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Full Length Article

Effect of vibration on the separation efficiency of oil shale in a compound dry separator

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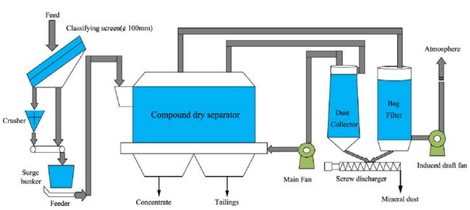
GRAPHICAL ABSTRACT



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ABSTRACT

Oil shale is a special energy source between coal and petroleum and is a potential alternative energy source. However, during oil shale mining, a large amount of Inorganic mineral impurities is produced. Thus, the grade of the oil shale is reduced, it can be effectively utilized by performing beneficiation through physical sorting to reduce impurities and upgrade the oil content. In this paper, the physical properties of oil shale were analyzed, beneficiation of 50-0 mm oil shale using a compound dry separator was proposed. The effect of vibration on the beneficiation process was emphatically investigated. The law of force between particles in different sorting areas and the effects of amplitude, frequency and angle of vibration on the energy law of different sorting area are systematically analyzed, The optimum operation parameters were obtained, and the sorting test was carried out. The results showed that when the force uniformity between the concentrate area and the tailings area is the best and the fluctuation range is minimum and the peak force of the particles corresponding to the concentrate area and the tailings area is 8.24 mN, 10.57 mN, 12.34 mN, 8.13 mN under the amplitude is 3.8–4.0 mm, frequency is 38-39hz. When frequency is 38 hz, Amplitude is 3.9 mm, the vibration acceleration of the concentrate area and tailings area are 24.78 m/s^2, 17.89 m/s^2, and the concentrate area was the main separation area, and the tailings area was mainly used to transport and discharge gangue. The separation tests were carried out under the optimum vibration parameters (A = 3.9 mm, f = 38hz, θ = 45°), The yields and oil content of the concentrate are 34.63% and 11.03%, while those of tailings are 65.37% and 1.01%, and the separating accuracy (probable error E) is 0.14 g/cm^3, the actual separation density is 2.33 g/cm^3. The vibration plays an important role in the compound dry separating oil shale efficiently.

1. Introduction

Energy is one of the most important foundation for human survival and development, The exploitation and utilization of fossil energy has promoted the development of the world economy and human society [1]. However, With scientific and economic development, the demand for energy is constantly increasing, The increase of energy consumption has become the objective necessity of today's economy and society, at

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the same time, energy security and resources shortage are also problems that human beings cannot be ignored [2]. However, coal and oil are non renewable fossil fuels that will eventually be consumed. Therefore, the search and development of alternative energy sources has become a priority [3].

Oil shale is a kind of special energy between coal and petroleum, it is a kind of special sedimentary rock containing abundant organic matter in the mineral body [4,5]. Globally, about 4.11 × 10^{12} t shale oil can be extracted out of this type of rock, it's reserves are up to 3 times of the global conventional oil and gas reserves which have been proved to be exploited and among fossil fuels, oil shale is second to coal in terms of calories [6–8]. Oil shale resources exploration and development potential is huge, is an important potential energy. However, during oil shale mining, a large amount of Inorganic mineral impurities is produced [9], which the grade of the oil shale is reduced and seriously affected the development and utilization value of oil shale [10]. If the oil shale ore to be sorted and purified can effectively discharge inorganic mineral impurities to improve the oil content and then improve the grade and greatly enhance the comprehensive utilization of oil shale efficiency, reduce environmental pollution [11,12].

Oil shale is a high-density material and some similarities exist in the physical properties between oil shale and coal [13]; the principle of coal beneficiation provides insights that are relevant to oil shale separation processes, while, the nature of the material determines the selection process. At present, the separation process mainly includes two kinds of wet separation and dry separation, traditional water separation processes mainly include the jigging washing process and heavy medium separation. Both these processes are barely able to provide the required oil shale separation density, and therefore ineffective with respect to the separation effects and inadequate for oil shale upgrading [14,15]. Oil shale has lower moisture content and higher density of inorganic mineral impurities, which is suitable for dry process. Oil shale can be separated effectively from inorganic mineral impurities by dry separation methods and improve the oil content. Existing researches on the dry sorting of oil shale show that the separation of > 6 mm oil shale using a compound dry separator and the separation of < 6 mm fine grain oil shale using a vibrating air-dense medium fluidized bed separator and better separation effect has been achieved [16–18]. However, studies concerning on the effect of vibration on the sorting effect are few. In this paper, we proposed the use of compound dry separation beneficiation oil shale and the effect of vibration on composite dry method separation oil shale is emphatically studied and the optimum vibration operation parameters are obtained. The paper is expected to provide technological and theoretical support for the promotion of oil shale dry beneficiation technologies in industries.

2. Experimental

2.1. Compound dry separating apparatus

Fig. 1 shows the apparatus used for the compound dry separation of oil shale in the present study. The apparatus is composed of a crude ore preparation system, a separator system, and an air supply and dust removal system. The crude ore preparation system comprises a pre-classification screen, crusher, surge bin, and other related elements. The crude ore is pre-classified and crushed before being conveyed to the surge bin and is fed to the compound dry separator, which produces concentrate and tailings. The air supply and dust removal system contains an air blower, induced draft fan, dust collector, air bag, and valve. This system is used for air supply and dust collection. The separation in the compound dry separator is carried out under the coordinative effect of airflow and vibration. Then the ores are layered by density. The low-density ores are layered on the upper layer, and high-density ores are in the bottom layer. As a result, the ores are beneficiated by density.

2.2. Vibration test system

2.2.1. Vibration acceleration test system

The separation process of the compound dry cleaning apparatus depends on density, particles obtain vibrational energy to move, due to the existence of a certain velocity difference between the particles of different density, the final separation is completed. However, the size of the speed have a certain relationship with acceleration. Therefore, it is necessary to study the effect of vibration on the sorting effect. First, we should investigate the variation law and the trajectory of vibration acceleration in different sorting areas. Vibration acceleration test system consists of an acceleration transducer, a digital vibration controller, and a computer. The system is used to test the bed acceleration of the compound dry separator. It is noted from Fig. 2 that the discharge baffle of the compound dry cleaning separator is divided into two parts from the feed end to the tailing discharge end, and were each placed at a measurement point in the two regions.

2.2.2. Particles force test system

The separation of particles by density is a dynamic process, Particles collide with each other during the sorting process, resulting in enhanced motion activity until the final sorting is completed. Based on this, it is helpful to optimize the particle movement parameters and improve the equipment sorting accuracy by studying the force characteristics of the particles on the bed. The particle force test system consists of a PCB-208C01 force transducer, data acquisition card, and computer. It is noted from Fig. 3 that the force transducer is installed at the test point in the concentrate area and tailings area and is fixed with a steel tube to test the force of the particle in the bed.

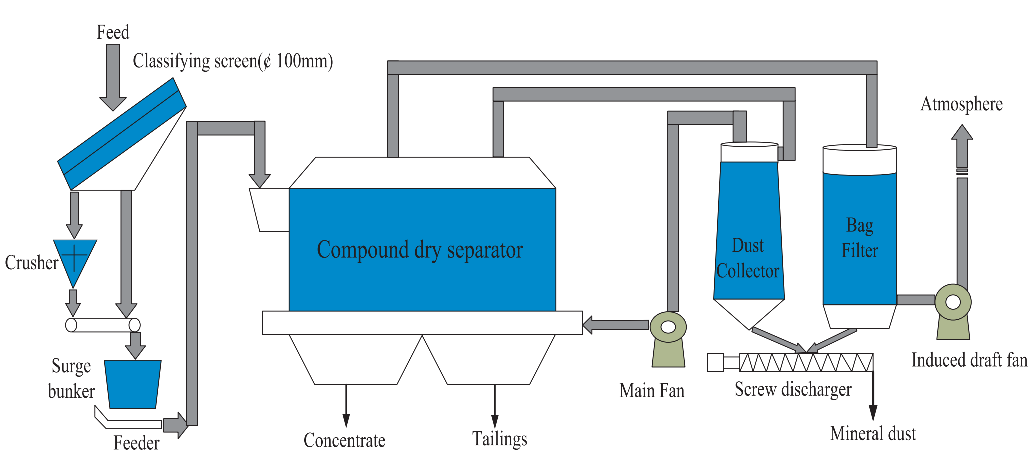

Fig. 1. Diagram of the oil shale compound dry separation system.

