Powder Technology 264 (2014) 1–8

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Selection and mathematical modelling of high efficiency air classifiers

Okay Altun *, Hakan Benzer

Hacettepe University, Mining Engineering Department, 06800 Beytepe, Ankara, Turkey

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 2 May 2014
Accepted 10 May 2014
Available online 17 May 2014

Keywords:
Air classifier
Classification
Efficiency curve
Modelling

ABSTRACT

Air classification is a method used to classify feed material according to the shape, specific gravity and size of the particles and preferred where water interaction is avoided. Since it is widely used by many of the industries, this study contributes to the literature related with high efficiency air classification by considering the design and modelling aspects for cement industry. In this context, various types of high efficiency classifiers operated at cement grinding circuits were sampled at the same cement quality then mass balancing studies were carried out. After all, the variation of rotor size and air amount parameters with the capacity of the classification process was investigated. Moreover, a mathematical model for high efficiency air classifiers was developed by applying the efficiency curve approach. In contrast to previous studies, the sharpness parameter (α) was found to be dependent on the capacity of the separation process and the diameter of the classification chamber which made the model structure unique.

1. Introduction

Air classification is a process employed to control or adjust the final product fineness of the grinding circuit where water interaction with the material is avoided. This technology was developed early in the 19th century to meet the demand of cement industry where tube mills with high capacities were employed. High milling capacities and the need for fine particle classification had driven the technology. Up to now, various types of air classifiers have been developed to be used in different industries, i.e., pharmaceutical, food, pigment, coal, and cement.

Air classifiers can be grouped as static classifiers and dynamic classifiers. Static classifiers have no moving parts and the target size is adjusted by changing magnitude and direction of the air flow. Vane-type [1] and V-separators [2] are the two examples for these types of classifiers. Dynamic air classifier technology has been evolving since 1885 and nowadays their classification range changes between 300 μm and sub-micron (<10 μm) with a specific type of classifiers [3]. Typically, dynamic classifiers have a rotating plate on which the material is poured and dispersed with the aid of centrifugal force. As the particles are thrown towards the separator wall, air is introduced into the separation chamber where final classification is carried out [4]. Following the first generation technology, second and third generation air classifiers were developed. The second generation classifiers are operated with cyclones in order to increase the fine collection efficiency; additionally, fan is mounted outside of the separator body so as to supply air for the classification. Third generation (high efficiency separator) classifier was unveiled in the 1980s. In these classifiers fineness is adjusted by changing either rotor speed or air flow [5]. As the rotor speed increases, the product gets finer; on the other hand, increasing the air flow rate makes the product coarser [4,6–8]. High efficiency separators are demanded mostly by cement industry and some of the studies reported that it was achievable to decrease the bypass percentage of the classification process down to 5–10% [9] and increase the overall production rate of the grinding circuit by 15–35% at the same cement quality [10]. High efficiency separators are also found applications in integrated grinding systems such as vertical roller mill [11], air classifier mill [12] and air jet mills [13] where classification down to fine sizes is performed.

The performance of an air classifier is evaluated by drawing the “actual efficiency curve” or “Tromp curve” that explains what portion of the material in the feed subjects to the underflow or overflow streams at a given size fraction [7,14]. The *x*-axis of the curve denotes to particle size and the *y*-axis denotes to the probability for being separated as fines and coarse. Fig. 1 illustrates an observed efficiency curve of an air classifier. Because the classification process is not 100% efficient, in actual cases, the *y*-axis does not reach to 0%. This portion of the curve is named as the bypass fraction and is defined as the fine material not appearing in the fines but circulating back to the mill with the reject stream for re-grinding [7,15,16]. The bypass fraction is mainly influenced by the solid air concentration (dust loading) of the separator feed [4,5,7]. In addition, poor feed dispersion and fine agglomeration are thought to be effective on the amount of bypass fraction [16,17]. The d_{50} is denoted as the cut size where the forces equally affect the particles; hence, they have 50% probability either subject to underflow or overflow streams. The sharpness of the curve is another performance indicator for the classification process. The steeper the curve,

* Corresponding author. Tel.: +90 3122977600; fax: +90 3122992155.
E-mail address: okyaltun@hacettepe.edu.tr (O. Altun).

http://dx.doi.org/10.1016/j.powtec.2014.05.013
0032-5910/

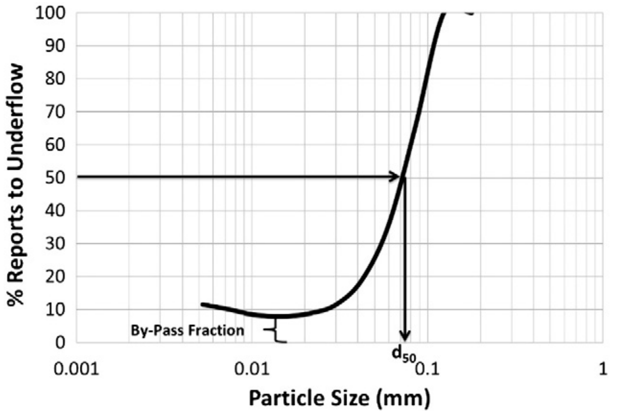

Fig. 1. Actual efficiency curve (Tromp curve) of an air classifier.

Table 1
Technical specifications of the classifiers sampled and number of surveys performed.

	Rotor diameter (m)	Rotor circumferential area (m^2)	No. of surveys
SEPOL®	2	3.14	3
	2.15	3.63	14
	2.5	4.91	6
	2.9	6.61	6
	3.1	7.55	5
SEPAX®	1.77	2.46	4
	1.9	2.84	4
	2.24	3.94	15
	2.53	5.03	4
SEPMASTER®	2.68	5.64	2

the sharper the separation. Developments in air classification technology allowed performing sharper classification operations [18].

Air classification process has attracted interests of researchers as it is widely used in dry processing, particularly in cement grinding area. Its selection and efficient operation are of crucial importance for the plants. Within the scope of the study, a methodology for selecting high efficiency separators was developed and then the modelling studies were performed by using the data obtained from cement grinding circuits. In this context, sampling campaigns around high efficiency separators were conducted initially. Operational parameters, i.e., feed tonnage, product tonnage and air flow rate, were correlated with the design of the rotor. The obtained results from the sampling campaigns were then used in modelling studies so as to develop a software that could be used in simulating closed circuit cement grinding operations accurately. In this context, the efficiency curve approach was applied and all the parameters in the equation were correlated with the operating conditions and design variables. The novelty of the model structure with respect to previous modelling studies is;

- The development of the correlations with the sharpness of separation parameter. This parameter was assumed as constant in the previous modelling works; however, it was found to have a correlation with the design and operating parameters of the classifier.

