Research Article

Dynamic Characteristics of a Vibrating Flip-Flow Screen and Analysis for Screening 3 mm Iron Ore

Chi Yu, Xinwen Wang , Kunfeng Pang, Guofeng Zhao, and Wenpeng Sun

School of Chemical and Environmental Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

Correspondence should be addressed to Xinwen Wang; xinwen.w@cumtb.edu.cn

Received 15 December 2019; Revised 29 April 2020; Accepted 4 May 2020; Published 20 May 2020

Academic Editor: C. M. Wang

Copyright © 2020 Chi Yu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Deep dry screening is the key unit in mineral processing. A vibrating flip-flow screen (VFFS) can provide effective solutions for screening fine-grained minerals, and it has been extensively used in many industrial fields. An accurate dynamic model of VFFS considering the influence of materials is significant for its dynamic analysis and screening process research, but it has rarely been studied in detail. In this paper, an improved dynamic model of VFFS is proposed and its dynamic equations are solved to find the reasonable operating condition, and experiments are carried out to verify the reasonability of the proposed model under no-load and loading materials conditions. Furthermore, the method of multistage sampling and multilayer screening is also applied to evaluate the screening performance of iron ore at 3 mm cut size on VFFS. Results show that when the mass of materials, relative amplitude, and operating frequency have values of 107 kg, about 6 mm and 80.79 rad/s, respectively, the screening efficiency gradually increases with an increase of screening length, reaching 89.05%; however, it does not change much when the screening length exceeds 1900.8 mm. Additionally, the misplaced materials of coarse particles will continue to increase as the screening length increases. This provides theoretical and technical support for the optimization of the length of the VFFS.

1. Introduction

Screening is a vital unit in mineral processing and utilization [1, 2]. In recent years, the dry deep screening of moist and fine-grained minerals has become increasingly essential in many industries. The dry deep screening technology, which can simplify the cleaning process, has become the technology of choice for power coal preparation plants [3]. In construction of waste industry, it also can increase the recovery rate of recycled aggregate. In the concentrator plant, deep screening of products of a high-pressure roller mill can increase the processing capacity of the ball mill due to the finer materials and reduce the consumption of medium. However, adjacent moist particles combine to form a covering film on the sieve aperture and thus block the aperture, which seriously reduces the screening performance [4, 5]. Therefore, the

vibrating flip-flow screen (VFFS) with elastic sieve mats has been widely used for screening fine-grained minerals due to its good performance [6–10].

It is difficult to obtain large acceleration for materials on the ordinary screen; therefore, the VFFS with double vibration principle from a single drive was developed to solve this problem. In order to be ejected, the fine particles that block the aperture require greater force. A single drive provides two vibration movements, and thus the sieve mats are stretched and slackened achieving high acceleration values. The most striking feature of VFFS is that only 2~3 vibration intensity is needed for the screen frame, but the maximum acceleration on the elastic sieve mats can reach 50 g, thus increasing the service life of the screen machine. The dynamic characteristics of VFFS determine the movement and spatial distribution of materials during the screening process, which attract considerable attentions.

Gong et al. [11] analyzed the nonlinear characteristics of VFFS based on the Duffing equation and then discussed the influence of the nonlinear stiffness and materials on the system response. Xiong et al. [12] analyzed the dynamics of a banana flip-flow screen with linear springs and proposed an analytical model for an elastic sieve mat based on catenary theory. Yu et al. [13] investigated the influence of several parameters on the dynamic characteristics of VFFS and proposed a method to adjust its amplitude. Zhang et al. [14] reported the influence of eccentric mass, inclination, and the size composition on the screening efficiency on VFFS by the mean of EDEM simulation. Dong et al. [15] revealed the complicated influence of aperture shape on the screening performance of the vibrating screen, in which the elongation of the rectangular aperture will lead to the increase of the percentage passing, especially for larger particles. Jiang et al. [16, 17] reported that the equal-thickness vibrating screen has better screening performance than the normal vibrating screen, especially when dealing with a large amount of materials with high moisture. Cleary et al. [18, 19] investigated the separation performance of a full industrial-scale double-deck banana screen for a peak acceleration of 5 g. Zhou et al. [20] reported that, due to the effects of collisions and the resonance, the average vibration intensities of the elastic screen rod and tube were larger than 20. Akbari et al. [21] evaluated the dry screening efficiency of the Liwell flip-flow screen at 1 mm and 2 mm cut sizes. Differing from the VFFS, the Liwell flip-flow screen is driven by a crank and connecting rod, and its dynamic characteristics are stable during screening process.

