath each pair of rolls. As mentioned, replicates were available for all the samples.

5. Results

An example of the overall operation performance of the studied crusher is presented in Fig. 3, which shows the size reduction of the feed as it passes through the upper and lower pair of rolls (gaps set in 2.1 and 1.4 mm, respectively). According to the selected gaps, the upper pair of rolls reduced the feed size significantly, while the lower pair of rolls conditioned the still coarse material to the specification required for the granulator operation. By using the Athena Visual Studio Software (www.AthenaVisual.com), the breakage parameters for each pair of rolls were fitted in order to reproduce the corresponding crushed streams. In view of the different roll surface configurations of the upper and lower pairs of rolls and

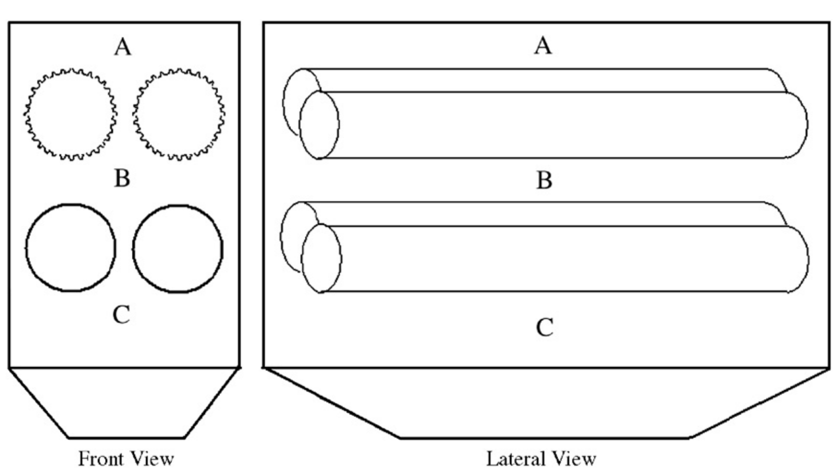

Fig. 2. Scheme of the industrial double-roll crusher.

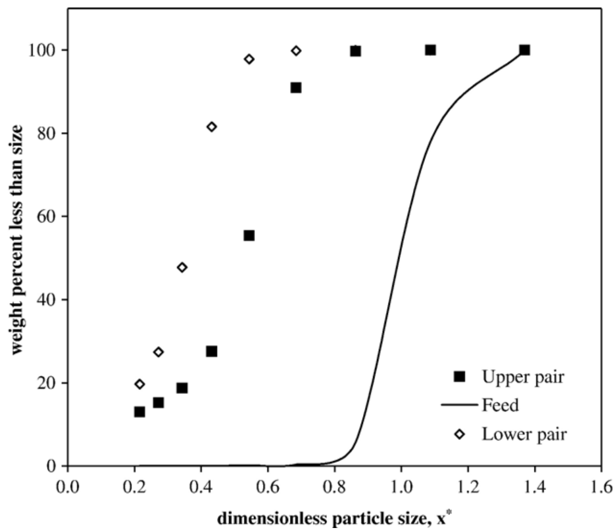

Fig. 3. Typical crusher performance.

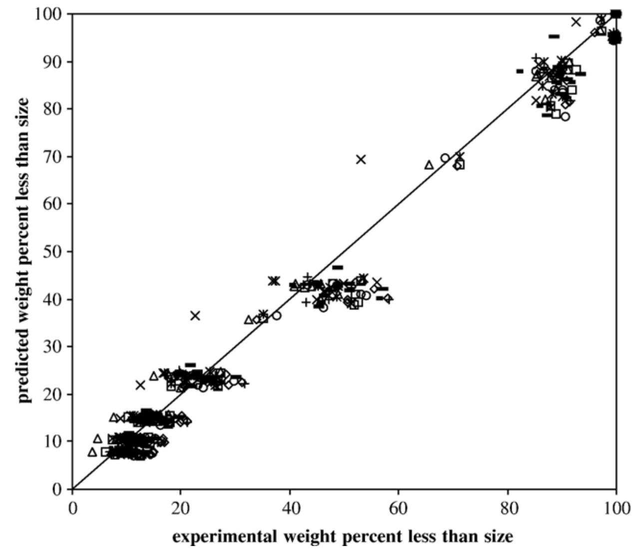

Fig. 4. Correspondence between predicted and experimental size distributions for the upper pair of rolls.