In the following sections, the findings obtained are discussed in details with the literature related to modelling of air classifiers.

2. Materials and methods

2.1. Sampling campaigns

In this study, several sampling campaigns were arranged around different brands of high efficiency air classifiers. All of the sampling studies were conducted at the same cement type (CEM I 42.5R) having the final product fineness (% retained on 45 μm sieve) ranging between 6.4% and 7.24%. Table 1 summarizes the technical specifications of the classifiers sampled. As can be seen from the table, the performances of Sepol®, Sepax® and Sepmaster® classifiers were evaluated within the scope of the study. The details on the operating principles of the classifiers are reported in the literature [7,19–21].

Prior to performing a sampling survey around a classifier, steady state conditions were provided that is, minimum fluctuations were observed in power draws of the mill discharge elevator (that feeds the classifier), rotor and product conveying systems. In other words, what came into the grinding circuit came out from the final product stream equally. Simplified representation of a classifier with the sampled streams and control room trends is illustrated in Fig. 2.

2.2. Experimental and mass balancing studies

The collected samples from sampling surveys were subjected to the size characterization studies. Sympatek Laser Sizer was used to determine the whole size distribution of the material starting from the top size, down to 1.8 μm. Fig. 3 shows obtained cumulative particle size distribution curves by mass around a high efficiency separator. Similar trends were observed for each of the sampling campaign and Table 2 gives the ranges of the d_{50} and d_{80} values of the classifiers sampled. As can be understood, although the sampling campaigns were performed at the same cement quality and cement type, the variations in raw material properties result in obtaining different product size distributions. Within the study it was observed that $d_{50,3}$ of the final product varied between 12 and 15 μm.

The measured particle size distributions were then used to perform mass balancing studies in order to calculate the flow rates of each

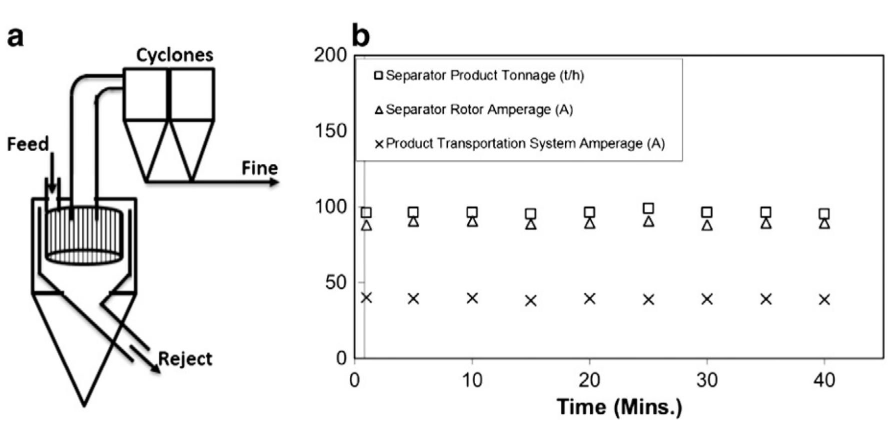

Fig. 2. Sampling points (a) and typical control room trends (b) of a high efficiency classifier.

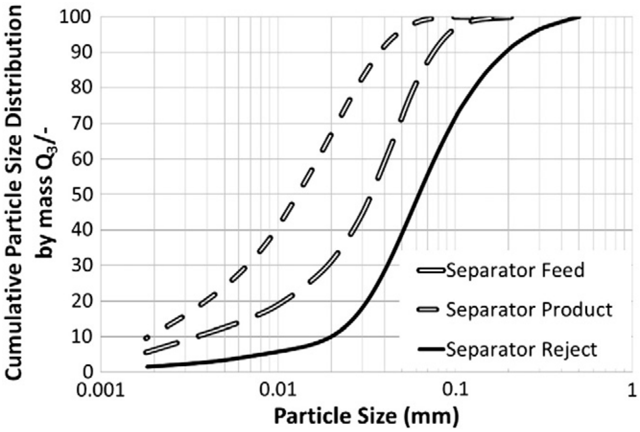

Fig. 3. The cumulative particle size distributions by mass.

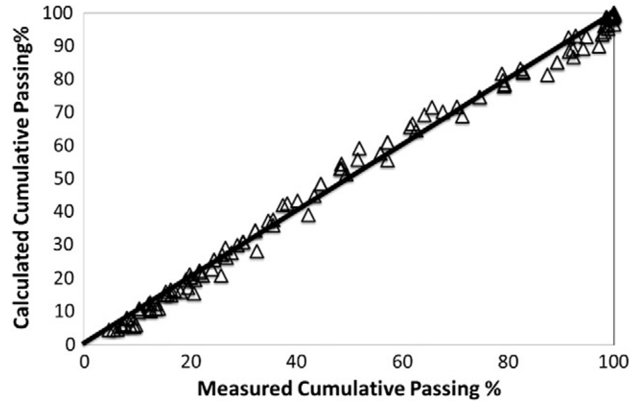

Fig. 4. Measured and calculated cumulative passing values.

stream and to disperse errors occurred during sampling campaigns. For this purpose, JK-SimMet software was used and the accuracy of the results was assessed by plotting the measured cumulative passing percentages against the calculated values (Fig. 4). As a result of the mass balance studies, the efficiency curves were graphed to estimate bypass, cut size, sharpness of separation parameters, etc. which were both used in developing a selection methodology and model structure for high efficiency classifiers. Fig. 5 illustrates some of the actual curves of the classifiers with their types, rotor speeds and dust loadings.

3. Results & discussion

3.1. The selection and performance of high efficiency air classifiers

The selection of an air classifier for a given application is accomplished by sizing the separator body and choosing sufficient fan capacity that are actually functions of throughput required and fineness desired from the classification operation. Within the scope of this study, correlations were developed between the operational and design parameters of high efficiency classifiers. It should be emphasized that the presented correlations are valid within the product d_{50} range of 12 μm and 15 μm.