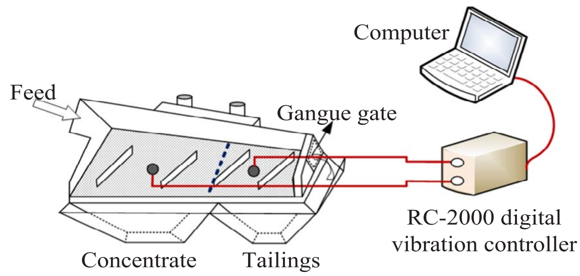

Fig. 2. Diagram of the vibration acceleration test system.

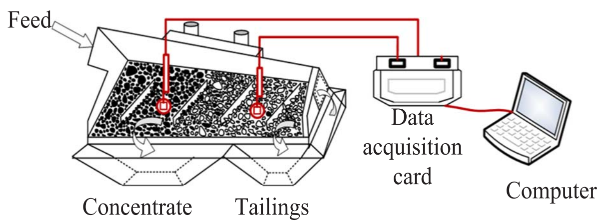

Fig. 3. Diagram of the particles force test system.

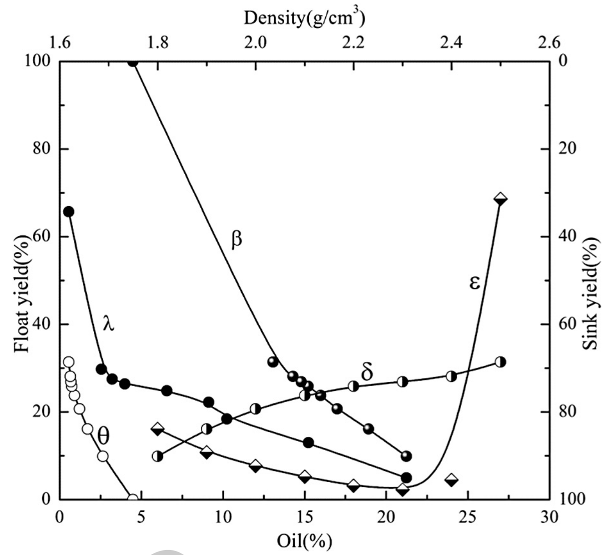

Fig. 4. Washability curves of oil shale with size of 50-0 mm.

2.3. Material properties

Oil shale is a particular type of geo-material. The physical properties of oil shale affect separation results. It was therefore necessary to analyze the physical properties of oil shale in order to determine the optimum separation process. The oil content is an important parameter to evaluate oil shale grade and is expressed by "ω", and the oil shale is divided into of high grade (ω > 10%), medium grade (5% < ω ≤ 10%) and low grade (3.5% < ω ≤ 5%). A scanning electron microscope and an energy dispersive spectrometer are also used to analyze the surface morphological structure, density and oil content characteristics of the those three grades of oil shale. The oil content of the oil shale considered in this study was 4.13%, char content was 87.41%, gas loss was 1.83%, moisture content was 2.17%, which belong to low grade oil shale. Table 1 shows oil shale sink-float test results, upon which are based the washability curves shown in Fig. 4. Table 1 gives the aluminum retort analysis results of raw ores with different particle sizes. According to Table 2, the oil content of crude ore decreases with the increase of density, and the content of inorganic mineral increases with the density, which shows that inorganic mineral impurities are mainly found in high-density gangue. Therefore, the oil shale is suitable for physical sorting and will be dissociated and recovered.

2.4. Evaluation

The purpose of separating oil shale is to remove inorganic mineral impurities, enrich organic matters, raise the grade of oil shale and hence the oil content. The beneficiation process of the compound dry separator depends on the density, because the oil content of oil shale decreases with the increase of density, the beneficiation of oil shale is actually the process of oil content enrichment. The beneficiation of oil shale in compound dry separator is gravity separation which the probable error (E) is defined as follows:

$$E_p = \frac{1}{2}(\delta_{75} - \delta_{25}) \quad (1)$$

The probable error, E, was used to evaluate the separation efficiency of the PGBFB. The lower the E value, the higher the separation efficiency. Where δ_{75} is the density when the partition coefficient is 75%, g/cm^3; δ_{25} is the density when the partition coefficient is 25%, g/cm^3.

Because of the correlation between density and oil content, the oil content distribution in the material on the bed can directly indicate material movement and beneficiation effect at a particular point in time. In this paper, the force law of particles in different areas of the bed and the effect of vibration on the separation effect are investigated. To simplify the study of oil content distribution on the bed, a coordinate system based was setup, as shown in Fig. 5. The X-axis extends from the feed end to the tailings end and the bed in this direction is divided into 20 equal parts. From the feed end along the X axis direction, 0–450 mm and 450–1000 mm parts of the trapezoidal area, respectively as the concentrate area and tailings area. The Y-axis extends from the backboard to the discharge end and the bed concentrate area and tailings area in this direction is respectively divided into 5 equal parts and 7

Table 1
Result of sink-float test for 50–0 mm oil shale.

Density (g/cm^3)	Yield (%)	Oil content (%)	Float products		Sink products		$\delta_p \pm 0.1$	
			Yield (%)	Oil content (%)	Yield (%)	Oil content (%)	Density (g/cm^3)	Yield (%)
−1.8	9.89	21.24	9.89	21.24	100	4.48	1.8	16.12
1.8–1.9	6.23	15.23	16.12	18.92	90.11	2.64	1.9	10.79
1.9–2.0	4.56	10.23	20.68	17.00	83.88	1.71	2.0	7.64
2.0–2.1	3.08	9.12	23.76	15.98	79.32	1.22	2.1	5.20
2.1–2.2	2.12	6.56	25.88	15.21	76.24	0.90	2.2	8.24
2.2–2.3	6.12	2.12	32.00	12.71	74.12	0.74	2.3	7.35
2.3–2.4	1.23	1.81	33.23	12.30	68.00	0.61	2.4	4.49
2.4–2.5	3.26	1.22	36.49	11.31	66.77	0.59	2.5	63.51
+2.5	63.51	0.56	100	4.48	63.51	0.56		
Total	100.00							

Table 2
Results of different sizes oil shale particles aluminum retort analysis.

Particle size (mm)	Yield (%)	Oil content (%)	Char content (%)	Moisture content (%)	Gas loss (%)
+ 100	21.34	5.56	81.56	2.87	1.23
− 100 + 50	23.45	6.02	79.73	3.56	1.78
− 50 + 25	16.56	4.81	89.34	2.01	1.45
− 25 + 13	13.56	4.11	91.12	1.81	1.29
− 13 + 6	7.92	2.01	97.21	0.56	2.24
− 6	17.17	2.12	95.86	0.61	3.24
Total	100	4.48	87.41	2.17	1.83

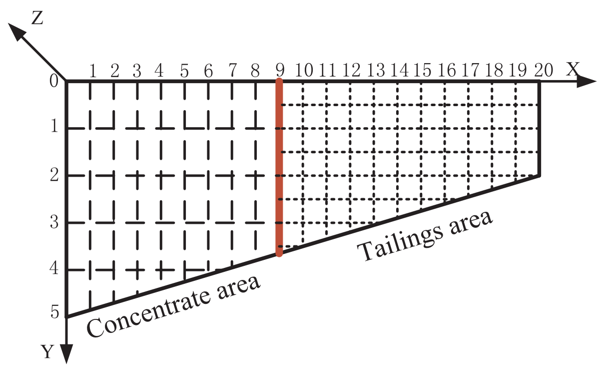

Fig. 5. Distribution of sampled material on compound dry separator bed for oil content measurement.

equal parts. The Z-axis extends from the vertical bed. Material was sampled at the cross region, where oil content was measured.

