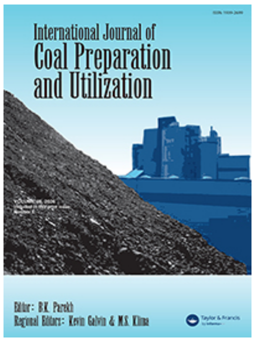

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Determining the optimal duration of effective sieving time based on sieve characteristic of coal particle

Peizhuang Han[a,b*], Xiaodong Lu[a,b*], Qingquan Liu[a,b,c], Kunsang Lee[d], Liang Wang[a,b], and Yuanping Cheng[a,b]

[a]Key Laboratory of Gas and Fire Control for Coal Mines, China University of Mining and Technology, Xuzhou, China; [b]State Key Laboratory of Coal Mine Disaster Prevention and Control, China University of Mining and Technology, Xuzhou, China; [c]Geotechnical Institute, TU Bergakademie Freiberg, Freiberg, Germany; [d]Department of Earth Resources and Environmental Engineering, Hanyang University, Seoul, South Korea

ABSTRACT

Sieving is a continuous process for obtaining particles of specific sizes. In engineering and scientific research, it is important to determine the optimal duration of sieving time. The paper investigates the effects of three factors – rotation speed, added mass, and sieve size – on sieving productivity through 57 experimental groups. Once the rotation speed reaches a certain level, the effective sieving time stabilizes. The effective sieving time for speeds above level 6 is almost identical to that for level 6, which is approximately 3 minutes. The effective sieving time increases with the rise in added mass at the fourth level of speed. However, as the rotation speed increases beyond the fourth level, the impact of added mass on the effective sieving time diminishes. Specifically, at the sixth level of speed, the effective sieving time under different added masses remains approximately 4 minutes. At the sixth level of speed, a smaller sieve size results in a longer effective sieving time. Additionally, as the feed mass increases, the difference in time becomes more pronounced. The results of this study contribute valuable insights into the evaluation of effective sieving time under different working conditions.

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Coal particle; sieving productivity; effective sieving time; rotation speed; adding mass; sieve size

Introduction

Coal particles are widely employed in experiments associated with basic parameters of coal, such as coal industry analysis (Y. Zhang et al. 2017), firmness coefficients, adsorption constants (H. Jiang, Xu, and Cheng 2021; Yang and Saunders 1985; W. Zhao et al. 2014), and others (L. Wang et al. 2020). To mitigate the effect of particle size, sieving coal samples into specific particle sizes is required for conducting various experiments (T. Li and Wu 2021; Yuan et al. 2010; L. Zhang et al. 2014). Typically, coal samples are obtained by crushing, resulting in composite particle sizes. Consequently, these samples often fail to meet the requirements for a specific particle size range, necessitating the sieving of coal samples. Additionally, coal is classified as a weak rock. During the screening process, small coal particles (such as pulverous particles) may emerge. Moreover, the softer the coal, the

CONTACT Qingquan Liu cumtsafe@cumt.edu.cn Key Laboratory of Gas and Fire Control for Coal Mines, China University of Mining and Technology, No. 1 Daxue Road, Tongshan District, Xuzhou 221116, China; Kunsang Lee kunslee@hanyang.ac.kr Department of Earth Resources and Environmental Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, South Korea

*Peizhuang Han and Xiaodong Lu contribute equally to the article.

powdery debris is produced during screening. Softer coal is broken down into powdery coal more severely with slightly longer screening times. While sieving time may not be an intuitive factor, its influence manifests through the effects of other contributing factors during the sieving process.