As given in Table 1 there are more than 1 sampling campaigns arranged for each of the classifier. While developing a selection methodology the average values of the calculated feed and product tonnages as well as the operational air amount were taken for each classifier type. The results are presented in Table 3. Fig. 6 illustrates the variation of feed and product tonnages with rotor circumferential area. These kinds of correlations enable to determine what size of rotor is needed for a given feed and product rate. The trends imply that the use of higher rotor diameter allows processing higher feed rates. Consequently, the production rate increases. Within the study, the ratio of the separator feed rate (t/h) to rotor circumferential area was found to be ranging between 23 and 90 (t/h)/m^2. Kershaw and Yardi [17] in their studies reported that this ratio changed between 23 and 28.7 (t/h)/m^2 for O-Sepa® separators.

The other important parameter is the amount of air to be used during classification operation. This study also proved that the air amount varied with the rotor area as well. Fig. 7 indicates that rotor area and air amount are directly proportional to each other.

In this study the influences of operating parameters on performance of air classifiers were discussed in order to estimate what performance data is obtained when an air classifier is selected for the specified applications. As indicated previously, the main parameters used in evaluating the performance of an air classifier are; the bypass amount and the cut size. Within this study it was found that the bypass obtained from the efficiency curves varied between 2% and 40% depending on the separator feed tonnage and the air amount. Fig. 8a shows the trend between the feed tonnage and bypass. As can be understood, there is a direct correlation between them. However, an improved correlation is obtained when the dust load is correlated with bypass fraction (Fig. 8b). The graph shows that 30% bypass is obtained at 2.8 kg/m^3 which is quite similar to what has been reported in the literature [17,22].

The cut size of the classification was another parameter considered in performance evaluation studies. As reported in the literature, rotor speed and air speed are the main parameters used in adjusting the fine stream product size of a high efficiency air classifier. In fact, these parameters mainly shift the efficiency curve and thus have an influence on the cut size. Within the study, air speed was calculated by dividing the air flow rate by the rotor cage area. Fig. 9a shows the variation of rotor speed with cut size parameter. It implies that as the rotor speed increases the cut size decreases. When the rotor speed is normalized with the air speed Fig. 9b is obtained. The graph shows that there is a steadily upward trend between the air speed-rotor speed ratio and the cut size.

Table 2
$d_{50,3}$ and $d_{80,3}$ values around the classifiers sampled.

	$d_{50,3}$ (μm)		$d_{80,3}$ (μm)	
	Min.	Max.	Min.	Max.
Feed	32	46	56	102
Reject	45	65	78	122
Product	12	15	25	30

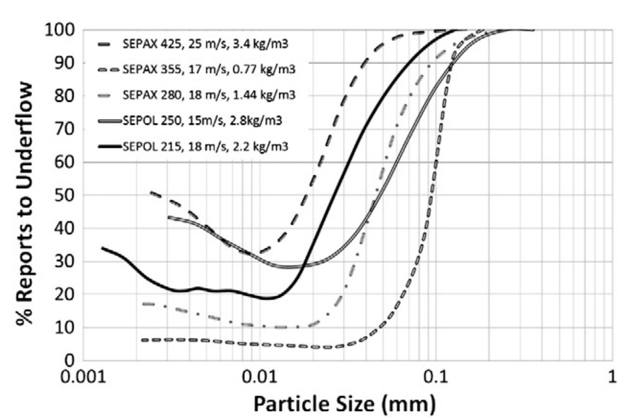

Fig. 5. Some of the actual efficiency curves of the classifiers sampled with their types, rotor speeds and dust loadings.

Table 3
The calculated flow rates and the design of the classifiers.

	Rotor circumferential area (m^2)	Separator feed (t/h)	Separator reject (t/h)	Air amount (m^3/h)
SEPOL®	3.14	173	118.2	112,000
	3.63	235	176.06	120,222
	4.91	445	332	166,307
	6.61	548	432	216,000
	7.55	512	345	230,810
SEPAX®	2.46	59	21	55,433
	2.84	75	21.4	57,390
	3.94	231	127	103,978
	5.03	369	232	143,045
SEPMASTER®	5.64	470	352	223,000

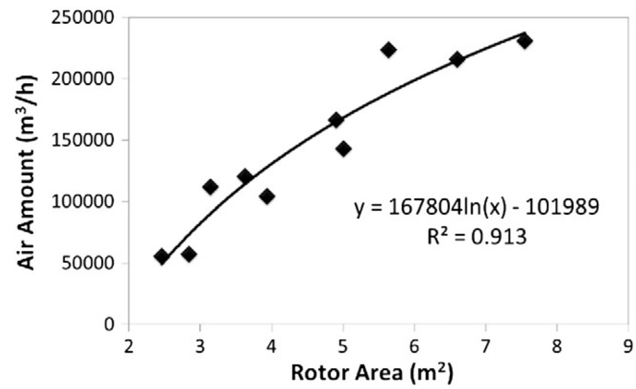

Fig. 7. The relationship between rotor area and air amount needed in classification.

3.2. Mathematical modelling of dynamic air classifiers

There are number of different approaches in modelling of air classifiers. Within the scope of this study, efficiency curve approach was applied to develop a model structure for high efficiency air classifiers. This approach basically depends on developing the relations between the parameters in equation and the operational or design parameters. Up to now, a number of equations have been developed defining the efficiency curve [16,23–27]. Altun [28] compared the accuracy of different equations and found that Whiten's approach fitted the curve with the least sum of squares of deviations, in particular at fine sizes, when compared to the others. Therefore, within this study Whiten's equation was used in modelling of high efficiency air classifiers. The mathematical expression of Whiten's approach, which uses overflow efficiency of separation process, is given in Eq. (1) [14].

$$E_{oa} = C * \left[\frac{\left(1+\beta*\beta^{*}*\frac{d}{d_{50c}}\right)*(\exp(\alpha)-1)}{\exp\left(\alpha*\beta^{*}*\frac{d}{d_{50c}}\right)+\exp(\alpha)-2} \right] \quad (1)$$

where;