Many studies have shown that the screening efficiency on ordinary screen decreases sharply with the cutting size below 6 mm, let alone with the 3 mm screening [22–25]. In fact, the dynamic response of VFFS interacts with the motion of materials. Currently, the existing dynamic model of VFFS usually did not consider the influence of materials, and most of studies were just focused on theoretical analyses, but less on experimental verification. In addition, to improve the screening efficiency, the classification performance of VFFS is required to be better understood, while it has also rarely been studied in detail at present.

In this paper, the VFFS was employed for screening 3 mm iron ore, and an improved dynamic model of VFFS is proposed considering the effects of loading materials and verified by analyzing the vibration data obtained from a vibration test and analysis unit. Furthermore, the particle distribution characteristics of various size fractions and screening performance of different sections on VFFS are investigated in the screening process. This study provides theoretical and technical support for optimally structural design and industrial applications of VFFS.

2. Experimental

2.1. Materials. The raw materials of iron ore used in this study were provided by Heishangou (Shanxi, China) with the total mass of 107.00 kg. The characteristics of the sample

screening materials are showed in Figure 1, demonstrating that the dominant size fractions are 25–13 mm and 13–6 mm, with the total contents covering more than 50% of the sample. The size fractions of 3–0 mm, 6–3 mm, and 50–25 mm take up over 10% of the sample and the corresponding yields account for 11.76%, 18.89%, and 17.30%, respectively. It is worth noting that the moisture contents in each size fraction take up more than 3.12% and increase as the particle size decreases, and the moisture contents 6–3 mm and 3–0 mm of samples account for 7.31% and 7.72%, respectively.

2.2. Experimental Test System. The experimental test system consists of a silo, a receiver, and the VFFS, as shown in Figure 2. The materials of iron ore were fed into the VFFS from the silo, and the receiver was grouped into five sections, the first four sections to collect the undersized materials and the last one to collect the oversized materials. The VFFS consists of the main and floating screen frames, rubber shear springs, elastic sieve mats, support springs, and supporting frames with a width and length of 800 mm and 2624 mm. Each elastic sieve mat is 328 mm wide, so eight pieces mats can be installed in the VFFS. The elastic sieve mats have the rectangle array, and the shape of the sieve aperture is the straight slot with a length and width of 10 mm and 3 mm, respectively. The beams of the main and floating screen frames are arranged alternately, and the elastic sieve mats are mounted on two adjacent beams. Besides, a vibration test and an analysis unit also are included in the experimental system, as shown in Figure 3, which consists of two triaxial acceleration transducers and a multichannel signal acquisition unit with analysis software and a computer for receiving, storing, and analyzing the acceleration signals collected from the measuring points.

2.3. Evaluation. Since screening is a very complicated process, there are always some misplaced materials existing in the oversized and undersized products, as shown in Figure 4. The screening efficiency and total misplaced materials were used to evaluate the screening performance in this paper, which is calculated with equations (1) and (2), respectively [26, 27].

$$\begin{cases} \eta = E_c + E_f - 100, \\ E_c = \frac{\gamma_o \times O_c}{F_c^r} \times 100, \\ E_f = \frac{F_f^r - \gamma_o \times O_f}{F_f^r} \times 100. \end{cases} \quad (1)$$

$$\begin{cases} M_o = M_c + M_f, \\ M_c = 100 \times \gamma_u U_c, \\ M_f = 100 \times \gamma_o O_f, \end{cases} \quad (2)$$