Particle sieving is a dynamic and continuous process that employs one or more screen meshes to separate particles into two or more size ranges. The objective of sieving is to obtain particles within a specific size range. Several factors influence the results of sieving, including vibration frequency (Huang et al. 2014; Ning et al. 2023), the type and size of the screen (Xie et al. 2022), and the moisture and mass of the material (Ke et al. 2021; Shanmugam et al. 2022; Zhu 2017). Sieving is widely utilized in various industries, such as metallurgy (H. Jiang et al. 2023; Q. Liu et al. 2020), pharmaceuticals (Hulko et al. 2018; Pruteanu et al. 2018), construction (Ge et al. 2011), materials (Popławski and Lelusz 2023), and agriculture (Chinedu and Isaiah 2016; Sugita and Marumo 2001). Although each industry employs distinct sieving methods, these methods may not be fully applicable in other fields due to differences in material properties. The effects of identical factors on sieving are not consistently uniform. For instance, Y. Zhao, Jiang, and Zheng (2009) suggests that in the vibration bed separation process, optimal separation efficiency occurs at a vibration frequency of 60 hz and an amplitude of 0.6 cm; deviations from this frequency range result in diminished separation efficiency. H. Liu et al. (2022) demonstrates that in the vibration sieving of drilling fluids, the number of particles passing through the sieve increases within a certain range as vibration frequency rises. However, once the frequency exceeds 60 hz, further increments do not enhance the passage rate (the number of particles passing through the sieve). In a study of a swing screen surface, Q. Li and Xiao (2015) revealed that particles of different sizes have distinct optimal vibration frequencies. For small particles with diameters of 0.5 and 0.6 mm, the optimal frequency is approximately 60 hz; for larger particles with diameters of 0.7, 0.8, and 0.9 mm, the optimal frequency is around 30 hz. Exceeding these optimal frequencies results in a reduction in sieving efficiency for both small and large particles. Using a model of a multi-layer banana screen, Dong, Yu, and Brake (2009) simulated that reducing vibration frequency and amplitude enhances sieving efficiency. Chen, Yao, and Liu (2019) utilized a circular rotary vibrating screen to conclude that sieving efficiency initially increases and then decreases with an increase in bed thickness (mass of particles), with the optimum bed thickness being 12 mm. The conclusions of the above studies primarily indicate the results at specific moments.

From the mentioned research, the conclusions of the aforementioned studies predominantly indicate the results of the metrics at specific time points. It can be inferred that these conclusions are at least valid in terms of time. In a sense, the significance of guidance on sieving is insufficient. While these studies provide insights into selecting appropriate vibration frequency, screen angle, and feeding rate during sieving, they do not specify when certain sieving effects can be achieved.

Some researchers have also turned their attention to the role of time. Akbar J. Nezhad suggests that an increase in vibration frequency can lead to screen wear and emphasizes the need to avoid excessively prolonged sieving times, which may result in both screen and particle wear (Jafari and Nezhad 2016). Nan Ning, in a study on the relationship between sieving time and mass added, demonstrates that the minimum sieving time varies with different masses. If the sieving time during testing is less than the minimum, it may lead to highly unreliable results (Nan et al. 2016). Insufficient sieving time leads to poor sieving outcomes, such as low sieving efficiency. However, the effect of excessive sieving time is often overlooked or challenging to observe. Consequently, in practical sieving, if the impact of sieve time under specific conditions is uncertain, the choice is often made to prolong the sieving time to ensure better results. However, this approach is considered undesirable for rigorous research purposes.

The role of different factors may change due to variations in sieving time. Understanding the pattern of other factors in relation to changes in sieving time can directly guide the actual sieving tests. Both excessive and insufficient sieving times can significantly impact the sieving results. The effective sieving time varies under different conditions. This paper focuses on determining the appropriate sieving time while achieving specified sieving efficiency. The sieving of coal particles is used as an example to investigate the issue of sieving time under different working conditions in the laboratory.

Materials and methods

Samples and apparatus

The coal sample for this experiment was collected from the 7228 working face of the Qinan Coal Mine in Huainan, Anhui Province, China. The parameters of the coal sample are presented in Table 1.