E_{oa} : The actual efficiency to overflow
C : Fraction subjected to real classification; (100-bypass)
β : Parameter that controls the initial rise of the curve in fine sizes (fish-hook)
β^* : Parameter that preserves the definition of d_{50c}; $d = d_{50c}$ when $E = (1/2)C$
α : Sharpness of separation
d : Size
d_{50c} : Corrected cut size

In this equation, some of the parameters are explained by drawing the corrected and reduced efficiency curves. Corrected or normalised curve methodology was developed to compare the efficiency curves of classifiers operated at different operating and design conditions [14,29]. It is calculated by extracting bypass fraction from each size class. This graph (Fig. 10) enables estimation of corrected cut size parameter (d_{50c}). A reduced efficiency curve [14,30] is graphed to observe the differences in the shape of the curves. It shows how sharp the classification operation is carried out, and, how β parameter varies. Literature reports that the agglomeration behaviour of fine powders affects β parameter directly and it is also called as the fish hook behaviour of the efficiency curve [14]. Lynch [25] proposed that the reduced efficiency curve was dependent on cyclone size and processed material and independent on design and operating conditions. On the contrary, Nageswararao [30] reported that Plitt's approach had accepted the variable reduced efficiency curve (varied sharpness) as a function of throughput, cyclone diameter and volumetric flow in underflow and overflow streams.

So far, air classifiers have been mathematically modelled by various researchers [27,31,32]. Zhang et al. [27] in their study used efficiency curve function developed by themselves and the operating parameters, i.e., separator feed fineness (proportion of mass between 53 and 19 μm), separator feed tonnage, and separator air flow, were correlated with d_{50c} and C parameters. Benzer et al. [31] and Gunlu [32] performed modelling studies based on Whiten's efficiency curve approach so as to correlate rotor speed, air speed, and separator feed rate parameters with C and d_{50c}. The modelling studies performed to date have proved that bypass correlates directly with separator feed dust load. Additionally, cut size parameter is found to be directly proportional to air flow and inversely proportional to rotor speed. Besides, these studies assumed that the sharpness of the separation parameter was constant for the same separator; however, the sampling campaigns conducted within the study proved that it changes depending on the working conditions considerably. In addition, the air classifier models mentioned above do not include the design features which were in the scope of this study. It is believed that such kind of correlations improves the

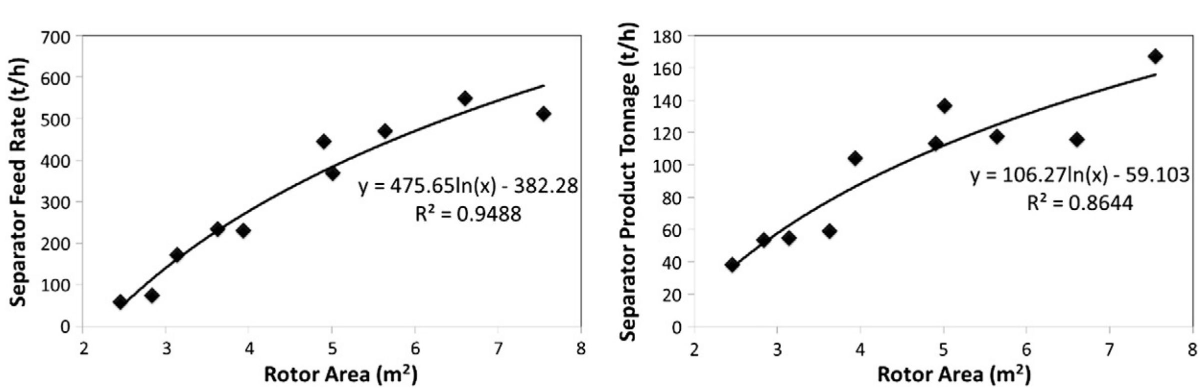

Fig. 6. The separator feed and product tonnages as a function of the rotor area.

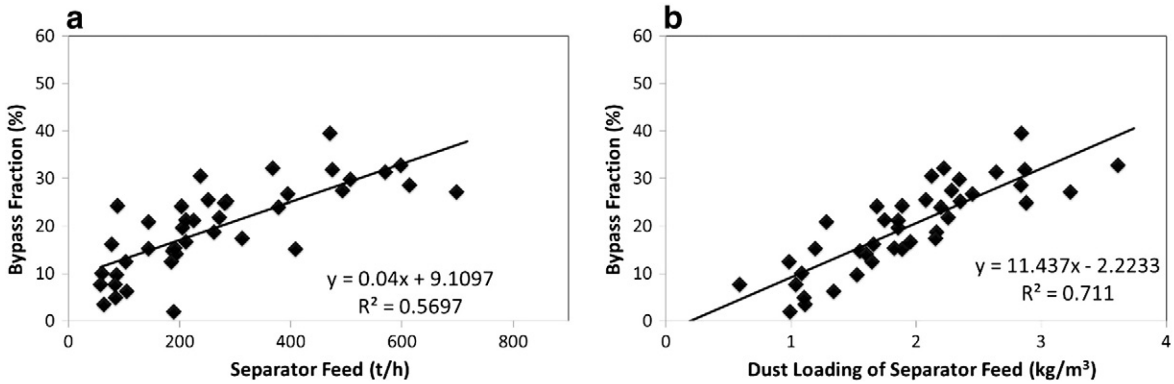

Fig. 8. The trends between separator feed-bypass fraction (a) and dust loading-bypass fraction (b).

reliability of the model since different designs have different classification performance.

In this study, the modelling studies were performed for Sepax® high efficiency classifiers processing CEM I 42.5R type cement (Table 1, Table 3). Initially, the corrected (Fig. 11a) and reduced (Fig. 11b) efficiency curves were graphed both to determine the corrected cut size parameters and to make observations on how the sharpness of separation changes. As can be seen from Fig. 11b, the sharpness changes considerably. Therefore within the study, modelling of air classifier with the variable reduced efficiency curve is aimed that makes the model structure unique and advantageous over the models developed so far.

The modelling works commenced with the model fitting studies. For this purpose, JK-SimMet software was used and efficiency curve parameters for Sepax® separators were back calculated. A typical agreement between the measured and the fitted efficiency curve is illustrated in Fig. 12. This agreement was observed for all of the fitting studies.