3. Results and discussion

3.1. Physical properties of oil shale

As can be seen in Fig. 6, the white material in the SEM image is inorganic mineral. The figure shows that the white mineral contents of the oil shale with ω > 10% are obviously lower than those for 5% < ω≤10%, the white inorganic mineral content of the oil shale with 3.5% < ω < 5% is larger, when the oil content is low, the main components of oil shale are inorganic minerals. The XRD pattern in Fig. 6 shows that the inorganic mineral content of the oil shale with ω > 10% is less, the main inorganic minerals are calcite, montmorillonite, carbonate, pyrite, kaolinite, and the corresponding diffraction intensity is smaller. The inorganic mineral content of the oil shale with 3.5% < ω < 5% is increased, the main inorganic minerals are calcite, montmorillonite, carbonate, pyrite, kaolinite, quartz. The main inorganic minerals in 3.5% < ω < 5% oil shale are calcite, montmorillonite, carbonate, pyrite, kaolinite, gypsum, quartz, sulfate. It shows that the content and composition of inorganic minerals increase with the decrease of the oil content; on the contrary, the content of organic mineral increases.

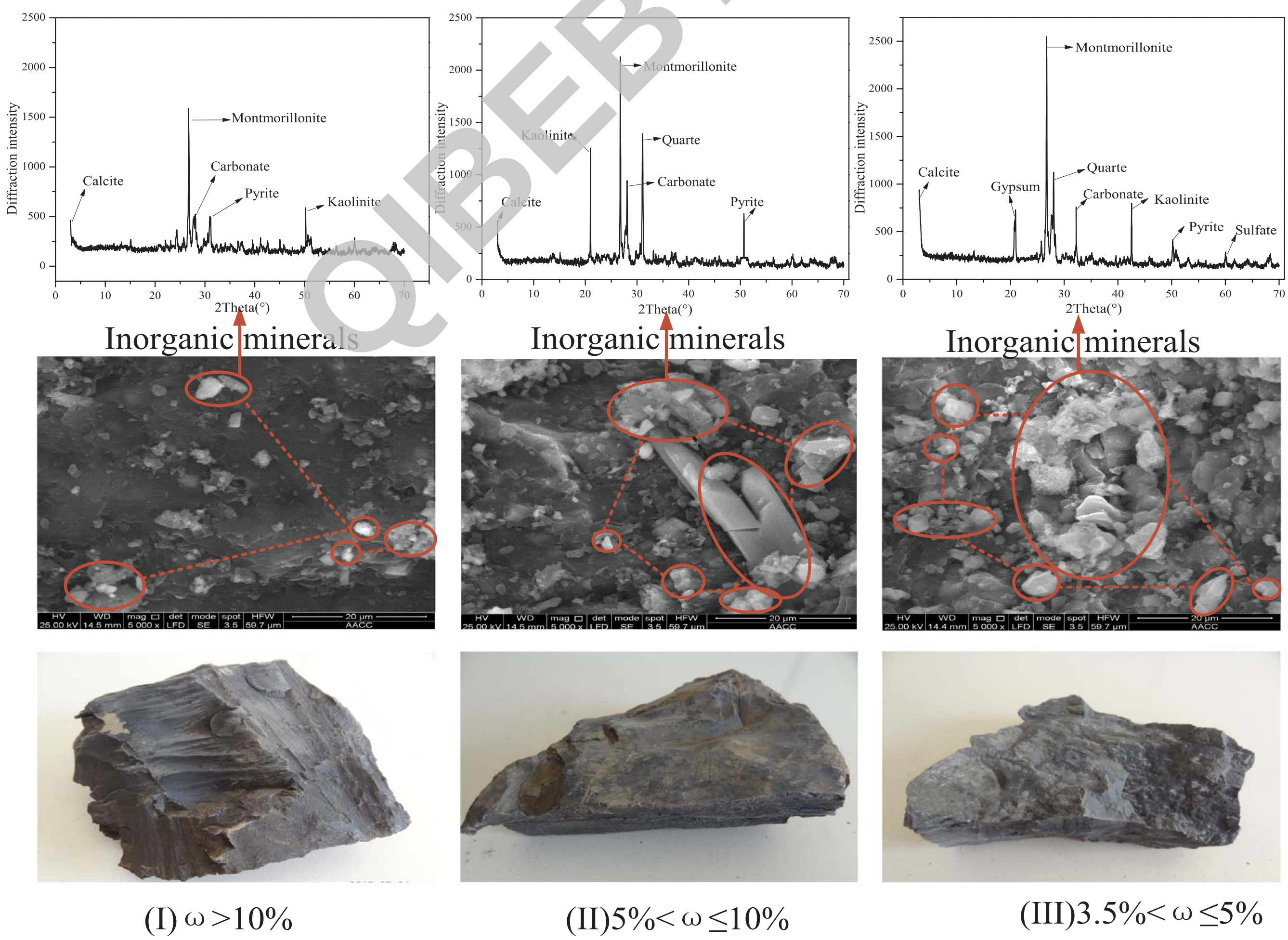

Fig. 6. Elemental analysis and microstructure of oil shale with different oil contents.

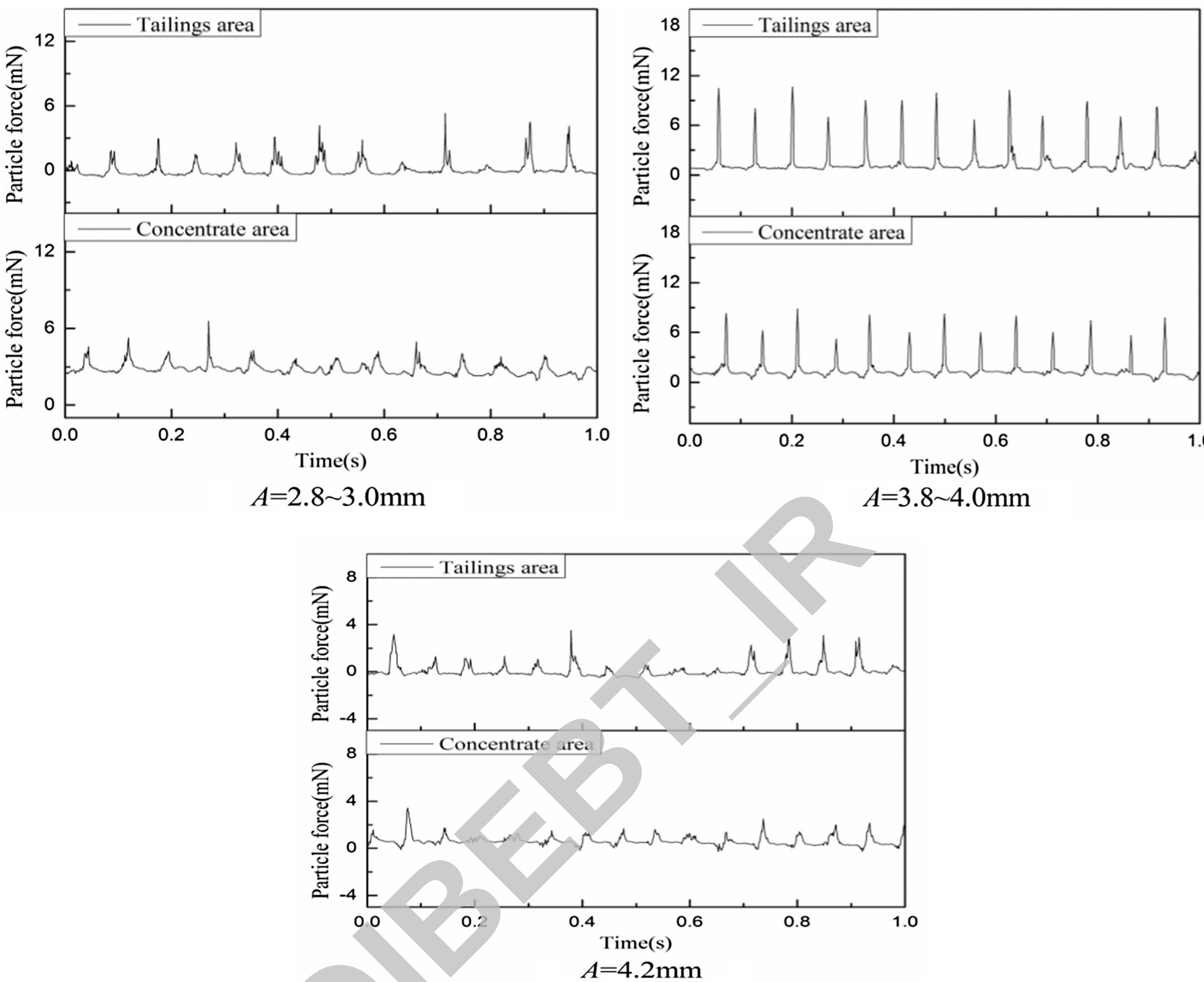

Fig. 7. Effect of Amplitude on Particle Force.