FIGURE 1: Materials properties of the samples.

where η is the screening efficiency (%), E_c represents the effective placement efficiency of coarse particles (%), E_f represents the effective placement efficiency of fine particles (%), M_o is the total misplaced materials (%), M_c is the misplaced materials of coarse particles (%), M_f is the misplaced materials of fine particles (%), γ_o is the yield of the oversized product (%), γ_u is the yield of the undersized product (%), O_f is the ratio of fine particles in the oversized product (%), O_c is the ratio of coarse particles in the oversized product (%), F_c^r is the ratio of coarse particles in the feeding (%), and F_f^r is the ratio of fine particles in the feeding (%).

3. Theoretical Analysis of the Dynamic Characteristics of VFFS

Relative movement along the direction of the elastic sieve mat will periodically stretch and slacken the mat, thereby affecting the movement of particles on its surface. The vibration along the vertical elastic sieve mat has little effect [28, 29]. Therefore, this paper studies the dynamic response of the coordinate system with the x -axis along the elastic sieve mat, and the dynamic model of VFFS is built, as shown in Figure 5. It is necessary to consider the damping effects of the rubber shear springs and the support springs, but the rotation of the VFFS is small and negligible. In addition, loading materials on VFFS will generate additional mass on the main and floating screen frames, respectively. Furthermore, the materials on the sieve mat will also cause its elastic deformation, resulting in an additional stiffness and damping in the vibration system, and these influences cannot be ignored. Therefore, the dynamic equations of the

VFFS are established by analyzing the viscously damped two-degree-of-freedom spring-mass system, which could be expressed as [30]

$$\begin{aligned} & \left(m_1 + \frac{\Delta m}{2}\right)\ddot{x}_1 + (c_{1x} + c_{2x} + \Delta c)\dot{x}_1 - (c_{2x} + \Delta c)\dot{x}_2 \\ & + (k_{1x} + k_{2x} + \Delta k)x_1 - (k_{2x} + \Delta k)x_2 \\ & = m_0\omega^2 r \cos \omega t, \end{aligned} \quad (3)$$

$$\begin{aligned} & \left(m_2 + \frac{\Delta m}{2}\right)\ddot{x}_2 - (c_{2x} + \Delta c)\dot{x}_1 + (c_{2x} + \Delta c)\dot{x}_2 \\ & - (k_{2x} + \Delta k)x_1 + (k_{2x} + \Delta k)x_2 = 0, \end{aligned} \quad (4)$$

where m_1 and m_2 are the masses of the main and floating screen frame, respectively (kg), k_{1x} is the stiffness of the support springs and k_{2x} is the stiffness of the rubber shear springs along the x -axis (N/m), and c_{1x} and c_{2x} are the resistance coefficients of the support springs and rubber shear springs along the x -axis, respectively, (Ns/m). m_0 is the eccentric mass (kg) and r is the eccentric radius (m), ω is the vibration circular frequency (rad/s), t is the time (s), x_1 , $\dot{x}_1$, and $\ddot{x}_1$ are the displacement, velocity, and acceleration of the centroid of the main screen frame along the x -axis (m, m/s, m/s²), respectively. x_2 , $\dot{x}_2$, and $\ddot{x}_2$ are the displacement, velocity, and acceleration of the centroid of the floating screen frame along the x -axis (m, m/s, m/s²). Δm is the additional mass in the vibration system caused by the materials, which is evenly divided into the mass of the main

FIGURE 2: Schematic diagram of VFFS and the screening system.

FIGURE 3: Schematic diagram of VFFS and the vibration test system.

and the floating screen frame. Δk and Δc are the additional stiffness and damping, respectively, in the vibration system. For $\Delta m = 0$, $\Delta k = 0$, and $\Delta c = 0$, this model represents a model without materials.