The range of the calculated efficiency curve parameters for the classifiers having different chamber/rotor diameters is given in Table 4. As can be understood, each parameter changes evidently owing to the variations in operating conditions and design parameters. Later in this section, the parameters and their influences on the efficiency curve are discussed plainly.

As reported in the literature, the bypass parameter is influenced by dust loading of the separator feed (DL). In this study, an inverse trend is observed between calculated C parameter and dust loading (Fig. 13). That is, an increase in dust loading increases bypass and reduces C parameter (Eq. (1)). Benzer et al. [31] drew similar conclusions with the modelling studies performed for Sepol® classifiers.

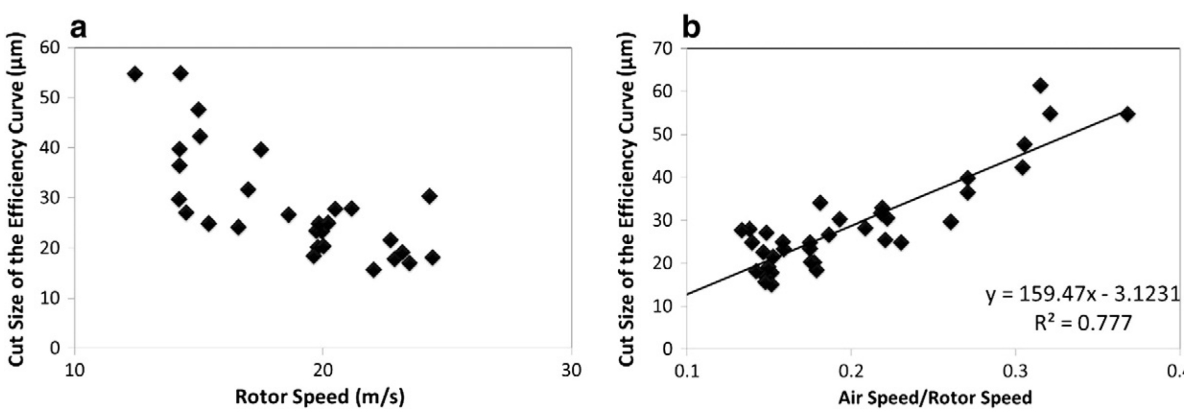

Fig. 9. The trends between rotor speed-cut size (a) and air/rotor speed-cut size (b).

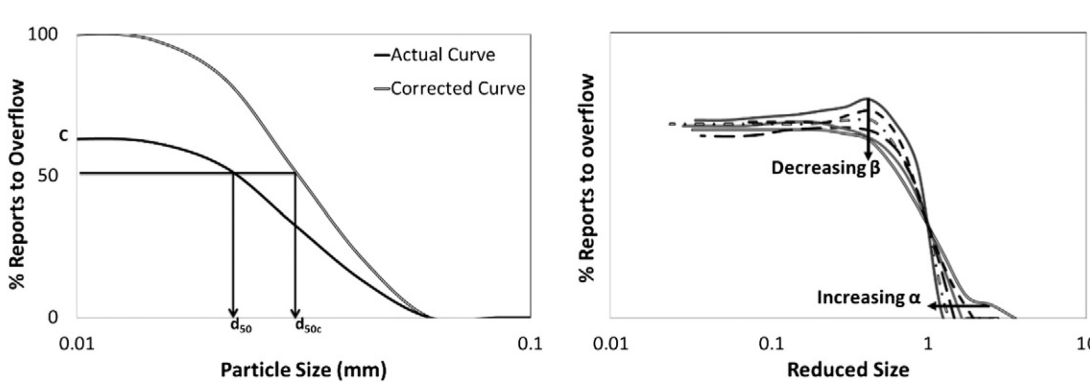

Fig. 10. Expressions of the parameters in Whiten's efficiency curve approach [14].

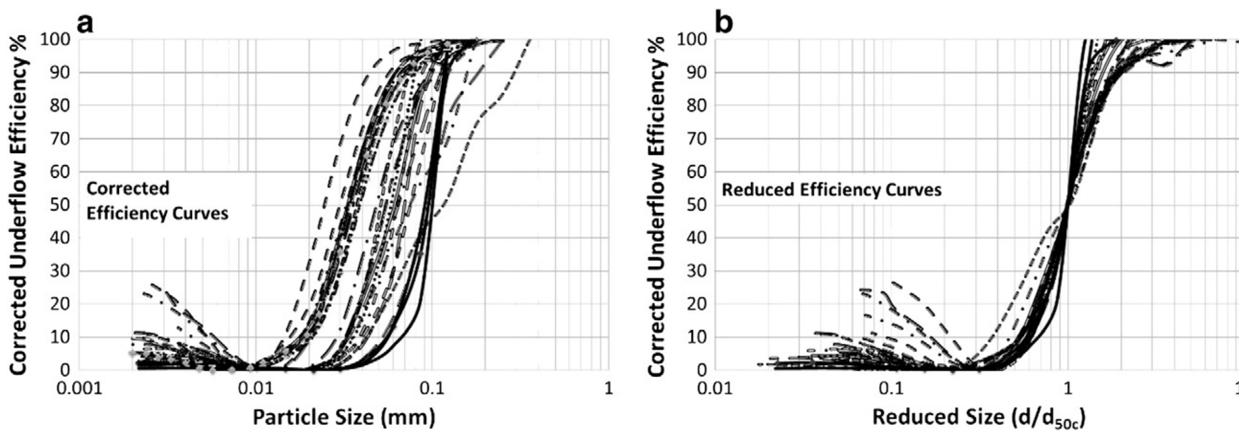

Fig. 11. Corrected (a) and reduced (b) efficiency curves of Sepax® separators.

Dust loading not only affects the bypass fraction but also changes the circulating load around the classifier at the same product fineness. Circulating load is calculated by dividing the flow rate of classifier reject stream by product stream. The trend illustrated in Fig. 14 implies that the higher the bypass the higher the circulating load.