3.2. Effects of the vibration on the force of particles and the acceleration of the bed surface

Vibration has an important effect on the compound dry separation process. It can enhance the activity of the material particles on the bed as the vibration propagates through the material layer. Then, the material obtains a certain energy that promotes stratification and sorting on the bed. To determine the vibration regularities of the sorting bed and reveal the effects of the vibration acceleration and particles force on material separation, the vibration regularities along the Z-axis of the bed was tested. The vibrations along the X-axis and Y-axis directions are mainly used for transporting materials and indirectly promoting rolling of the material. Therefore, the vibration acceleration and particles force in the Z-axis direction will be discussed systematically in this paper.

3.2.1. Effect of vibration amplitude on performance of the particle force

Fig. 7 shows the effects of the amplitude on the force law of the particles on the bed for a frequency of 34 hz, an air flow of 2.46 m/s, and a vibration direction angle (VDA) of 45°.

As shown in Fig. 7, when the amplitude is small, force of particles in concentrates and tailings is close to that in tailings, whereas, the force between particles is uneven and fluctuates greatly. When the amplitude is small, the particles on the bed is intensive and the vibration energy obtained by particles is small. Because of the intergranular resistance, the vibration energy cannot be transferred, which leads to the fact that the collision between particles are decreased. In this condition, the peak force is small and the mean value is 6.12 mN. As the amplitude increases, the particles obtain more vibration energy and the activity is enhanced. The dense particles move to the tailings section while the light particles move to the concentrate section. In this process, the particles layer according to density, and both of particles in concentrate section and tailings section distribute uniformly and the difference tends to be obvious. The forces are uniform and fluctuate gently. When the amplitude A = 3.8 ~ 4.0 mm, both of particle forces in concentrate section and tailings section reach the most uniform and the fluctuation is least. In that case, the peak forces for concentrate and tailings are 8.24 mN, 10.57 mN, respectively, and the separation effect is the best. As the amplitude increases further, the activity of particles increase excessively. At this time, the collision between the particles is large, which lead to the phenomenon that the low density particles are thrown to the tailings section and mixed with high density particles, and the back-mixing are enhanced. The gap between particles becomes larger and the probability of collision is reduced, which lead to the fact that the force is nonuniform and the peak force decreases greatly. When the amplitude A = 4.2 mm, the back-mixing of the bed particles is reinforced. The peak force values of particles in concentrate section and tailings section are 3.89 mN, 4.12 mN, respectively. The separation effect gets bad.

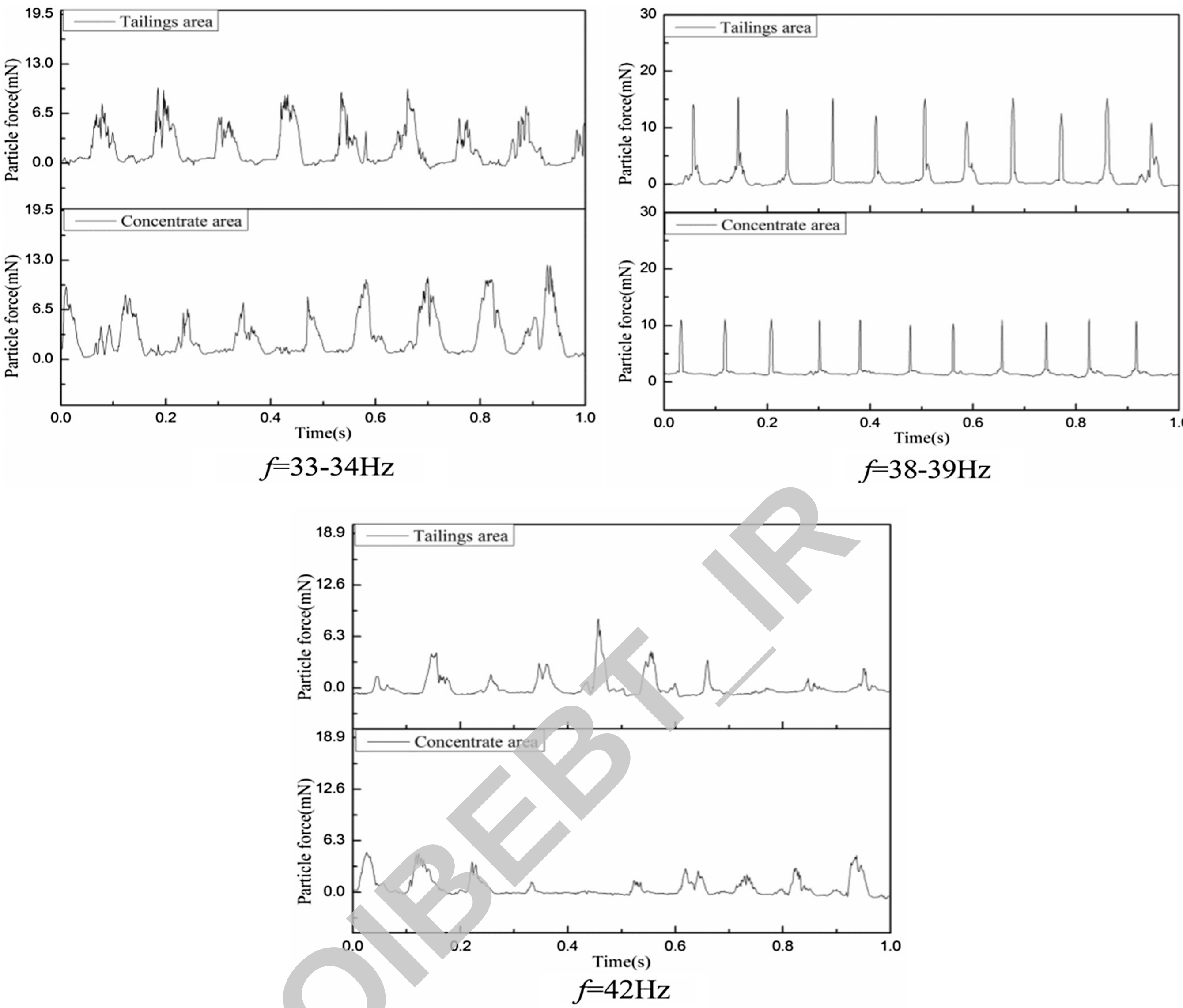

Fig. 8. Effect of frequency on Particle Force.

3.2.2. Effects of the frequency on the force law of particles

Fig. 8 shows the effects of the frequency on the force law of the particles on the bed for an amplitude of 3.8 mm, an air flow of 2.46 m/s, and a VDA of 45°.

As shown in Fig. 8, when the vibration frequency is 33–34 hz, the peak value of particles force in the concentrate area and tailings area are equal to 9.75 mN, Although a low vibration frequency activates the materials at the bottom of the bed, the vibration energy is weak for the overall poor activity of the bed material at low frequencies, which cannot sufficiently stratify the material. The collision force between particles is weak, the peak value of force is small, the force between particles is not uniform, and the fluctuation range is larger. With increasing frequency of vibration, the materials at the bottom of the bed to be more active, and the looseness of the entire bed gradually increases, the probability of collision between particles increased, the density of different particles begin to migrate along their tracks. The low density and high density particles are concentrated on the concentrate section and the tailings section respectively, and the force between the particles is even and the fluctuation range is smaller. The density distribution of particles was most notable at 38–39 hz, the force between the particles is uniform, the fluctuation range is minimum, and the peak value of the particles between the concentrate section and the tailings section is 12.34 mN, 18.13 mN, indicating optimal separation, and the materials entirely divided according to density. With further increases in frequency, excessive vibration energy led to undesirable activity of materials within the bed. Additionally, the distance limitation of material movement significantly enhanced back mixing, leading to ore particle mixing becoming dominant, the force between particles is not uniform, and the fluctuation range becomes larger, the peak value of the particles between the concentrate area and the tailings area are 5.42 mN, 8.65 mN. As a consequence, materials could not be stratified by density.

