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Residual moisture content and separation efficiency optimization in pilot-scale vibrating screen

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ABSTRACT

Vibrating screening is still one of the main operations considering solid–solid and solid–liquid separation processes. Although it is an equipment of simple design and execution, the full description of a screening unit operation may be difficult to predict, considering that several operational variables can influence it. Therefore, the main objective of this work was to evaluate the best possible combination between the process variables screen aperture size, the volumetric concentration of solids in the feed, and the g-force (measurement of the vibration). This configuration predetermined values for moisture content of the retained material over the screen and separation efficiency regarding particle size. For this, a suspension of phosphate rock concentrate (with a particle density of 3.25 g/cm^3 and average particle size of 95 μm) was diluted in water to perform the experiments in a pilot-scale vibrating screen. The results were analyzed statistically and correlations for each response were fit. The highest values of separation efficiency were found with the lowest values of cut-size diameter, which is desirable in terms of separation. A multi-objective optimization in the experimental range was developed, finding the optimal point for the moisture content of 17.29% and the separation efficiency of 86.88%. The effects of screen aperture size and g-force had important roles in this study.

1. Introduction

Screening is considered one of the oldest unit operations of relevance to separation in the industry and is also widely used as a method of particle size characterization [1]. There are several goals for performing screening in the minerals industry, for example. According to Wills and Munn [2], some of the main purposes in this area are: sizing, to separate particles according to their size; scalping, to remove the coarsest particles in the feed; and dewatering, to remove moisture from a wet feed. Screening is also important in oil well drilling, where the purposes are to maximize the recovery of drilling fluid adhered to the drilled cuttings generated by the rotary drill and to maximize the removal of these solids from the drilling fluid [3].

Screens have evolved throughout the years, from small and simple equipment, capable of processing only coarse solids, to modern designs installed in various industry sectors. Historically, the evolution of vibrating screen design has allowed the use of finer screen cloths. This evolutionary process has led to four different phases of technology to reach a better screening performance. Such phases can be defined by the type of motion produced by the rotating vibrators, which depend on the location and number of the vibrators: unbalanced elliptical, circular, linear or balanced elliptical [3]. Today there are screen models operating with two types of motion: linear and balanced elliptical, that can be chosen according to process needs.

Although screening is a unit operation of simple execution, its mathematical description and detailed understanding may not be trivial [4,5]. The difficulties are based on the assumption that many variables affect the performance of a typical vibrating screen, such as: screen cloth (shape and size of the apertures), amplitude and frequency of vibration, screen angle, density, shape and size of the particles to be screened, viscosity of the suspension and feed rate [6,7]. Moreover, there are several interactions among the variables, which make the operation still more complex. All those features explain why no general and effective methodology for the prediction of screening performance has been developed [1].

The effect of some variables on the vibrating screening performance has been investigated by many researchers both in the minerals industry and in the oil well drilling area. In dry screening, Fowler and Lim [7] investigated the effects of feed rate, frequency of vibration, angle of inclination and screen aperture size on the effectiveness of a vibrating screen. Beeckmans et al. [8] studied the behavior of cut-size diameter under the influence of screen angle, feed rate, screen width, frequency and amplitude of vibration, screen aperture size and density of solids used in the experiments. Standish et al. [9] studied the effects of screen aperture, feed rate, screen angle, frequency of vibration, particle size distribution, and proportion of particles larger than the screen aperture with two solid materials of different densities on the separation efficiency by using a kinetic approach. Trumic and Magdalinovic [10] also

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conducted a kinetic approach to analyze the influence of the dimensions of the screen cloth, particle size distribution and shape of the particulate material, initial mass of solids and density on screen undersize recovery. In wet screening, Rogers and Brame [11] analyzed the effects of slurry feed rate and feed solids concentration on the cut-size diameter, the sharpness of the partition curve and the water split by using high-frequency vibrating screens with different solid materials.

In screening applied in the oil well drilling area, El Dorry [12] conducted experiments using a fluid with similar physical properties to a drilling fluid in order to study the effect of the g-force on the screen capacity, solids conveyance, and dryness of the retained material. Furthermore, Raja [13] evaluated the effects of g-force, solid content in the feed, fluid viscosity and angle of inclination on the screen capacity.

This study aims to evaluate the best possible combination between the screen aperture size, the volumetric concentration of solids in the feed, and the g-force (measurement of the vibration), considering constant feed flow rate and screen tilt. This configuration predetermined values for moisture content of the retained material and separation efficiency using a suspension of phosphate rock concentrate with particle density of 3.25 g/cm^3 and average particle size of 95 μm.