Corrected cut size (d_{50c}) is the parameter that has a major influence on the product fineness of the classification process. Since the fineness is adjusted by changing the air flow and rotor speed of the classifier there should be a correlation between the cut size and the operating conditions. Moreover, the feed size distribution has an effect on the process. The finer the feed size, the finer the product; hence, the model should also include the changes in feed size characteristic. For this purpose, $(-36 + 3)$ μm size fraction amount in feed was used as a fineness criterion. Fig. 15 illustrates the effect of operating parameters on the corrected cut size.
where;

AF : Air flow used in the classification process (m^3/h)
RS : Rotor speed of the classifier (m/s)
F : The amount of $(-36 + 3)$ μm size fraction in the separator feed (t/h)

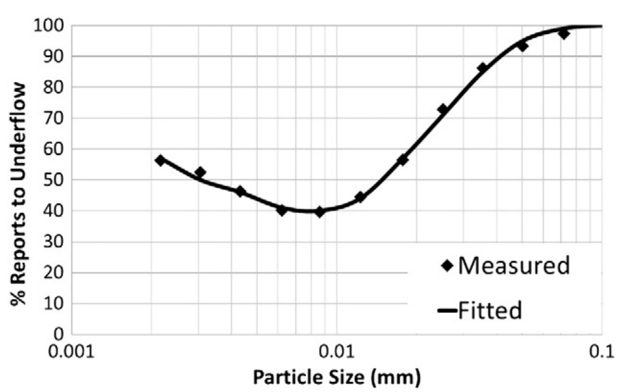

Fig. 12. Agreement between the measured and fitted actual efficiency curves.

Table 4
The range of the calculated efficiency curve parameters.

SEPAX® chamber diameter (cm)	SEPAX® rotor diameter (cm)	α	β	β^*	C	d_{50c} (mm)
280	177	1.76–1.95	0.5–0.6	1.5–1.6	83–87	0.06–0.07
300	190	1.98–3.5	0.3–0.7	1.1–1.5	82–92	0.05–0.1
355	224	1.14–6.74	0.001–1.69	1–2.7	56–94	0.04–0.11
400	253	0.98–1.4	1.3–1.83	2.1–2.7	35–60	0.03–0.04

From the reduced efficiency curves illustrated in Fig. 11b, it is seen that sharpness changes evidently with operating and design conditions of the classifiers. Any kind of classifier performs sharper classification at lower throughput rates; hence, it is thought that dust loading of the separator feed may influence the sharpness of separation (Fig. 16a). As can be seen from the figure, increased feed loading of the classifier reduces the sharpness. When dust loading is normalised by the separator diameter Fig. 16b is obtained. It is seen that, at the same dust loading, a larger diameter classifier carries out a sharper classification operation.
where;

DL : Dust loading of classifier feed (kg/m^3)
D : Classifier chamber diameter (m)

Figs. 17 and 18 illustrate the influences of parameters on β and β^* respectively. The studies imply that C parameter and β are inversely proportional to each other (Fig. 17). As explained in Eq. (1), the

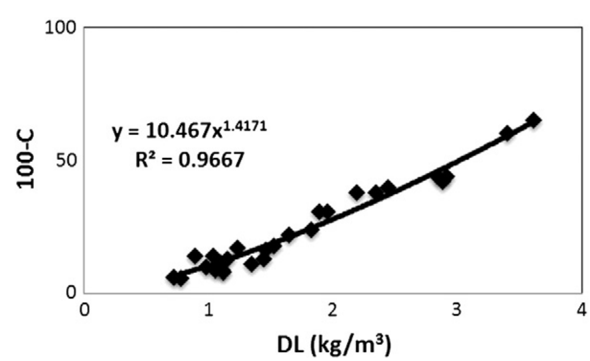

Fig. 13. Effect of separator feed dust loading on bypass or C parameter.

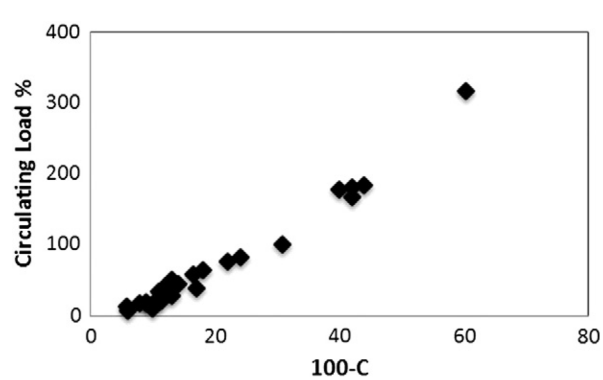

Fig. 14. Effect of bypass or C parameter on circulating load.

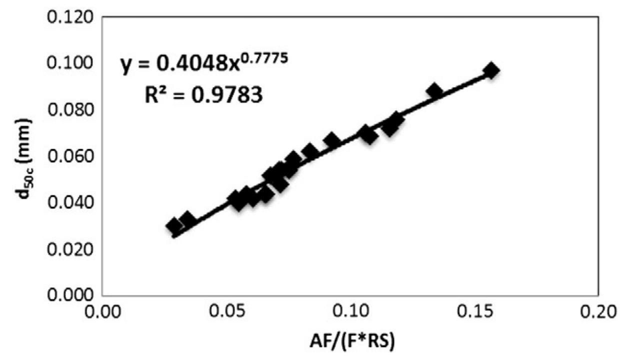

Fig. 15. The variation of d_{50c} with operating conditions.

β parameter represents the shape of the initial rise of the curve in fine size. It is also called as the fish hook. When the material load of the separator feed increases (C is lowered), the dispersion performance of the rotor is reduced and β increases. Consequently, the β^* parameter increases as well (Fig. 18).

So far, the results of the mathematical modelling studies presenting correlations between working conditions, design variables and efficiency curve parameters (Eq. (1)) have been reported. These correlations can be integrated into Eq. (1) to predict classifier performance under different operating and design conditions. It should be emphasized that, with the use of such a tool in closed circuit simulation studies, energy utilization of the cement grinding process can be optimized.