They represent a system of two coupled second-order differential equations. Therefore, we can expect that the motion of the mass m_1 will influence the motion of the mass m_2 , and vice versa. Equations (3) and (4) can be written in matrix form as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}, \quad (5)$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are called the mass, damping, and stiffness matrices, respectively, and are given by

$$\begin{aligned} \mathbf{M} &= \begin{bmatrix} m_1 + \frac{\Delta m}{2} & 0 \\ 0 & m_2 + \frac{\Delta m}{2} \end{bmatrix}, \\ \mathbf{C} &= \begin{bmatrix} c_{1x} + c_{2x} + \Delta c & -c_{2x} - \Delta c \\ -c_{2x} - \Delta c & c_{2x} + \Delta c \end{bmatrix}, \\ \mathbf{K} &= \begin{bmatrix} k_{1x} + k_{2x} + \Delta k & -k_{2x} - \Delta k \\ -k_{2x} - \Delta k & k_{2x} + \Delta k \end{bmatrix}, \end{aligned} \quad (6)$$

TABLE 1: The parameters of the vibrating flip-flow screen.

Symbol	m_1	m_2	m_0	r	k_{1x}	k_{2x}	c_{1x}	c_{2x}	Δm	Δk	Δc
Unit	Kg	kg	kg	mm	kN/m	kN/m	Ns/m	Ns/m	kg	kN/m	Ns/m
Value	916	310	48.78	85.45	602.2	2700	9866	2605	10.7	270	260.5

Substituting the parameters in Table 1 into equations (3) and (4), we can obtain the theoretical amplitude of the main and floating screen frames and the phase angle and the relative amplitude between two frames under no-load and load conditions.

It can be observed from Figures 6(a) and 6(b) that loading materials will change the dynamic response of VFFS. In detail, the amplitude of the main screen frame will rise slightly, the amplitude of the floating screen frame will decrease, and the phase angle and relative amplitude between the two screen frames also decrease.

4. Results and Discussion

4.1. Vibration Tests and Analyses under No-Load Condition. The designed centroids of the main and floating screen frame are usually regarded as measuring points, respectively, because the influence of manufacturing and particles on the position of the centroids of two frames can be ignored. The vibration test and an analysis unit were used to collect and analyze the acceleration signals of two points along the x -axis direction. Based on the double integral principle, the amplitudes of displacement were obtained from the steady acceleration signal of the measuring points.

Due to the limitation of the structure of the VFFS, the highest vibration frequency point that can be measured is only 97.37 rad/s, at which frequency the amplitude of the main screen frame is 1.89 mm, the amplitude of the floating screen frame is 14.89 mm, and the relative amplitude is 15.90 mm. Therefore, the experimental dynamic response of VFFS can be obtained, as shown in Figure 7.

A comparison of the measured data with theoretical values under no-load condition is illustrated in Figure 8. As can be observed, the maximum relative errors between the measured amplitudes of the main screen frame, floating screen frame, and the theoretical values are 5.624% and 3.734%, respectively, and the corresponding maximum relative error of the relative amplitude is 6.444%. Besides, the maximum relative error between the measured data of the phase angle and the theoretical value is 12.620%. The correlation between measured amplitudes of the main screen frame, floating screen frame, relative amplitude, and theoretical values is very strong, with the coefficient of determination (R^2) being 0.9988, 0.9982, and 0.9976, respectively. In addition, the R^2 of measured phase angle and the theoretical value is 0.9906. Clearly, a few slight differences are observed between them, verifying the reasonability of the dynamic model of the VFFS under no-load condition.