3.2.3. Effects of the vibration on the acceleration of the bed surface

The material in contact with the vibrating bed obtain energy to produce a certain acceleration, and the acceleration produced by materials of different density is different. The change of the vibration acceleration of the bed directly influences the acceleration of the sorted material, and then indirectly influences the separation effect. In this paper, the influence of the vibration intensity on the acceleration of the bed is investigated according to the law of amplitude and frequency of the upper section. The result is shown in Fig. 9.

The time-domain analysis and frequency-domain analysis for the vibration acceleration of the bed are shown in Fig. 9. When f = 34 Hz,

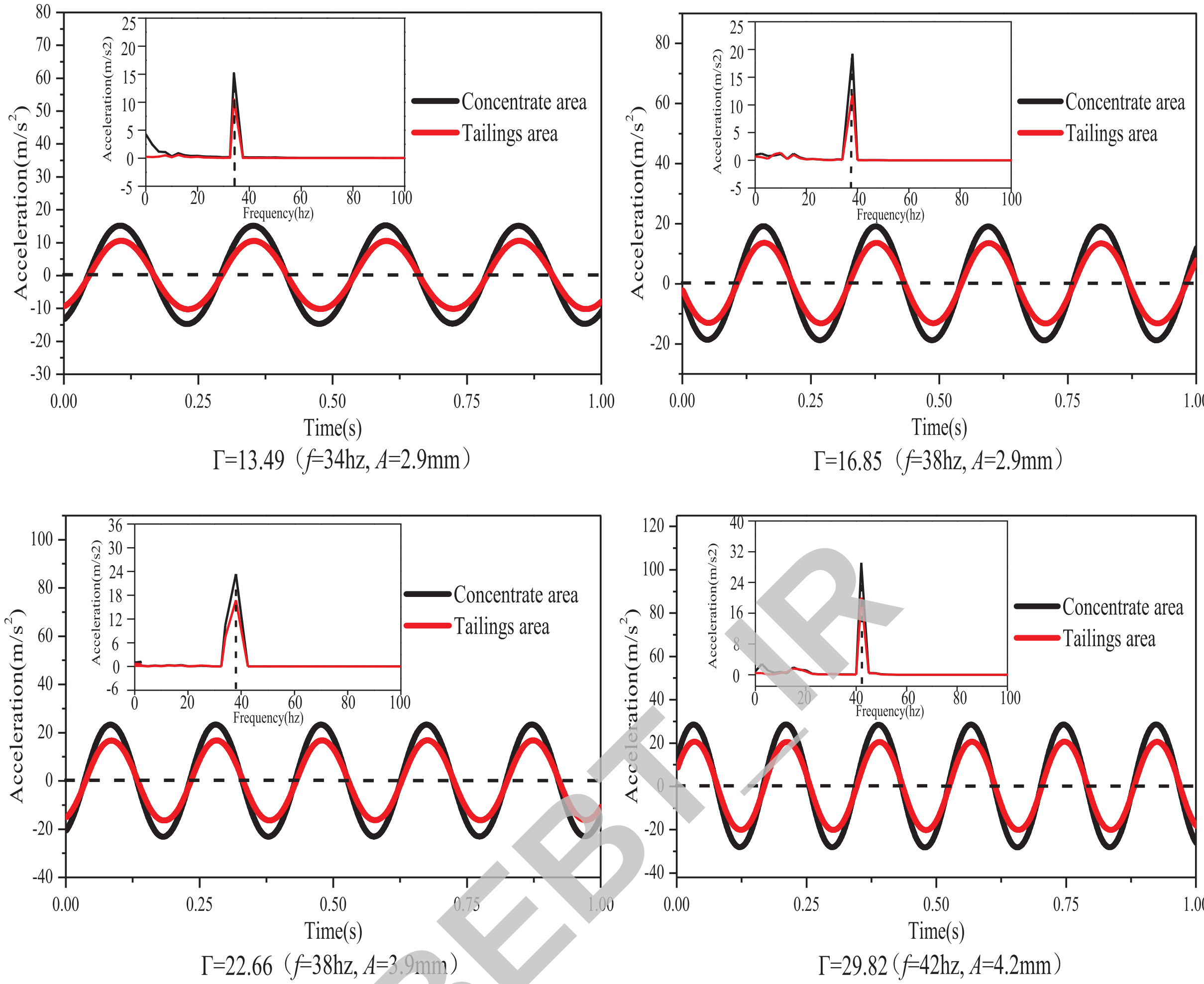

Fig. 9. Influence of Vibration on Bed Surface Acceleration.

A = 2.9 mm, Γ = 13.49, the maximum vibration acceleration of the concentrate and tailings area is 15.12 m/s^2 and 10.08 m/s^2, respectively. The separation bed is a trapezoid structure, and when the vibration energy is transmitted to the bed surface, more vibration energy is obtained in the concentrate area due to the effective separation area of concentrate is larger than that of tailings. As a result, the vibration acceleration obtained in the concentrate area is also greater than that in the tailings area. When fixed vibration amplitude, the bed acceleration increases with increasing frequency. When f = 38 Hz, A = 2.9 mm, Γ = 16.85, the maximum vibration acceleration of concentrate and tailings area are 19.87 m/s^2 and 14.38 m/s^2, respectively. Indicating that the bed acceleration increases with the increase of frequency, and the acceleration of concentrate is 38.18% higher than that of tailings area. When the vibration frequency is stable, the bed acceleration increases as the vibration amplitude increases. At f = 38 Hz, A = 3.9 mm, Γ = 22.66, the maximum vibration acceleration of concentrate area is 24.78 m/s^2, which is 38.51% higher than that of tailings area of 17.89 m/s^2. When the vibration amplitude is 4.2 mm and frequency is 42 Hz, the maximum acceleration of the bed in concentrate and tailings area are 29.8 m/s^2 and 21.2 m/s^2, respectively. Which shows that the bed vibration acceleration in concentrates and tailings area increases with the increase of the vibration intensity, and the maximum vibration acceleration of the concentrate is 40.57% higher than that of tailings area. In general, the vibration acceleration of the concentrate area is significantly higher than that of the tailing area. The energy of the concentrate area is greater, which is the main separation area. The tailings area mainly plays the role of material transport, separating function as a supplement.

3.3. Effects of the vibration on the separation

3.3.1. Effects of the vibration intensity on the separation

The separation process of the compound dry cleaning apparatus depends on density and also on the oil content. Stability of the oil content of material in different parts of the bed is key to maintaining separation. The oil content distribution of material on the bed can directly indicate material movement and separation effects at a particular point in time. This section examines the effect of vibration intensity on the oil content of the bed material. The result is shown in Fig. 10.