The particle screening test instrument consists of an MVS-1N electromagnetic vibrating screen, a balance, and several sample bags (see Fig. 1). The electromagnetic vibrating screen, shown in Fig. 1(a), mainly comprises isolation springs, electromagnetic exciters, screen

Table 1. Coal sample parameter table.

Parameter	Value
Water content M_{ad}/%	1.35
Ash content A_d/%	8.91
Volatile matter V_{daf}/%	35.72
Fixed carbon FC_{ad}/%	57.76
Robustness coefficient/1	0.3016
Density/(kg/m^3)	1310
Adsorption constant a/(m^3/t)	19.68
Adsorption constant b/MPa^{-1}	1.13
Coal grade	Bituminous coal
Grindability Index (HGI)	39
Abrasion (AI)	17
Mirror rental reflectivity Ro/%	0.77

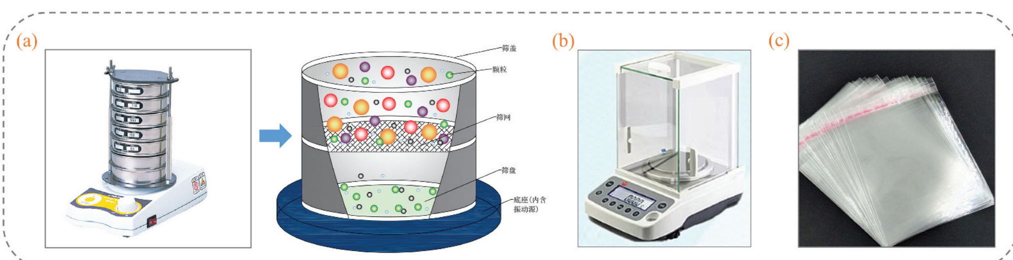

Figure 1. Sieving schematic and sieve equipment.

Table 2. Actual distribution values for different speed levels.

Speed level	1	2	3	4	5	6	7	8	9	10
Rotation speed/rpm	960	1020	1100	1220	1350	1590	1780	1950	2100	2340

mesh, and the screen frame. The vibration source is the electromagnetic exciter, which operates at a speed of 1000–2500 rpm. The specific configuration values are provided in Table 2. The rotational speed refers to the number of times the same motion returns to the same position within a given time period. The fixed vibration amplitude is approximately 4.5 mm in the lower section and about 1.5 mm in the upper section, with horizontal rotation as the working mode. The electromagnetic vibrating screen achieves efficient material classification by combining a rotating screen mesh with auxiliary vibrations to facilitate the rotation of the screening instrument. The screening process effectively utilizes factors such as particle size differences, sieve aperture, centrifugal force, gravity, and material vibration, which help reduce material adhesion and blockage, enhance screening efficiency, and accommodate the screening requirements of materials with varying particle size distributions. This system is characterized by its simple structure, ease of operation, and broad applicability.

The measurement range of the balance shown in Fig. 1(b) is 0 to 100 g, with a measurement accuracy of 0.001 g. It is important to note that the balance has an inherent systematic error of ± 0.001 g. During measurement, the mass of the empty sample bag, as shown in Fig. 1(c), is first recorded. Then, the sieved coal particles are placed into the sample bag, and the balance is used to measure the total mass of the sample bag and coal particles. The mass of the coal particles is obtained by subtracting the mass of the empty sample bag from the total mass of the sample bag and coal particles. However, due to the balance's systematic error of ± 0.001 g, this uncertainty should be accounted for when calculating the mass of the coal particles, ensuring the accuracy of the measurements.