4.2. Analysis of Loading Materials Experiment. Because the operating amplitude of VFFS applied in industries is about 6 mm and the frequency is in the range from 77.49

to 83.78 rad/s [31, 32]. In this experiment, the operating frequency of the VFFS was 80.79 rad/s, and dynamic response of the displacement signals in time domain at two measuring points is shown in Figure 9. The whole process of time domain response of the VFFS is divided into five stages, namely, the start stage, the steady-state stage, the loading materials stage, the steady-state stage, and the end stage. Several phenomena need to be noticed in this process. In the start stage and the end stage, the amplitude of the main and floating screen frames and the relative amplitude will rocket when the exciting frequency reaches the natural frequency of the VFFS, which is called "resonance." After the start stage, the VFFS will work in the steady-state stage where the amplitudes maintain basically at a constant value. In the stage of loading materials, the amplitude of the main screen frame will ascend from 1.97 mm to 2.24 mm and the amplitude of the floating screen frame will slide from 8.01 mm to 7.71 mm. Meanwhile, the phase angle decreases from 0.076π to 0.074π and the relative amplitude decreases slightly from 6.19 mm to 5.62 mm when the materials are loaded on the VFFS, which indicates that loading material has an effect on the stability of amplitude in the system, but the impact is weak and acceptable for practical production. These phenomena are fit with the results obtained from the theoretical analysis of the dynamics characteristics of VFFS (Figure 6). Furthermore, the amplitude will increase to the steady-state amplitude with the materials decrease.

4.3. Screening Experiments and Analyses. The purpose of studying the dynamic characteristics of VFFS is to ensure it has better screening performance in the screening process. The method of multistage sampling and multilayer screening was used to analyze the screening process and classification performance of VFFS [33]. The undersized materials were divided into four sections equally along the direction of materials flow. Two elastic sieve mats corresponded to one section, so there were four sections. Since the width of each sieve mat was 328 mm and the inclination of the VFFS was 15 degrees, the width of one section in the horizontal direction was 633.6 mm, and the screen lengths of sections I, II, III, and IV were 0–633.6 mm, 633.6–1267.2 mm, 1267.2–1900.8 mm, and 1900.8–2534.4 mm, respectively. In addition, Section V corresponded to the oversized materials. The yield and screening percentages of each size fraction in different sections and lengths of the VFFS are presented in Figures 10 and 11.

Figure 10 illustrates that particles of 3–0 mm size fraction are the dominant particles in both sections I and II with the yields of 73.37% and 64.75%, respectively, and so are particles of 6–3 mm size fraction in sections III and IV with the corresponding yields of 61.31% and 80.00%. It is also worth noticing that the particles of size fraction 13–6 mm are

FIGURE 6: Theoretical dynamic response of VFFS. (a) Amplitude. (b) Phase angle.

FIGURE 7: Experimental dynamic response of VFFS. (a) Amplitude. (b) Phase angle.

mostly concentrated in Section V, accounting for 99.88% of this size fraction, and only a tiny number of materials become undersized products, which can be observed in sections I, II, III, and IV. The 3D structure of the undersized particles of 13–6 mm is flat shale, as shown in Figure 4. The major size fraction is over 6 mm in Section V, covering 85.80% and comparatively 3–0 mm size fraction in Section V takes up a tiny of it, with 2.21%. Furthermore, covering 40.61% of 6–3 mm size fraction particles pass through the screen apertures and become the undersized products, that is, the misplaced materials. Figures 10(b) and 11 demonstrate that the size fractions of 50–25 mm and 25–13 mm all

enter into Section V and become oversized particles; therefore, the screening percentage of these two size fractions are all zero in different sections and lengths of VFFS.

The 3–0 mm size fraction particles pass through the screen apertures and enter in Section I firstly due to the large thickness of the materials layer at the feeding end. With the decrease in the thickness of the materials layer, the yield of 3–0 mm size fraction gradually decreases. The 6–3 mm size fraction particles are relatively difficult to pass through the apertures when the materials layer is thick, so the proportion of 6–3 mm size fraction gradually increases with the thinness of the materials layer. The VFFS is an approximate sieving

FIGURE 8: Comparison of the measured data of (a) amplitudes and the (b) phase angle with the theoretical values.