Fig. 10 shows the oil content distribution on the bed of the different separation area with respect to the vibration intensity, together with the corresponding contour maps. The color represent oil content. When the amplitude and frequency are small, the vibration intensity of the bed is smaller. These particles on the surface of the bed could not obtain enough energy to become activated. The energy transfer between particles is poor, the material distribution on the surface of the bed was uneven, particularly within 5–30 cm range along the X-axis and 0–25 cm and 40–50 cm along the Y-axis, and within 45–65 cm along the X-axis and 25–30 cm along the Y-axis, indicating that the spatial distribution of the oil content on the bed surface fluctuates greatly, oil content distribution being messy, most of the high oil content of the material is mainly concentrated in the back plate area and can not be discharged from the discharge end, producing poor separation results. With increasing frequency and amplitude, the vibration intensity increased, the energy of particle increases gradually, movement speed of material with different density is different, the formation of orderly trajectory, the looseness of the entire bed gradually increases as a result

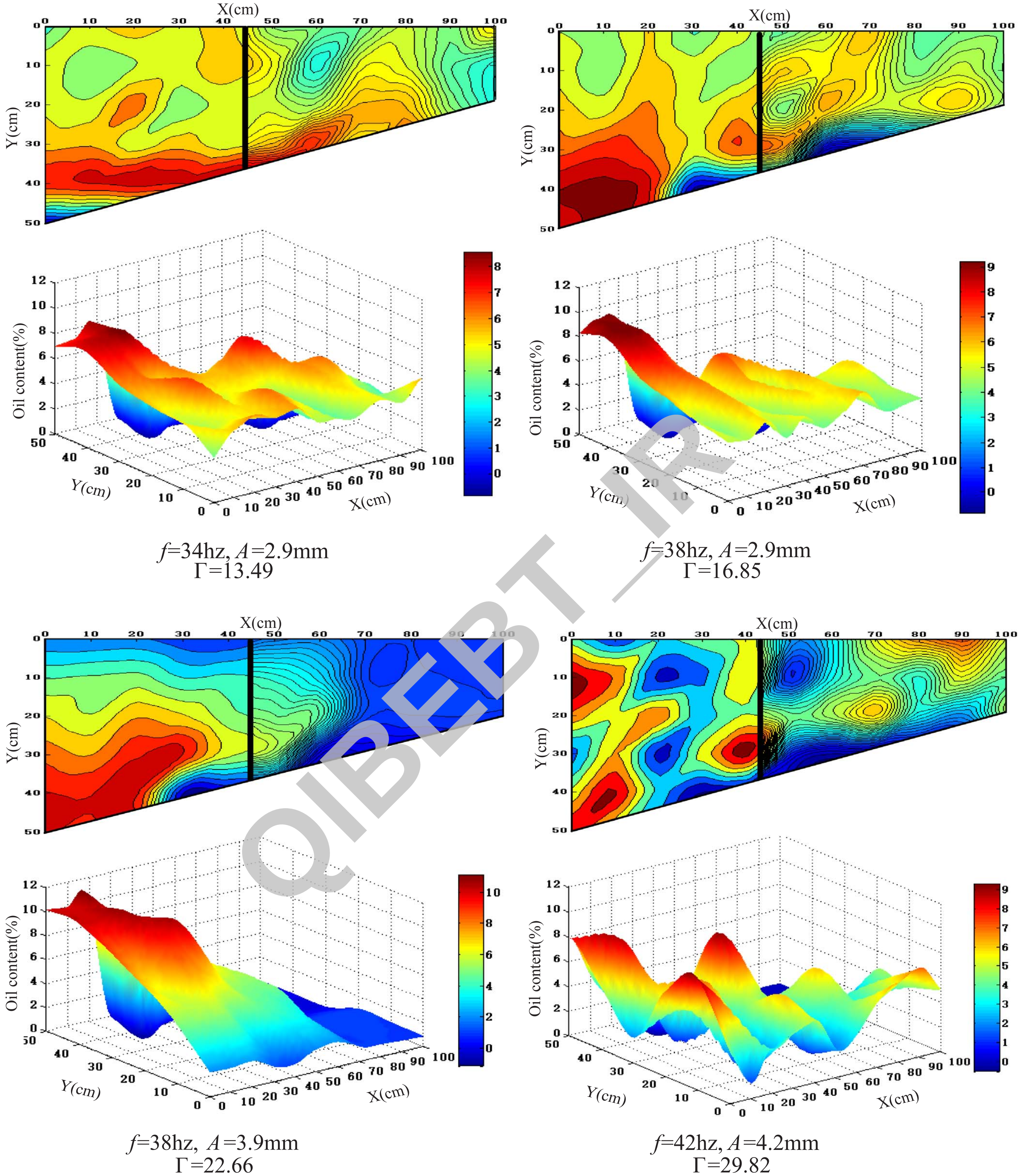

Fig. 10. Influence of Amplitude and Frequency on Sorting Effect.

of the transfer of vibration energy to inter-particles, the distribution of bed oil content gradually become obvious and the fluctuation of oil content spatial distribution is weakened. Oil content distribution was most notable at f = 38hz, A = 3.9 mm, Γ = 22.66; at this vibration intensity, the oil content of bed material gradually decreased along the X-axis while increasing along the Y-axis, high oil content material are mainly concentrated in the discharge side area, low oil content materials are mainly concentrated in the back plate and gangue area, indicating optimal separation, the bed material layer could achieve fully loose, with materials entirely divided according to density. With continued increase in vibration intensity to 29.82 (f = 42hz, A = 4.2 mm), the oil content distribution on the surface of the bed was uneven, particularly within 0–30 cm range along the X-axis and 0–20 cm and 30–50 cm along the Y-axis. The excessive vibration energy

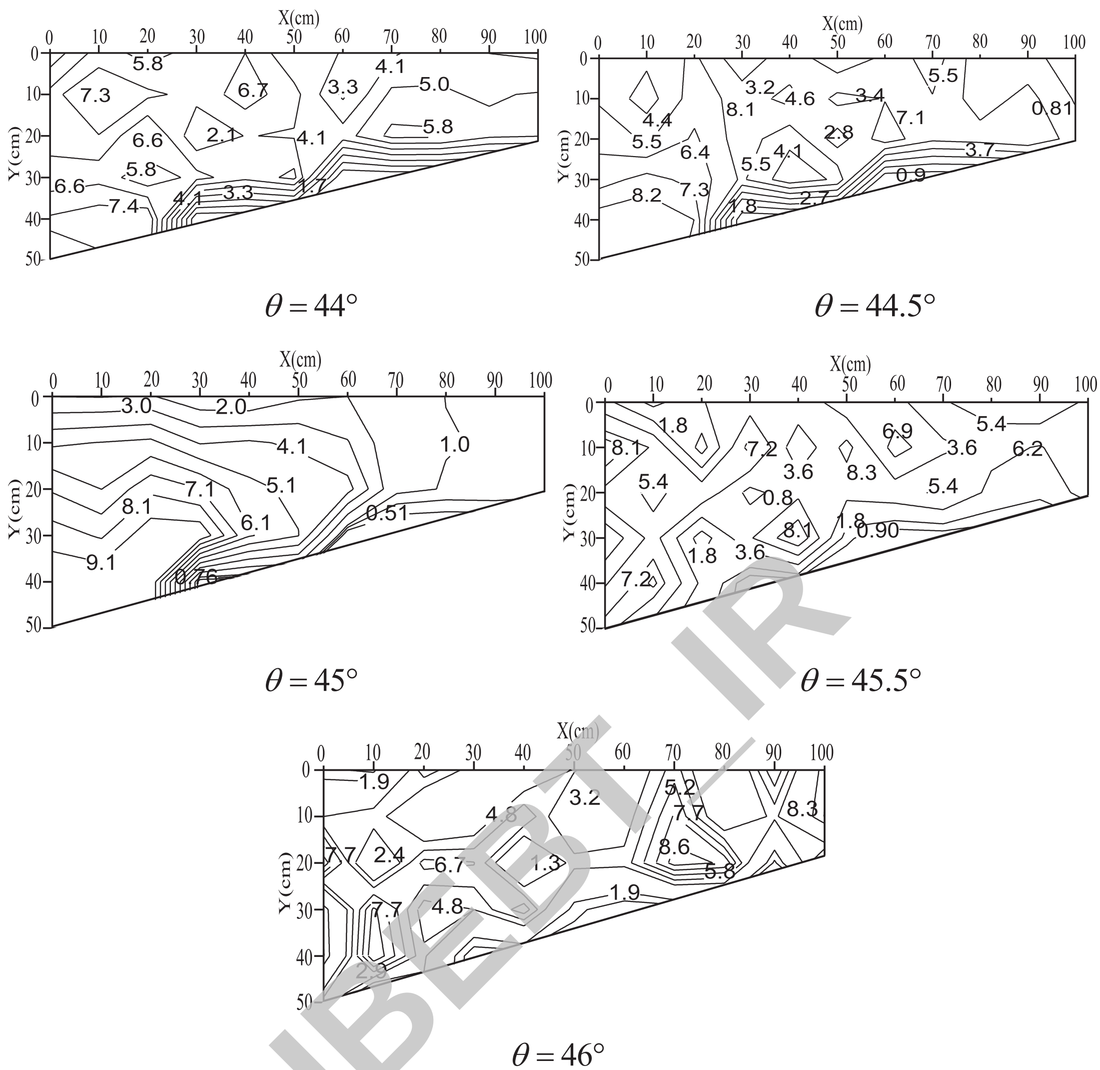

Fig. 11. Influence of vibration angle on sorting effect.

led to undesirable activity of materials within the bed, the particle gap is too large, the particle collision force is too strong, resulting in the distance of particle of different density is too large. This leads to intense back-mixing of the particles.