according to the results given by Rogers and Shoji [19], the parameter adjustments for both pairs were independently performed. Table 1 reports the estimated parameters together with the regression coefficients (r^2) found from the fitting procedures. The values of the estimated parameters well satisfy the above-mentioned constraints (i.e., $\beta \geq \gamma \geq 0$, $0 \leq \phi \leq 1$, $\lambda > 0$ and $\mu > 0$).

Fig. 4 shows for the upper pair of rolls, in a condensed manner, the overall correspondence between the experimental size distributions and the calculated ones. Considering the relatively high number of experimental points (i.e., 612) to be predicted by fitting 5 parameters and the errors inherent to the samples collection, it can be concluded that the model together with the estimated parameters satisfactorily reproduce the available experimental data. Some typical results comparing experimental and calculated particle size distributions are shown in Fig. 5. Two distributions (among the 68 available ones) were selected to show the goodness of the fitting performed for the upper pair of rolls. As it can be seen, the agreement is very good and the model proposed for the upper pair of rolls reproduces accurately the particle size distributions of the intermediate stream B for different gap settings.

The same analysis was performed for the lower pair of rolls. Fig. 6 presents the goodness of the fitting for the complete set of data. Fig. 7 shows some selected experimental and predicted size distributions of the product stream C. For the lower pair of rolls the predictions are also in very good agreement with the experimental data. Therefore the model described by Eqs. (3), (5), (6) and (7), together with the parameters presented in Table 1, can be considered a suitable mathematical representation of industrial double-roll crushers. In fact, it gives valuable estimations of the size distributions of the crushed urea granules that are recycled to the granulator unit.

Table 1
Estimated parameters and regression coefficients for the upper and lower pair of rolls

Parameter	Upper pair of rolls	Lower pair of rolls
λ	50.050	16.013
μ	1.901	1.820
γ	0.988	1.920
β	4.205	24.998
ϕ	0.187	0.404
r^2	0.942	0.939

Plant experiments are often difficult to be implemented due to production requirements; they are too time consuming and very expensive. Hence, the availability of industrial data is not frequent. As the studied plant has two parallel urea granulation circuits, the disturbances introduced in one of them did not damage the overall product quality.

The generation of dust in crushers is unavoidable; however it has to be minimized in order to prevent the addition of many nuclei to the granulation unit. On the other hand the crushed product always contains material coarser than the desired size,

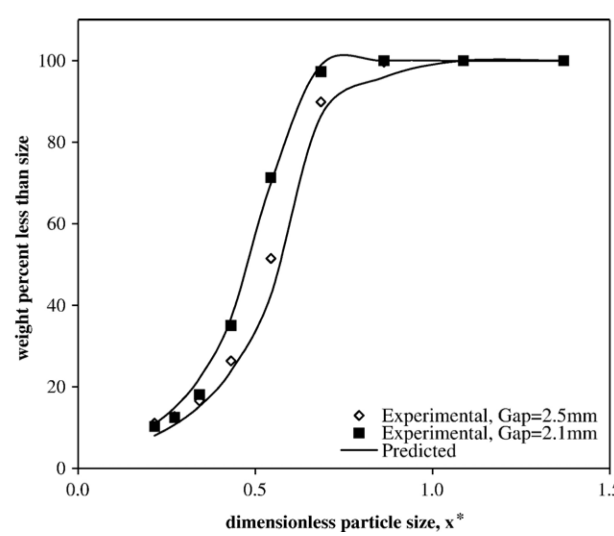

Fig. 5. Some selected experimental and predicted size distributions for the upper pair of rolls.