FIGURE 9: Dynamic response of the displacements of two frames and relative displacement in time domain at the frequency of 80.79 rad/s.

form because the sieve apertures have a straight slot shape with length and width of 10 mm and 3 mm, respectively. Therefore, the 6–3 mm size fraction particles and the 13–6 mm size fraction of flat shale-shaped materials can pass through the sieve aperture and be observed in the sections I, II, III, and IV.

Figures 12 and 13 show the screening performance of different sections and lengths in the VFFS. Figure 12 shows that the sectional finer materials placement efficiency E_f first increases and then gradually decreases, while there is a little change in the coarser materials placement efficiency along the direction of materials flow, which indicates that the

screening efficiency has a similar change law with E_f . The majority of 3–0 mm size fraction materials firstly pass through the apertures in sections I and II. Furthermore, the amount of 3–0 mm fine particles decreases significantly after Section II, and some of them do not pass through the apertures, leading to the decrease of the finer materials placement efficiency in the sections III and IV. The coarser materials placement efficiency E_c decreases and finer materials placement efficiency E_f increases gradually along the flow direction of materials, as shown in Figure 13(a). Meanwhile, the misplaced materials of fine particles M_f gradually decrease (Figure 13(b)). In detail, M_f successively

FIGURE 10: Distribution of various size fractions in different sections of the VFFS.

FIGURE 11: Screening percentages of various size fractions in different areas and length of the VFFS.

subside in the sections I, II, and III and creep down between sections III and IV, indicating that most of the fine particles have passed through the apertures before Section III. Besides, the misplaced materials of coarse particles M_c increase with the increase of screening length, and the longer the materials stay on the screen, the easier they pass through the apertures. It also can be observed that the screening efficiency increases and the total misplaced materials first decrease and then increase with an increase in the screen length. This is mainly due to the reason that the screening process on VFFS is an

approximate screening form with the straight slot of the sieve aperture. With the increase of the screening length on VFFS, some of 6-3 mm size fraction materials lose their ways and become the undersized products. It is also worth noticing that the screening efficiency η shows a little increase from 88.08% to 89.06%; however, total misplaced materials increase from 7.18% to 7.96% as the length changes from 1900.8 mm to 2534.4 mm. Therefore, the screen surface of the VFFS needs an appropriate length to ensure better screening efficiency and lower misplaced materials.

FIGURE 12: Screening performance of different sections of the VFFS.

FIGURE 13: Screening performance of different lengths in the VFFS (a) Effective placement efficiency. (b) Misplaced material.

5. Conclusions

To date, the dynamic characteristics of VFFS has been studied and analyzed by many scholars; however, the existing dynamic model of VFFS usually did not consider the influence of materials, and there is a little report on screening experimental research of VFFS.

In this paper, an improved dynamic model of VFFS is proposed considering the effects of loading materials. For the validation of this model, no-load and loading materials experiments on the VFFS were both conducted, with results

indicating that the proposed model is capable to describe its dynamic characteristics in the operating frequency range.

Secondly, the method of multistage sampling and multilayer screening was used to analyze the screening process and classification performance of VFFS. When the mass of materials, relative amplitude, and operating frequency have values of 107 kg, about 6 mm, and 80.79 rad/s, respectively, the VFFS has good screening performance in screening 3 mm iron ore, with the screening efficiency up to 89.06%. The screening efficiency gradually increases with an increase of the screening length; however, it does not change

much when the screening length exceeds 1900.8 mm. The appropriate screening length is essential to achieve better screening performance, thereby optimizing the structural design.

Yet, the screening efficiency can be easily affected by several operating factors of VFFS, such as frequency, amplitude, inclination, and feeding rate. In future work, we will investigate the effects of these factors on the screening process and screening efficiency.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this work.

Acknowledgments

The authors would like to thank the TianGong Technology for their support in enabling this research. The authors gratefully acknowledge the support from the National Innovation Training Project (C201803813).