3.3.2. Effects of the VDA on the separation

The VDA of the bed can be changed by adjusting the angle between the backboard and the bed, thereby changing the force conditions for the bed material and achieving a different separation efficiency. The effects of the VDA on the separation are shown in Fig. 11 for an amplitude of 3.9 mm, a wind speed of 2.46 m/s, and a frequency of 38 Hz.

Fig. 11 shows the oil content distribution on the bed with respect to the vibration angle, when the VDA is small, the distribution of oil content was uneven, The distribution of oil content on the bed is especially uneven in the region from 5 to 15 cm, 25 to 30 cm along the Y axis and from10 to 30 cm, 80 to 90 cm along the X axis, this indicates that the vibrational energy is smaller at this time, and the particles on the bed is intensive, could not achieve fully loose, the particles can not be stratified by density. Material distribution is disorder and high oil content material is concentrated in the back plate area and discharge end area. As the VDA is gradually increased, the forces on the particles in the Z-axis direction increase, which promotes the activity of the particles of the bed, the vibration energy of the particles, the energy transfer among particles, and the looseness of the separation bed, and the material is gradually stratified by density. when the VDA is 45°, the oil content of bed material gradually decreased along the X-axis while increasing along the Y-axis, the high oil content material concentrated in the discharge end, low oil content materials concentrated in the back plate and tailings area, indicating optimal separation, the bed material layer could achieve fully loose, with materials entirely divided according to density. The forces on the particles in the Z-axis direction become small with a further increase in the VDA, which leads to deterioration in the particle activity, and the energy transfer among particles weakens. Then, the material cannot be efficiently stratified by the density, and random motion is apparent, which further deteriorates the separation efficiency.

3.3.3. Determination of the optimal vibration parameters

The effects of the frequency, amplitude, and VDA on the oil shale separation using the compound dry separator by single-factor experiments have been discussed in previous sections to study the significance of these parameters on the separation and the interaction of parameters. To determine the optimal operating parameters, a response surface method is utilized for the analysis of probable error *E*. The relation between the probable error *E* and parameters is studied. The experimental designs for the response surface method and model analysis are summarized in Tables 3 and 4.

As deduced from Table 4, the quadratic polynomial model is recommended. The Prob > F values are considerably less than 0.5, suggesting that the response surface model has a greater fitting

Table 3
Basic operation parameters in the separation experiments.

Code	Factors	Unit	Minimum	Maximum	Level
A	Amplitude	mm	3.0	4.2	3
B	Frequency	Hz	30	42	3
C	Angle	°	44	46	3

accuracy. The results of an analysis of variance for the recommended quadratic polynomial model are summarized in Table 5.

Table 5 indicates that the F value of the quadratic polynomial model is 148.06, which indicates that the effects of combinations of factors on the segregation intensity are significant. The Prob > F values for the investigated items A, AB, Prob A2, B2, C2 are < 0.05, which indicates that the items have a marginal impact on the segregation intensity. Further, the values of R2, corrected R2, and the deviation coefficient are 0.9948, 0.9881, and 0.9164 respectively. They indicate that the recommended model has high credibility.

The response surface for the effects of the vibration Amplitude, frequency and vibration angle on the probable *E* is shown in Fig. 12. In addition, the contours for different operating conditions are shown.

The response surface is very steep in the amplitude-axis direction, as shown in Fig. 12(I), The results show that the variation of vibration amplitude has a great influence on the probable error E in a compound dry separator. The *E* values decreases to a minimum and then increases as the amplitude increases, and the peak probable error *E* is achieved when the amplitude and frequency are 3.9 mm and 38 Hz, respectively. In contrast, the corresponding operating frequency has little influence on the probable error, because the response surface shape is gentler along with the variation direction of frequency. The effect of the amplitude on the probable error (*E*) is more sensitive than that of the frequency, as concluded above. The vibration intensity affects the probable error (E) more significantly than the VDA as illustrated in Fig. 12(II). The response surface shape is gentler along with the variation direction of the VDA, the probable error is mainly influenced by vibration intensity. The minimum probable error (*E*) is achieved at an amplitude of 3.9 mm and a VDA of 45°. The response surface similarly varies in the VDA and frequency directions, the response surface changes more gentle along the VDA and frequency direction with no obvious steep changes, which illustrates that the effects of the frequency and VDA on the probable error (*E*) are comparable in Fig. 12 (III). However, the response surface has a greater concavity in the frequency-axis direction than in the VDA-axis direction, the response surface changes more gentle along the VDA-axis direction, which indicates that the effect of the frequency on the probable error (*E*) is more significant.

The mathematical model for the probable error (E) is determined by a regression analysis. The influence of the parameters on the probable error (E) is vibration intensity, frequency, angle from big to small. The mathematical models are expressed in Eqs. (2) and (3).

Mathematical model in terms of factors of codes:

$$E = 0.14 - 3.25\times10^{-3}A + 2.5\times10^{-3}B - 1.75\times10^{-3}C + 5\times10^{-3}AB - 3.5\times10^{-3}AC + 0.062A^2 + 0.018B^2 + 6.75\times10^{-3}C^2 \quad (2)$$

where A is the amplitude (mm), B is the frequency (Hz), and C is the vibration angle (°).

Mathematical model in terms of actual operational factors:

$$E = 14.76 - 0.49A - 0.02f - 0.59\theta + 7.81\times10^{-4}Af - 4.38\times10^{-3}A\theta + 0.1A^2 + 2.85\times10^{-4}f^2 + 6.75\times10^{-3}\theta^2 \quad (3)$$

where *A* is the amplitude (mm), *f* is the frequency (Hz), and *θ* is the vibration angle (°).

3.3.4. Separation results

The effects of the vibration parameters of the compound dry separator on the cleaning of oil shale were systematically studied. A separation test for 50–0 mm oil shale using the compound dry separator was conducted using the optimized operation conditions (A = 38hz, f = 3.9 mm, θ = 45°). The oil content of raw ore is 4.48%. The yields of the concentrate and tailing are 34.63% and 65.37%, respectively.

Table 4
Models comparison and selection.

Source	Sum of squares	df	Mean square	*F* Value	*P*-value prob > *F*	
Mean vs Total	0.56	1	0.56			
Linear vs Mean	1.590E − 004	3	5.300E − 005	0.037	.9902	
2FI vs Linear	1.490E − 004	3	4.967E − 005	0.027	.9937	
Quadratic vs 2FI	0.019	3	6.179E − 003	436.91	< .0001	Suggested
Cubic vs Quadratic	9.900E − 005	3	3.300E − 005	6.366E + 007	< .0001	Aliased
Residual	0.000	4	0.000			
Total	0.57	17	0.034			

Table 5
Variance analysis of quadratic model.