The trends developed in this study have also been obtained from the mechanistic approaches e.g. (CFD, DEM, LPT etc.) used in modelling of air classifiers whether it is dynamic or static. These techniques are applied to calculate the flow fields and particle trajectories in the unit. Karunakumari et al. [33] reported studies on wheel air classifiers and concluded that the cut size increased with increasing fan speed and decreasing rotor speed that is similar to findings obtained in this paper. Gao et al. [34] studied on modelling of turbo air classifiers where they calculated the particle trajectories and reported the influences of parameters on cut size. They found that rotor speed had effects on the efficiency curve and the higher the rotor speed the lower the cut size. Similar conclusions were drawn by Eswaraiah et al. [35]. The CFD works referred in this paper consider the joint action of centrifugal force, drag force and wall-rebound characteristics in their calculations. The particles in certain ranges are influenced primarily by drag force whereas the trajectories of large ones are affected by centrifugal and wall-rebound actions. That explains why rotor speed, creating centrifugal force, and air speed, creating the drag force, are correlated with the cut size. The mechanistic modelling techniques have also been applied to static air classifiers, e.g., gas cyclones that separate dust from the gas, in order to understand the process and to predict the efficiency of separation. Hoffmann and Stein [36], Chu et al. [37] reported the results of CFD-DEM studies performed for gas cyclones and concluded that the solid loading ratio had effects on both particle flow and separation efficiency. Kepa [38] carried out CFD calculations for gas cyclones having different geometries. All of the studies conclude that solid loading and cyclone geometry have a pronounced effect on separation performance since the bypass and sharpness of separation parameters vary considerably. Similar conclusions were drawn within the paper (Fig. 16) where the sharpness parameter was found to be varied with capacity and classifier chamber diameter.

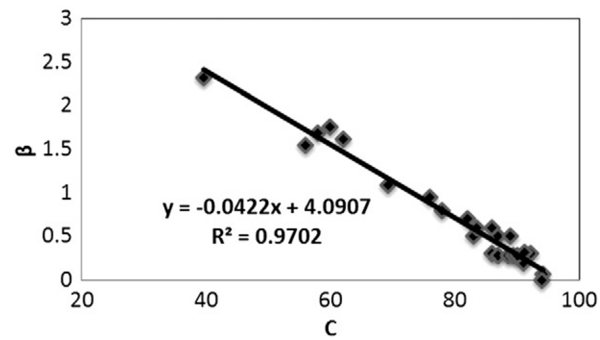

Fig. 17. Correlation between C and β parameters.

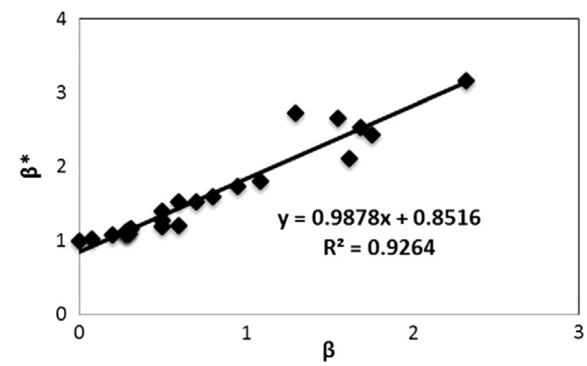

Fig. 18. The variation of β^* parameter with β.

4. Conclusions

Within the context of the study, the performance, selection and modelling of the high efficiency air classifiers were overviewed depending directly on collected industrial data from cement industry. The studies showed that;

- Performance of a high efficiency classifier was influenced by feed dust loading, rotor speed and air flow. These parameters had an influence on bypass and cut size parameters.

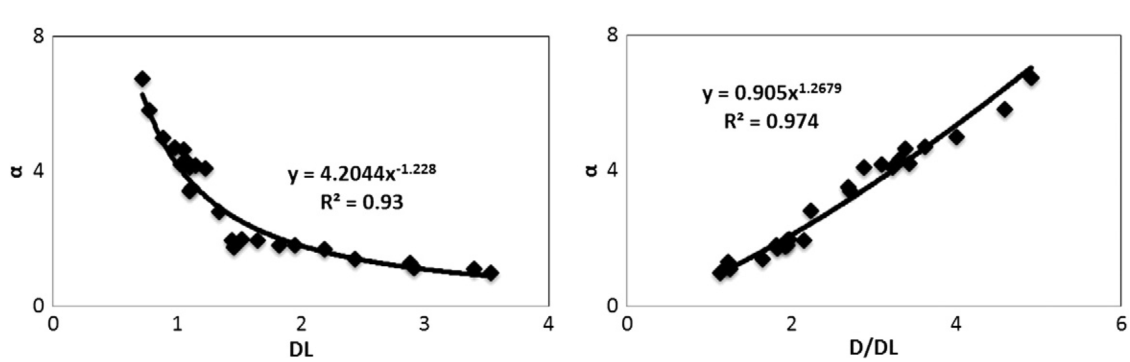

Fig. 16. Effect of dust loading and classifier chamber diameter on the sharpness of separation (α).

- Design parameters of high efficiency classifiers, e.g., rotor diameter/area, air flow, could be correlated with the feed/product flow rates. Therefore a classifier with the required capacity could be selected with regards to rotor area and fan capacity depending on the target size.
- Within the study high efficiency classifiers were mathematically modelled with the efficiency curve approach. The novelty of the model structure developed is the use of the variable reduced efficiency curve approach since the sharpness parameter was found to be changing with the separator feed dust load and separation chamber diameter. It is the first application of changing sharpness parameter in modelling of air classifiers that makes the model structure advantageous over the previous studies.
- As a result of the modelling works, all of the efficiency curve parameters (Eq. (1)) were correlated with the operating and design variables. The equations derived are summarized below;

$$C = 100 - 10.467 * (DL)^{1.4171} \tag{2}$$

$$\frac{d}{d_{50c}} = 2.47 * \left(\frac{AF}{RS * F}\right)^{-0.7775} * d \tag{3}$$

$$\alpha = 0.905 * \left(\frac{D}{DL}\right)^{1.2679} \tag{4}$$

$$\beta = 0.4417 * DL^{1.4171} - 0.1293 \tag{5}$$

$$\beta * = 0.4365 * DL^{1.4171} + 0.7224 \tag{6}$$

where;

D : Classifier chamber diameter (m)
DL : Dust loading of classifier feed (kg/m^3)
AF : Air flow used in the classification process (m^3/h)
RS : Rotor speed of the classifier (m/s)
F : The amount of $(-36+3)$ μm size fraction in separator feed (t/h)

Developed correlations can be integrated into Whiten's efficiency curve equation (Eq. (1)) to predict the classifier performance under certain operating and design conditions, which can be used in simulating closed circuit cement grinding operations.