Sieving experiment scheme

To prevent the effects of moisture on sieve blockage (M. Wang, Liu, and Shen 2020), the coal particles were placed in a drying oven for 8 hours before the experiment and allowed to reach an air-dried state for later use. The test sieve was found to accommodate up to 60 g of coal particles. Four different feeding ratios, M_1, M_2, M_3, and M_4, were designed (as shown in Fig. 2) to study their effects on screening. The maximum dosage is M_4, accounting for 66.7%. The dosage was not increased further because, in the experiment, the particles rarely filled the entire sieve. If the sieve were filled, the particles would have no space for movement in their initial state. Additionally, further increases in dosage would lead to sample loss during the opening and closing of the sieve cover, which would significantly affect the accuracy of the experiment. The sieve sizes used in this experiment are 1.4, 0.5, 0.3, and 0.1 mm, as shown in Fig. 3. Among them, the 0.5 mm, 0.3 mm, and 0.1 mm sieves are experimental sieves, while the 1.4 mm sieve is primarily used for coarse screening (pre-screening).

The specific experimental procedure is as follows:

(1) First, pre-screen the dried coal sample.
(2) Add pre-screened coal particles in varying dosages for further screening.

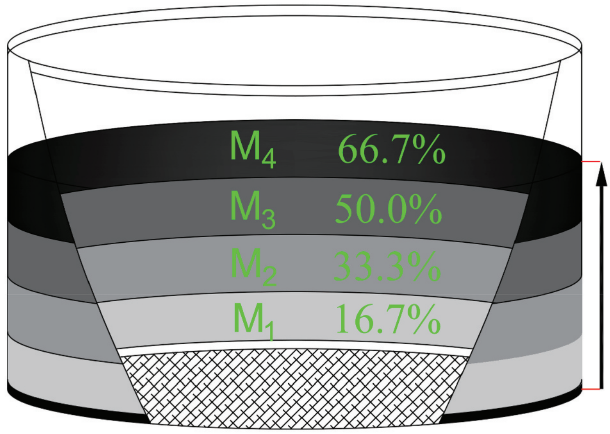

Figure 2. Ratio of adding mass.

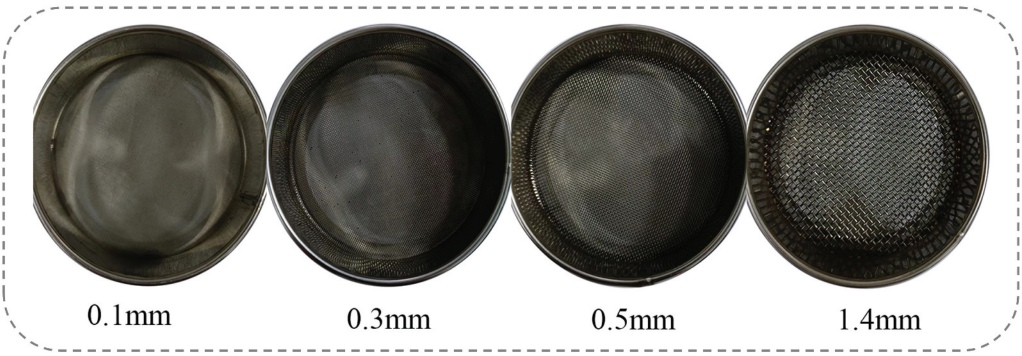

Figure 3. Standard sieve.

Different sieve sizes are used for screening, and the mass of coal particles of different sizes is measured after screening at varying speeds and durations. Data are then recorded.

During the experiment, external factors such as environmental temperature were strictly controlled. Both single-factor and orthogonal experiments were designed to investigate the effects of rotational speed, dosage, and sieve size on screening. The detailed experimental plan is shown in Table 3. Initially, the mesh size and dosage were kept constant to examine the effect of different rotational speeds on screening. Subsequently, an orthogonal experiment was conducted to assess the impact of varying dosages on screening at rotational speeds of the 4th, 5th, and 6th levels, with a total of 12 experiments. Further orthogonal experiments were performed to study the effects of three different sieve specifications and four different dosages on screening, considering sieve specifications, dosage, and rotational speed at rotational speeds of levels 4, 5, and 6. A total of 36 experiments were conducted in this phase.

Table 3. Experimental contents.