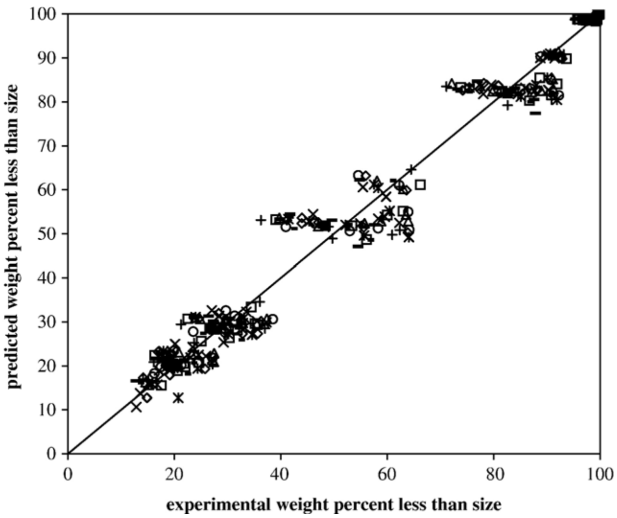

Fig. 6. Correspondence between predicted and experimental size distributions for the lower pair of rolls.

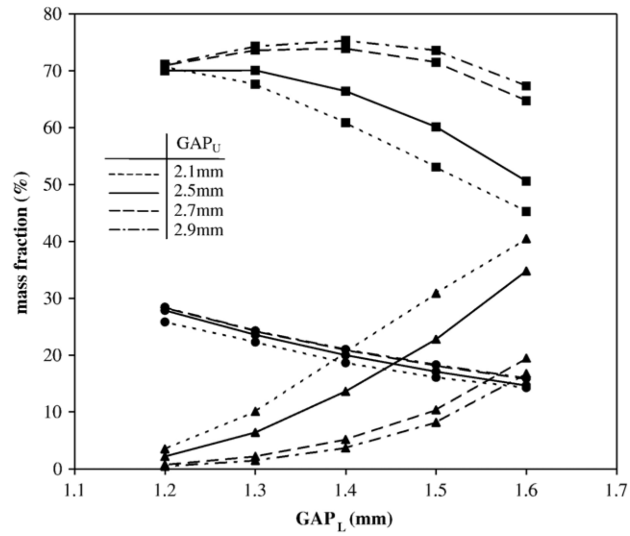

Fig. 8. Influence of the gaps settings on the product that leaves the crusher. (■): m_S, (●): m_U, (▲): m_O.

which also has to be limited in order to have good sphericity of the granular product. Therefore, frequently the crushed material has to meet a given specification. In this work, the crushed material is divided into three fractions: m_U represents the mass fraction lower than 1 mm, m_S denotes the crushed material (on specification) that is within the desired sizes (1 mm $\leq m_S$ $\leq$ 2 mm) and m_O symbolizes the product fraction higher than 2 mm. Fig. 8 presents these three fractions of the crushed stream that leaves the unit for different gaps settings and a typical feed size distribution. As it can be seen, the gap setting for the upper pair of rolls almost does not affect the fines generation at the crusher outlet. In fact, the m_U fraction is more influenced by the gap setting selected for the lower pair of rolls. The other mass fractions, m_S and m_O, are substantially affected by the selection of both gaps. The fraction m_S increases as the gap of the upper pair of rolls is augmented, however for settings higher than 2.7 mm the improvements in the m_S fraction are no significant.

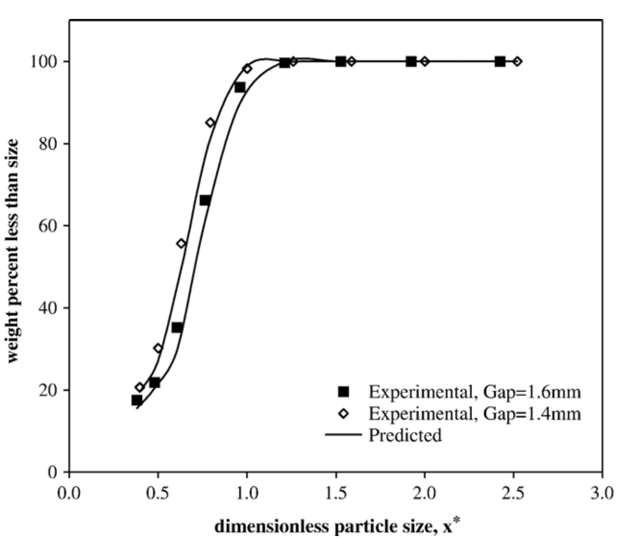

Fig. 7. Some selected experimental and predicted size distributions for the lower pair of rolls.