References

- [1] M. F. Eskibalci and M. F. Ozkan, "Comparison of conventional coagulation and electrocoagulation methods for dewatering of coal preparation plant," *Minerals Engineering*, vol. 122, pp. 106–112, 2018.
- [2] G. Chalavadi, R. K. Singh, M. Sharma, R. Singh, and A. Das, "Development of a generalized strategy for dry beneficiation of fine coal over a vibrating inclined deck," *International Journal of Coal Preparation and Utilization*, vol. 36, no. 1, pp. 10–27, 2016.
- [3] P. Zhao, Y. Zhao, Z. Chen, and Z. Luo, "Dry cleaning of fine lignite in a vibrated gas-fluidized bed: segregation characteristics," *Fuel*, vol. 142, pp. 274–282, 2015.
- [4] X. Yu, Z. Luo, H. Li et al., "Effect of vibration on the separation efficiency of high-sulfur coal in a compound dry separator," *International Journal of Mineral Processing*, vol. 157, pp. 195–204, 2016.
- [5] L. Peng, F. Li, H. Dong, C. Liu, Y. Zhao, and C. Duan, "Characteristics analysis of a novel centralized-driving flip-flow screen," *International Journal of Mining Science and Technology*, vol. 24, no. 2, pp. 195–200, 2014.
- [6] H. X. Zhai, "Determination of the operation range for flip-flow screen in industrial scale based on amplitude-frequency response," *Journal of China Coal Society (China)*, vol. 32, no. 7, pp. 753–756, 2007.
- [7] J. W. Fernandez, P. W. Cleary, M. D. Sinnott, and R. D. Morrison, "Using SPH one-way coupled to DEM to model wet industrial banana screens," *Minerals Engineering*, vol. 24, no. 8, pp. 741–753, 2011.
- [8] C. Sheng, C. Duan, Y. Zhao, P. Zhang, and L. Dong, "Separation and upgrading of fine lignite in a pulsed fluidized bed. 2. Experimental study on lignite separation characteristics and improvement of separation efficiency," *Energy & Fuels*, vol. 32, no. 1, pp. 936–953, 2018.
- [9] C. Y. Zhou, X. C. Fan, C. L. Duan et al., "A method to improve fluidization quality in gas-solid fluidized bed for fine coal beneficiation," *Particuology*, vol. 43, pp. 181–192, 2019.
- [10] Y. M. Zhao, C. S. Liu, and C. Y. Zhang, "Progressing of coal screening theory and equipment," *Coal (China)*, vol. 2, pp. 15–18, 2008.
- [11] S. P. Gong, X. W. Wang, and S. Oberst, "Non-linear analysis of vibrating flip-flow screens," *MATEC Web of conferences*, vol. 221, p. 04007, 2018.
- [12] X. Xiong, L. Niu, C. Gu, and Y. Wang, "Vibration characteristics of an inclined flip-flow screen panel in banana flip-flow screens," *Journal of Sound and Vibration*, vol. 411, pp. 108–128, 2017.
- [13] C. Yu, X. W. Wang, H. B. Wei et al., "Research on debugging condition of vibrating flip-flow screen based on amplitude-frequency characteristics," *Journal of Mining Science and Technology (China)*, vol. 4, no. 4, pp. 365–374, 2019.
- [14] X. Zhang, B. Wu, L. K. Niu et al., "Dynamic characteristics of two-way coupling between flip-flow screen and particles based on DEM," *Journal of China Coal Society (China)*, vol. 44, no. 06, pp. 1930–1940, 2019.
- [15] K. Dong, A. H. Esfandiary, and A. B. Yu, "Discrete particle simulation of particle flow and separation on a vibrating screen: effect of aperture shape," *Powder Technology*, vol. 314, pp. 195–202, 2017.
- [16] H. Jiang, Y. Zhao, C. Duan et al., "Dynamic characteristics of an equal-thickness screen with a variable amplitude and screening analysis," *Powder Technology*, vol. 311, pp. 239–246, 2017.
- [17] H. Jiang, Y. Zhao, J. Qiao et al., "Process analysis and operational parameter optimization of a variable amplitude screen for coal classification," *Fuel*, vol. 194, pp. 329–338, 2017.
- [18] P. W. Cleary, M. D. Sinnott, and R. D. Morrison, "Separation performance of double deck banana screens - Part 1: flow and separation for different accelerations," *Minerals Engineering*, vol. 22, no. 14, pp. 1218–1229, 2009.
- [19] P. W. Cleary, M. D. Sinnott, and R. D. Morrison, "Separation performance of double deck banana screens - Part 2: quantitative predictions," *Minerals Engineering*, vol. 22, no. 14, pp. 1230–1244, 2009.
- [20] Z. Zhou, L. Huang, H. Jiang et al., "Kinematics of elastic screen surface and elimination mechanism of plugging during dry deep screening of moist coal," *Powder Technology*, vol. 346, pp. 452–461, 2019.
- [21] H. Akbari, L. Ackah, and M. Mohanty, "Performance optimization of a new air table and flip-flow screen for fine particle dry separation," *International Journal of Coal Preparation and Utilization*, vol. 39, pp. 1–23, 2017.
- [22] R. Weinstein and R. J. Snoby, "Advances in dry jigging improves coal quality," *Mining Engineering*, vol. 59, no. 1, pp. 29–34, 2007.
- [23] R. Q. Honaker, M. Saracoglu, E. Thompson, R. Bratton, G. H. Luttrell, and V. Richardson, "Upgrading coal using a pneumatic density-based separator," *International Journal of Coal Preparation and Utilization*, vol. 28, no. 1, pp. 51–67, 2008.
- [24] B. Zhang, H. Akbari, F. Yang et al., "Performance optimization of the FGX dry separator for cleaning high-sulfur coal," *International Journal of Coal Preparation and Utilization*, vol. 31, no. 3–4, pp. 161–186, 2011.
- [25] H. Akbari, L. A. Ackah, and M. K. Mohanty, "Development of a new fine particle dry separator," *Minerals & Metallurgical Processing*, vol. 35, no. 2, pp. 77–86, 2018.