Factors	Sets	Sieve size adopted/mm	Adding mass	Rotation speed adopted	Test moment/min
Rotation speed	9	0.5	M_3	1	0.5、1、1.5、2、3、4、5、7、9、12、15、20、25、30、40、50、60
				2	
				3	
				4	
				5	
				6	
				7	
				8	
				10	
Adding mass	12	0.5	M_1	4/5/6	
			M_2		
			M_3		
			M_4		
Sieve size	36	0.1	$M_1/M_2/M_3/M_4$	4/5/6	
		0.3			
		0.5			

Metrics of sieve performance

Sieving is the process of separating materials based on particle size, with the ultimate goal of isolating particles that meet specific size requirements. The quality of sieving not only affects the particle size distribution of the material itself but also impacts the accuracy of particle size measurements in other experiments (X. Jiang, Li, and Qiu 1999; Y. Li, Zheng, and Wang 2013). An ideal sieving process allows particles smaller than the size of the sieve aperture to pass through entirely, while particles larger than the sieve aperture remain above it. However, in practical engineering or laboratory settings, sieving is influenced by factors such as material properties, testing environment, human operation, and the inherent characteristics of the sieving machine, which makes achieving ideal sieving results challenging or even impossible.

In actual sieving, as the sieving progresses, the mass of material passing through the sieve tends to plateau, resulting in only a marginal increase despite an extended sieving time. Previous studies often employed sieving efficiency as a singular evaluation metric, which provides a good reflection of overall sieving effectiveness but neglects to describe the sieving processing capacity. This capacity is assessed through the average sieving rate over time. Therefore, this study employs both sieving efficiency and average sieving rate as performance indicators for a comprehensive evaluation of sieving effectiveness.

Sieve efficiency refers to the ratio of the actual mass of undersized particles obtained during the sieving process to the mass of the initial feed material with particle sizes smaller than the sieve aperture size. In conventional sieving operations, the process often involves multiple sieves. Therefore, the efficiency of the sieve layer is influenced not only by the particles passing through the layer itself but also by those passing through the layers above. To specifically investigate the variation in sieve efficiency, this study adopts a single-layer sieving approach.

Based on the definition of sieve efficiency proposed by the former author (L. Zhao et al. 2010), the concept of dynamic sieve efficiency is introduced. Dynamic sieve efficiency accounts for the variation in sieve efficiency over time during the sieving process. Its value can be determined using the following Equation (1).

$$\eta_t = \frac{B_t}{A} \times 100\% = \frac{B_t}{Q\frac{\alpha}{100}} \times 100\% \tag{1}$$

Where η_t stands for sieve efficiency at moment t. B_t is the mass of undersized particles obtained at t moment. A is the mass of particles in the initial feed smaller than the sieve aperture size. Q is the initial feed mass. α is the percentage of particles in the initial feed smaller than the sieve aperture size.

When the sieving efficiency is relatively high, it is essential to further consider the effective sieving time determined by the average sieving rate (when the sieving efficiency is excessively low, the significance of contemplating the average sieving rate becomes limited). Generally, the sieving capacity can be quantified by the sieving throughput. The more particles sieved in a certain time means that sieve capacity is good. This study employs the average sieving rate to characterize the sieving throughput, representing the mass of particles permeating the sieve per unit time. This parameter serves as a metric for evaluating the sieving process and is denoted by Equation (2).

$$\overline{v} = \frac{\Delta B}{\Delta t} \tag{2}$$

Where $\overline{v}$ represents the average sieving rate. ΔB denotes the mass difference between the measured point and the preceding point in the material passing through the sieve. Δt signifies the time interval between the current and the preceding point.