Consequently to maximize the desired mass fraction, for any value of the space between the lower rolls, the gap of the upper pair of rolls should be set in the 2.7–2.9 mm range. Within this GAP_U range and due to the influence of the gap of the lower pair of rolls on the m_O fraction, the desired mass fraction achieves its optimal value for a GAP_L around 1.4 mm. The previous example indicates that the fitted model presented in this work allows evaluating the combination of gap settings that leads to the required crushed product quality.

6. Conclusions

The mathematical model developed by Austin et al. [15,16], for minerals such as coals and rocks, is applied to granulated urea as the material being broken. The parameter estimation is assisted by experimental data from double-roll crushers of an industrial granulation circuit under normal performance. The goodness of the model predictions is widely confirmed over a large number of experimental samples collected from industrial units.

The performed parameter estimation generates valuable information for the understanding of the urea size reduction process. The fitted mathematical model presented in this work can be used as an accurate module in a plant simulator for future modeling and optimization of the complete granulation circuit. The proposed model does not only predict the product size distribution of industrial double-roll crushers, furthermore it can be used to determine the gaps settings required to obtain a desired crushed product with a particle size distribution that guarantees stable operation of the granulation plant.

Nomenclature

a_i Probability of a particle of size x_i to undergo primary breakage [−].

a'_i Probability of a particle of size x_i to re-break [−].

$b_{i,j}$ Breakage function, mass fraction of particles of size x_i generated by breakage of x_j size particles [−].

$B_{i,j}$ Cumulative breakage function, mass fraction of particles smaller than size x_i generated by breakage of x_j size particles [−].

f_i Feed mass percent of size x_i [%].
F Least-square objective function [−].
GAP_L Gap of the lower pair rolls [mm].
GAP_U Gap of the upper pair rolls [mm].
i Number of size interval, $i=1, 9$ [−].
i_g Number of size interval corresponding to x_g [−].
m_U Product mass fraction of size lower than 1 mm [%].
m_S Product mass fraction within the desired sizes ($1\ \text{mm} \leq m_s \leq 2\ \text{mm}$)[%].
m_O Product mass fraction of size higher than 2 mm [%].
n Sink class, number of total classes in which the particle size distribution is divided [−].
$p_{\text{calc}\ i}$ Calculated product mass percent of size x_i [%].
$p_{\text{exp}\ i}$ Experimental product mass percent of size x_i [%].
p_i Product mass percent of size x_i [%].
p'_i Mass percent of material generated by breakage of x_i size particles [%].
R Geometric ratio, two consecutive size intervals quotient x_{i+1}/x_i [−].
r^2 Regression coefficient [−].
x_i Size of class i [mm].
x_g Gap dimension [mm].
x_i^* Dimensionless particle size x_i/x_{50}[−].
x_{50} Feed median particle size, defined as the particle size for which 50% by weight of the sample is coarser and 50% is finer [mm].

Greek letters

λ Adjustable parameter corresponding to the a_i function [−].
μ Adjustable parameter corresponding to the a_i function [−].
γ Adjustable parameter corresponding to the $B_{i,j}$ function [−].
β Adjustable parameter corresponding to the $B_{i,j}$ function [−].
ϕ Adjustable parameter corresponding to the $B_{i,j}$ function [−].

Acknowledgments

The authors express their gratitude for the financial support by the Consejo de Investigaciones Científicas y Técnicas (CONICET), Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT) and Universidad Nacional del Sur (UNS) of Argentina. The experimental data provided by Profertil S.A. are gratefully acknowledged.

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