Source	Sum of squares	df	Mean square	*F* Value	prob > *F*	
Model	0.019	9	2.094E − 003	148.06	< .0001	Significant
A-Amplitude	8.450E − 005	1	8.450E − 005	5.97	.0445	
B-Frequency	5.000E − 005	1	5.000E − 005	3.54	.1021	
C-Angle	2.450E − 005	1	2.450E − 005	1.73	.2296	
AB	1.000E − 004	1	1.000E − 004	7.07	.0325	
AC	4.900E − 005	1	4.900E − 005	3.46	.1050	
BC	0.000	1	0.000	0.000	1.000	
A^2	0.016	1	0.016	1135.20	< .0001	
B^2	1.402E − 003	1	1.402E − 003	99.16	< .0001	
C^2	1.918E − 004	1	1.918E − 004	13.56	.0078	
Residual	9.900E − 005	7	1.414E − 005			
Lack of fit	9.900E − 005	3	3.300E − 005			
Pure error	0.000	4	0.000			
Cor total	0.019	16				

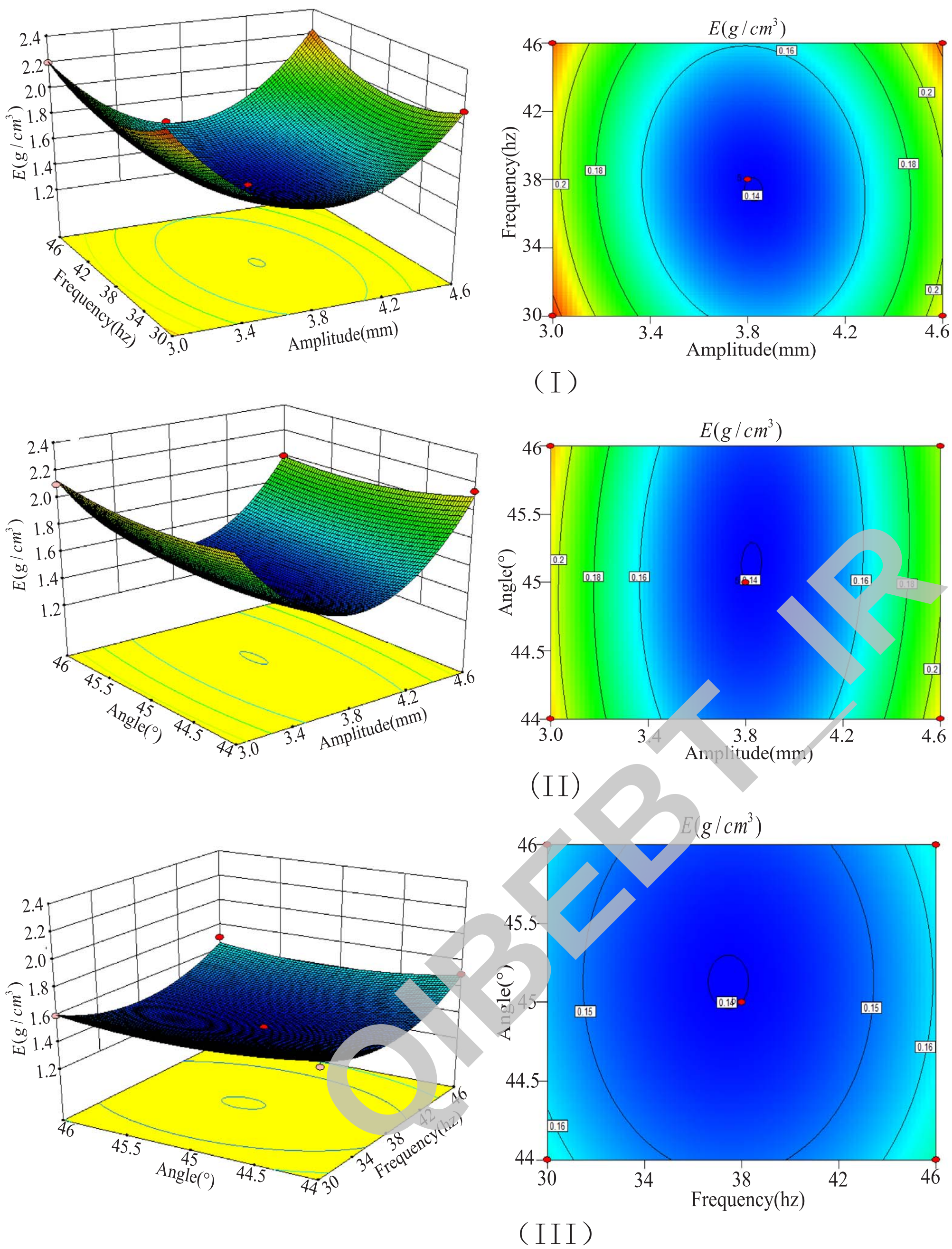

Fig. 12. Effects of the vibration factors on the separation.

Further, the oil contents of the concentrate and tailings are 11.03% and 1.01%, respectively. The partition coefficients and curve are presented in Table 6 and Fig. 13. The cleaning oil shale (ω > 10%) separated by the dry separating process was carbonized at high temperatures (500 °C) and the kerogen was decomposed to generate shale oil, which could be further refined into cheaper and higher quality gasoline and diesel than those refined oil shale(ω < 10%). The gangue is mainly used as the building material.

4. Conclusions

The effects of the vibration amplitude, frequency, and angle on the compound dry separation of oil shale were analyzed. The material distribution in the separation bed and the bed acceleration were also studied. .The law of force between particles in different sorting areas and the effects of amplitude, frequency and angle of vibration on the energy law of different sorting area are systematically analyzed, The optimum operation parameters were obtained, and the sorting test was carried out. The conclusions were drawn as follows:

1) In the process of separating oil shale using a compound dry separator, when the vibration amplitude is 3.8–4.0 mm and the frequency is 38–39 hz, the inter-particle force in the concentrate area and the tailings area is distributing most uniformly, with the smallest fluctuation. At this time, the peak values of the inter-particle force in the concentrate area and the tailings area are 8.24 mN, 10.57 mN and 12.34 mN, 8.13 mN, respectively.
2) The vibration acceleration of the concentration area and the tailings area increases with the increase of amplitude and frequency. The acceleration in the concentrate and tailings areas are 24.78 m/s^2,17.89 m/s^2, respectively. The acceleration in the concentrate area increases by 38.51% compared with the acceleration in the tailings area, which indicates that particles in the concentrate area absorb more vibrational energy, and it is the main separation area. The

Table 6
Partition coefficient results for 50-0 mm oil shale beneficiated using compound dry separator.

Density (g/cm^3)	Average density (g/cm^3)	Feedstock sink-float result (%)	Tailings sink-float results (%)		Concentrate sink-float results (%)		Calculated feedstock sink-float results (%)	Partition coefficient (%)
−1.9	1.75	16.12	1.19	0.78	44.27	15.33	16.11	4.84
1.9–2.0	1.95	4.56	0.43	0.28	12.39	4.29	4.57	6.13
2.0–2.1	2.05	3.08	0.61	0.4	7.68	2.66	3.06	13.07
2.1–2.2	2.15	2.12	0.70	0.46	4.85	1.68	2.14	21.50
2.2–2.3	2.25	6.12	3.66	2.39	10.80	3.74	6.13	38.99
2.3–2.5	2.4	4.49	4.62	3.02	4.22	1.46	4.48	67.41
+2.5	2.6	63.51	88.79	58.04	15.80	5.47	63.51	91.39
Total		100.00	100.00	65.37	100.00	34.63	100.00	

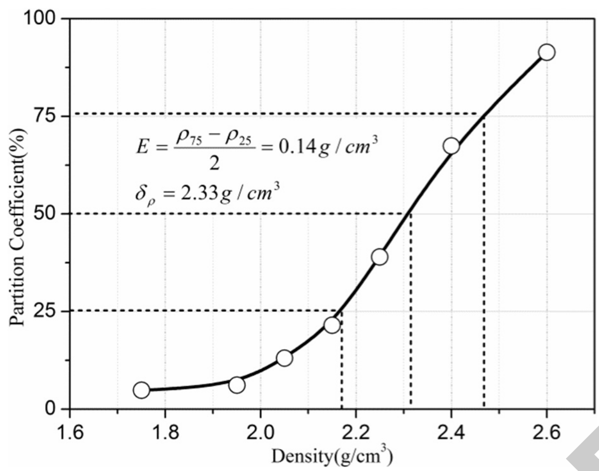

Fig. 13. Partition curves for compound dry separator beneficiation.

tailings area is mainly used for discharging tailings.

3) The significant sequence for the effects of the vibration parameters on the segregation intensity is obtained as follows: Amplitude > Angle > Frequency. The 50–0 mm oil shale is cleaned by a compound dry separator using the optimal parameters. The yields of the concentrate and tailings are 34.63% and 65.37%, respectively. The oil content of the concentrate and tailings are 11.03% and 1.01%, respectively. The actual separation density is 2.33 g/cm^3,and the probable error (E) is 0.14 g/cm^3.
4) The compound dry separator can effectively beneficiate 50–0 mm oil shale. The oil shale can be recycled and utilized efficiently.

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