Equation (2) represents the mass permeating the sieve per unit time under a fixed initial feed mass. The mass of particles above the sieve decreases gradually with sieving time, leading to an increase in sieving efficiency. When the average sieving rate does not exceed V_{Te} ($V_{Te} = 1\% * A$), the corresponding time (Diao 2015) is referred to as the effective sieving time, Te. The effective sieving time ensures optimal particle loosening and stratification on the sieve surface within the shortest duration, followed by effective passage through the sieve. Prolonging the sieving time beyond this point may pose risks such as particle abrasion and the potential for larger particles to permeate the sieve. Excessive sieving can distort the results of particle size distribution testing (C. Wang et al. 2020), directly impacting the analytical outcomes.

Sieve efficiency and average sieving rate, as two pivotal performance indicators for the vibrating sieve in this experiment, provide a comprehensive evaluation of sieving effectiveness from different perspectives. Sieving is a dynamic process, and insufficient sieving time can result in incomplete separation of the sample, leading to a reduction in particle content within the target size range. Conversely, excessive sieving time may induce sample wear (Gupta, Fuerstenau, and Mika 1975), contributing to an increased presence of finer particles in the undersize fraction. It is crucial to avoid a singular pursuit of ultimate sieving efficiency, as this may lead to an extended sieving duration. Striking a balance enables the achievement of high sieving efficiency while minimizing the time required for sieving.

Results and discussion

Effect of rotation speed on sieving

Rotation speed is a critical parameter for the vibrating sieve, serving as the driving force for material penetration through the sieve and determining the frequency of material movement on the sieve surface. At lower rotation speeds, particles on the sieve surface fail to loosen and stratify rapidly, resulting in diminished sieving efficiency. Conversely, higher rotation speeds promote more active particle movement on the sieve surface, intensifying collisions among particles and between particles and the sieve mesh, thereby enhancing sieving effectiveness. To meticulously investigate the impact of rotation speed on sieving performance, the experiment maintains a consistent feed mass and measures the mass of particles above the screen mesh at different time intervals for each rotation speed. The sieving efficiency, as illustrated in the scatter plot in Fig. 4, is determined using the formula outlined in Section 2.2.1 (Equation (1)).

The scatter plot in Fig. 4 illustrates the variation in sieving efficiency over time for each rotation speed. An analysis of the impact of rotation speed on sieving efficiency reveals a consistent trend: at any given moment, sieving efficiency increases with higher rotation speed. Sieving efficiency also increases with prolonged sieving time at different rotational speeds. Notably, the variation in sieving efficiency among speed levels 6, 7, 8, and 10 exhibits a close resemblance, with their maximum difference observed to be 5% at

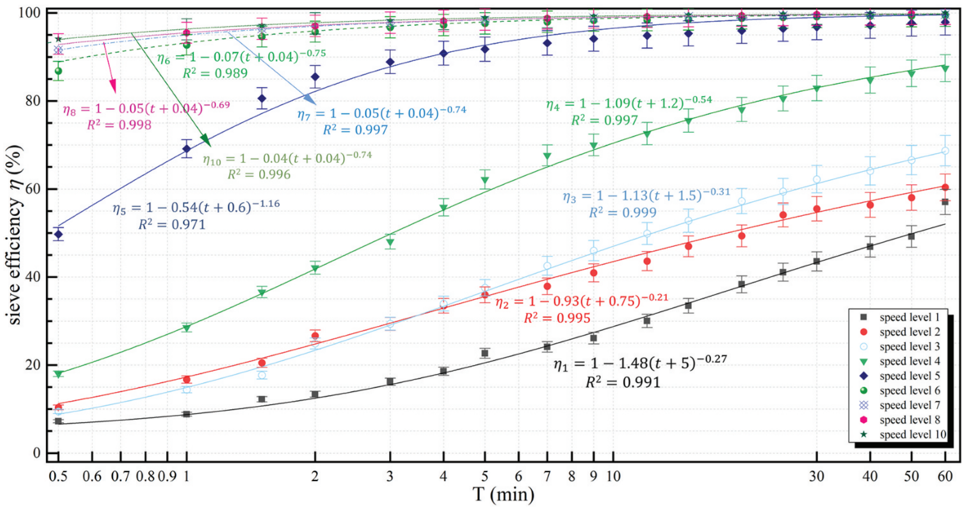

Figure 4. The changing of sieving efficiency and its fitted curve.