- The selection methodology and modelling approaches developed in this study can be used for the other types of high efficiency air classifiers as well, since the classification mechanisms and operating principles are quite similar to each other.

References

[1] W.H. Duda, Cement-Data-Book, International Process Engineering in the Cement Industry, Bauverlag GmbH, Wiesbaden and Berlin, 1985. 444.
[2] S. Strasser, R.A. Somani, A.K. Dembla, Improvements in the production of raw meal and cement by the combined use of roller press and V-separator, ZKG 50 (3) (1997) 140–146.
[3] J. Galk, W. Peukert, J. Krahnen, Industrial classification in a new impeller wheel classifier, Powder Technol. 105 (1–3) (1999) 186–189.
[4] A.L. Pastala, Contribution to the design of air separation equipment for closed circuit grinding systems, Cem. Technol. (1975) 119–1249.
[5] J.M. Brugan, High efficiency separators, ZKG 41 (7) (1988) 350–355.
[6] I.V. Klumpar, F.N. Currier, T.A. Ring, Air classifiers, Chem. Eng. 93 (5) (1986) 77–92.
[7] E. Onuma, M. Ito, Separators in grinding circuits, ZKG 47 (9) (1994) 535–542.
[8] M. Shapiro, V. Galperin, Air classification of solid particles: a review, Chem. Eng. Process. 44 (2) (2005) 279–285.
[9] R.J. Detwiler, High efficiency separators. Part: 1 Effect on Cement, ZKG 48 (7) (1995) 384–393.
[10] S. Tsivilis, S. Tsimas, A. Benetatou, E. Haniotakis, Study on the contribution of the fineness on cement strength, ZKG 43 (1) (1990) 26–29.
[11] G.R. Roy, J.W. Terembula, Operational results of vertical mill conversions, IEEE Cem. Ind. Tech. Conf. (Pap.) (2003) 151–158.
[12] P. Toneva, P. Epple, M. Breuer, W. Peukert, K.E. Wirth, Grinding in an air classifier mill—Part I: characterisation of the fluid flow, Powder Technol. 211 (1) (2011) 19–27.
[13] M. Nakach, J.-R. Authelin, A. Chamayou, J. Dodds, Comparison of various milling technologies for grinding pharmaceutical powders, Int. J. Miner. Process. 74 (10) (2004) 173–181.
[14] T.J. Napier-Munn, S. Morrell, R.D. Morrison, T. Kojovic, Mineral comminution circuits—their operation and optimization, JKMRC monograph series in mining and mineral processing, Brisbane, Australia, 1996.
[15] M.R. Dunn, A method for analyzing the performance of a mechanical air separator, World Cem. 8 (16) (1985) 326–332.
[16] M. Ito, K. Sutoh, T. Matsuda, Classification efficiency of cage-type air classifier, ZKG 49 (3) (1996) 134–141.
[17] M. Kershaw, J. Yardi, Analysis of O-Sepa separators at Blue Circle, Australia, World Cem. (1989) 400–404 (Nov.).
[18] J. Yardi, Separator technology, World Cem. 36 (10) (2005) 87–104.
[19] J. Folsberg, A new generation of high efficiency separators for ball mills and roller presses, ZKG 44 (1) (1991) 37–41.
[20] FLSmidth, Sepax(r) separator, www.flsmidth.com 2011.
[21] KHD, KHD separators, www.khd.com 2012 (April, 4 pp.).
[22] E. Onuma, T. Furukawa, O-Sepa a new high-performance air-classifiers, World Cem. 15 (1) (1984) 13–24.
[23] L.R. Plitt, A mathematical model of the hydrocyclone classifier, CIM Bull. 69 (776) (1976) 114–123.
[24] E. Lippek, D. Espig, Forschungsarbeiten zur Mathematischen, Modellierung von Trockenmahlangen, Freiberger Forschungsheft 602 (1978) 77–78.
[25] A.J. Lynch, Mineral Crushing and Grinding Circuits, Elsevier, New York, 1977.
[26] J.A. Finch, Modelling a fish-hook in hydrocyclone selectivity curves, Powder Technol. 36 (1983) 127–129.
[27] Y.M. Zhang, A. Kavetsky, T.J. Napier-Munn, Effects of separator efficiency on clinker grinding circuits, ZKG 41 (10) (1988) 501–505.
[28] O. Altun, Comparison of different efficiency curve approaches in modelling of air classifiers, Hacettepe University, MSc. Thesis, Ankara, Turkey, 2007.
[29] K. Nageswararao, Normalisation of the efficiency curves of hydrocyclone classifiers, Miner. Eng. 12 (1) (1999) 107–118.
[30] K. Nageswararao, Reduced efficiency curves of industrial hydrocyclones—an analysis for plant practice, Miner. Eng. 12 (5) (1999) 517–544.
[31] H. Benzer, L. Ergun, A.J. Lynch, M. Oner, A. Gunlu, I.B. Celik, N. Aydogan, Modelling cement grinding circuits, Miner. Eng. 14 (11) (2001) 1469–1482.
[32] A. Gunlu, Mathematical modelling of air separators used in cement grinding circuits, Hacettepe University, Ankara, Turkey, 2006. (Ph. D Thesis).
[33] L. Karunakumari, C. Eswaraiah, S. Jayanti, S.S. Narayanan, Experimental and numerical study of a rotating wheel air classifier, AIChE 51 (3) (2005) 776–790.
[34] L. Gao, Y. Yuan, J. Liu, Study on the cut size of a turbo air classifier, Powder Technol. 237 (2013) 520–528.
[35] C. Eswaraiah, S.I. Angadi, B.K. Mishra, Mechanism of particle separation and analysis of fish-hook phenomenon in a circulating air classifier, Powder Technol. 218 (2012) 57–63.
[36] A.C. Hoffmann, L.E. Stein, Gas Cyclones and Swirl Tubes, 2nd edition Springer-Verlag, Berlin, 2008.
[37] K.W. Chu, B. Wang, D.L. Xu, Y.X. Chen, A.B. Yu, CFD-DEM simulation of the gas–solid flow in a cyclone separator, Chem. Eng. Sci. 66 (5) (2011) 834–847.
[38] A. Kepa, The efficiency improvement of a large-diameter cyclone—the CFD calculations, Sep. Purif. Technol. 118 (2013) 105–111.