Although the screen aperture size cannot be continuously adjusted in real time, it was used as a process analysis variable in this study to achieve the goal defined previously, which could achieve a certain performance index for the vibrating screen. In the drilling of oil wells, for example, the screen of the vibrating screen must be replaced as the particle size distribution of the drilling fluid changes. This operation requires that the equipment stops to replace the screen. Three types of standard screen (Tyler) available on the market (130, 106 and 95 μm) were chosen. The screen market is growing up continuously and it offers diversified options of screen patterns, including customized screen aperture size.

The criterion adopted to choose the process variables was their relevance in the performance of the equipment; various industries adjust the process parameters to achieve satisfactory performance in the screening operation in the mineral processing and in oil and gas drilling wells. Additionally, the concentration of particulate matter in the suspension that is fed onto the vibrating screens fluctuates in industrial operations and justifies the selection of this variable.

The practical use of the results obtained in this study is to improve the capacity to predict the values of residual moisture in the retained material and the efficiency of particle size separation under different steady state conditions and with different cut-size diameters. This information can be applied to modern control systems and maximize the objective function in real time.

2. Materials, methods and experiments

2.1. Experimental design

The factorial design has been widely applied in basic and technological research, presenting advantages such as: better prediction of variables and the possibility of estimating interaction effects among different factors [14]. Hence, a 3^k factorial design was created to analyze the results [15]. The independent variables are coded as −1, which represents the lowest level; 0, representing the central level; and +1, which corresponds to the highest level. Table 1 shows the factorial design used to perform the experiments in this work.

The independent variables chosen were: the aperture size of each screen (φ and coded as X_1), the volumetric concentration of particulate material in the feed (C_V, X_2) and the g-force (i.e., the measurement of vibration) promoted by the screen (Γ, X_3). Table 2 depicts the values and the corresponding level of each variable.

According to the proposed design, the number of experiments would be 27. However, each experiment was carried out in triplicate, thus making a total of 81 experiments.

Table 1
Matrix considering the factorial design at three levels used in this work.

Experim.	X_1	X_2	X_3	Experim.	X_1	X_2	X_3	Experim.	X_1	X_2	X_3
1	−1	−1	−1	10	0	−1	−1	19	+1	−1	−1
2	−1	−1	0	11	0	−1	0	20	+1	−1	0
3	−1	−1	+1	12	0	−1	+1	21	+1	−1	+1
4	−1	0	−1	13	0	0	−1	22	+1	0	−1
5	−1	0	0	14	0	0	0	23	+1	0	0
6	−1	0	+1	15	0	0	+1	24	+1	0	+1
7	−1	+1	−1	16	0	+1	−1	25	+1	+1	−1
8	−1	+1	0	17	0	+1	0	26	+1	+1	0
9	−1	+1	+1	18	0	+1	+1	27	+1	+1	+1

2.2. Material for screening

To perform the experiments, one barrel (159 L) of suspension containing phosphate rock concentrate diluted in water was prepared [16]. This particulate matter was selected due to its importance at regional level and for being a raw material for phosphate fertilizer industries [17]. Its particle density determined by gas pycnometry was 3.25 g/cm^3. Fig. 1 shows the particle size distribution (PSD) of the phosphate rock concentrate determined by the laser diffraction method. It was observed that the distribution has a size range of 0.6–600 μm and 50% of the particles are smaller than 95 μm.

2.3. Response variables

In this work the following responses were evaluated:

Moisture content of the retained material (M): Determined from the material that was retained on the screen. Three samples of this material were collected, followed by oven-drying at 105 °C for 24 h. Such content was measured on a wet basis.

Separation efficiency of the retained material (η_R): Samples of both output streams were collected in order to determine their PSD. Due to sampling difficulties, the PSD of the feed was calculated from the distributions of the two outputs by means of a mass balance. The efficiency was calculated from Eq. (1) [18]:

$$\eta_R(\%) = 100\frac{W_{SR}}{W_{SF}}\frac{1-Y_R}{1-Y_F} \qquad (d_P \to \varphi) \tag{1}$$

where W_{SR} and W_{SF} are the mass of solids that was retained and in the feed, respectively, Y_R and Y_F are the accumulative PSD of retained material and feed, respectively, for a particle size d_P equal to the screen aperture size φ;

Cut-size diameter (d_{50}): calculated from the frequency distribution (% volume) of the retained solids and feed, where d_{50} is the particle size corresponding to 50% of collection efficiency [2]. This response was calculated using Eq. (2):

$$\frac{W_{SR}}{W_{SF}}\frac{f_{R-d_{50}}}{f_{F-d_{50}}} = 0.5 \tag{2}$$

where $f_{R-d_{50}}$ and $f_{F-d_{50}}$ are the frequencies, in volume, of the distributions evaluated in d_{50} of the retained material and feed, respectively.

Table 2
Variables and levels of the factorial design.

Level	φ (μm)	C_V (%)	Γ (−)
−1	130	1.0	1.00
0	106	2.0	2.25
+1	95	3.0	3.50