approximately 0.5 minutes. In contrast, the sieving efficiency for speed levels 1, 2, 3, and 4 shows a gradual increase, accompanied by a diminishing growth rate as time increases. Simultaneously, these lower speed levels (1, 2, 3, 4) exhibit a marginally lower final sieving efficiency. It is important to note that the observed variations in the data account for inherent random errors, which are typical in experimental studies. To reflect this, error bars have been added to Fig. 4 to illustrate the random error associated with the measurements. Despite these fluctuations, the trends remain consistent with the expected behavior, supporting the validity of the results.

To further analyze the effect of rotational speed on screening efficiency, we use a modified power function (refer to Equation (3)) based on the characteristics of the scatter plot to describe the variation in screening efficiency (Pinchuk and Kuzmin 2019). In this equation, η represents the sieving efficiency at a specific rotation speed when the sieving process is in equilibrium. The variable t denotes the time required to achieve sieving equilibrium (where $\bar{v} = V_{Te}$). A represents the ultimate screening efficiency, with a value of 100%; B, C, and N are formula parameters, where C < 0. The data were fitted using Equation (3), and the results are shown in Fig. 4.

$$\eta = A + B(t - C)^N \tag{3}$$

Based on the fitting results, the overall fit is good and has practical significance. Equation (3) can effectively describe the screening efficiency at different stage speeds. The highest screening efficiency at the three speeds (1, 2, 3) is approximately 70%, suggesting that even with an infinitely extended screening time during actual screening, achieving a high screening efficiency is difficult.

The time required to achieve the limited sieving efficiency varies noticeably across different rotation speeds. We illustrate this discrepancy by contrasting the time needed to attain a common sieving efficiency of 75%. Table 4 presents the time required for sieving efficiency to reach 75% at each rotation speed. It is evident that at lower speeds, some speed levels fail to reach the threshold of 75%. As the rotation speed

Table 4. The time required for the sieving efficiency to reach 75 % at different rotation speed.

Speed level	1	2	3	4	5	6	7	8	10
T/min	/	/	/	13.6	1.3	0.22	0.14	0.12	0.1

'/' indicates that the specified sieving efficiency is not achieved at matching speed level.

increases, the required time progressively decreases and approaches a more uniform duration.

Lower rotation speeds lead to reduced sieving efficiency because the intensity of particle vibration is diminished, making it difficult to achieve loosening and, consequently, stratification. As the rotation speed increases, the vibration intensity amplifies, enhancing the looseness among the particles and facilitating their stratification. This process promotes particle movement through the sieve. However, further increasing the rotation speed may reach a point where the vibrational intensity for particle sieving peaks, resulting in only marginal improvements in sieving efficiency. Figure 4 indicates that the effectiveness of prolonging sieving time to enhance efficiency is less pronounced at lower speed levels. Conversely, at higher speed levels, there is little need to extend sieving time, as sieving efficiency approaches its limit more quickly. Prolonging sieving time at higher speeds may even risk exacerbating wear on the mesh and coal particles.

Based on the above analysis, at low rotation speeds, the sieving efficiency gradually increases with the extension of sieving time. In contrast, at high rotation speeds, prolonged duration is unnecessary, as the sieving efficiency rapidly ascends with time and subsequently stabilizes. It can be inferred that rotation speed exerts a controlling influence on sieving efficiency, wherein higher speeds correspond to higher sieving efficiency. However, beyond a certain threshold, further increases in rotation speed do not yield a significant enhancement in sieving efficiency. Therefore, the determination of an appropriate sieving time is contingent upon the rotation speed. Achieving optimal sieving efficiency necessitates a balance; thus, it is especially important to determine the appropriate sieving time while obtaining high sieving efficiency.