- [26] K. Liu, "Some factors affecting sieving performance and efficiency," *Powder Technology*, vol. 193, no. 2, pp. 208–213, 2009.
- [27] H. Jiang, Y. Zhao, C. Duan et al., "Kinematics of variable-amplitude screen and analysis of particle behavior during the process of coal screening," *Powder Technology*, vol. 306, pp. 88–95, 2017.
- [28] S. P. Gong, X. W. Wang, C. Yu et al., "Dynamic analysis of vibrating flip-flow screen based on a nonlinear model of shear spring," *Journal of China Coal Society (China)*, vol. 44, no. 10, pp. 3241–3249, 2019.
- [29] S. P. Gong, S. Oberst, and X. W. Wang, "An experimentally validated rubber shear spring model for vibrating flip-flow screens," *Mechanical Systems and Signal Processing*, vol. 139, pp. 1–15, 2020.
- [30] B. C. Wen, H. Zhang, S. Y. Liu et al., "Vibrating machinery theory," *Techniques and Applications*, (in China), 2012.
- [31] X. B. Zhang, J. Y. Xie, F. K. Li et al., "Research and application of BFS3080RDD flip flow screen to coal preparation plant," *Coal Science and Technology*, vol. 44, pp. 150–154, 2016.
- [32] G. F. Zheng, J. B. Zhu, W. D. Xia, and S. L. Liu, "Banana flip-flow screen benefits coal preparation," *Filtration + Separation*, vol. 53, no. 4, 2016.
- [33] H. Jiang, Y. Zhao, C. Duan et al., "Properties of technological factors on screening performance of coal in an equal-thickness screen with variable amplitude," *Fuel*, vol. 188, pp. 511–521, 2017.