The average sieving rate at different rotation speed was obtained from the mass of the particles above the sieve at different moments with Eq. (2), as shown in Figure.

Figure 5 illustrates the average sieving rates at different rotation speeds. The effective sieving time for each speed level is defined as the duration corresponding to the first instance when the sieving rate falls below the critical value V_{Te} (as indicated in Table 7, where the critical value is $v = 0.2061$). The diagram is annotated with prism-shaped columns, highlighting the specific values of the average sieving rates. Across all rotation speeds, the average sieving rates diminish with the extension of sieving time, gradually approaching zero. Lower rotation speeds correspond to smaller average sieving rates, while higher speeds result in larger average sieving rates at the initial stage of the sieving process.

The effective sieving time at various rotation speed and the corresponding sieving efficiency at that moment were obtained by combining the information from Figure and Figure. Simultaneously, utilizing formula (3), the effective sieving time was inversely calculated based on the sieving efficiency at the Te moment. The summarized results are presented in Table 5.

The data in Table 5 indicate that the effective sieving times derived from the fitted data are generally consistent with those obtained from experimental testing.

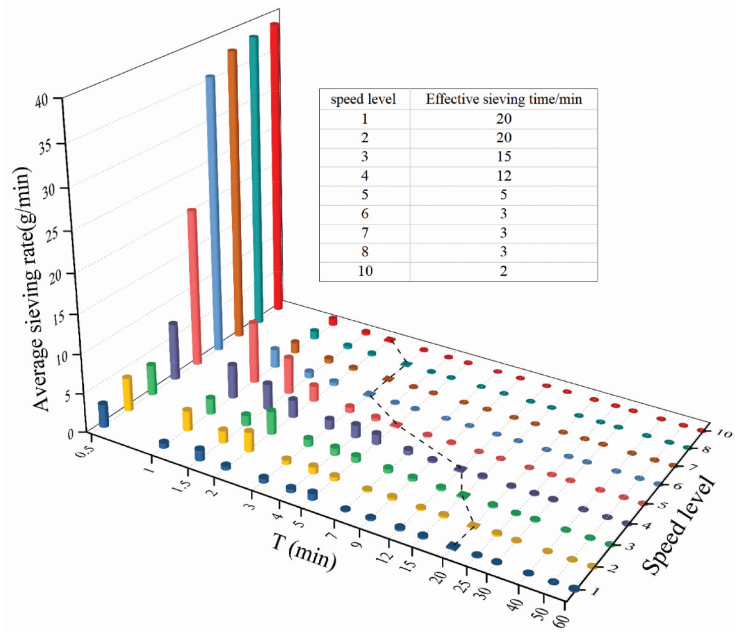

Figure 5. Average sieving rate at different rotation speed.

Table 5. Effective sieving time of different rotation speed.

Speed level	Final sieving efficiency/%	Effective sieving time(Te)/min	Sieving efficiency at Te/%	Te based Eq(3)/min
1	57.06	20	38.33	20.59
2	60.36	20	49.34	17.30
3	68.70	15	52.79	15.20
4	87.43	12	72.59	11.69
5	97.91	5	91.75	4.45
6	99.42	3	96.70	2.69
7	99.66	3	97.67	2.78
8	99.85	3	97.77	3.20
10	100	2	97.62	1.98

The final sieving efficiency in the table refers to the sieving efficiency at 60 minutes; the sieving efficiency is got at Te.

Figure 6 illustrates the effective sieving time obtained in relation to the corresponding sieving efficiency at that moment. It is evident that, with an increase in rotation speed, the effective sieving time decreases, while the sieving efficiency at that particular moment increases. At speed levels 1 and 2, the effective sieving time is approximately 20 minutes, and the corresponding sieving efficiency is less than 60%. At speed level 5, the effective sieving time is around 5 minutes, with a corresponding sieving efficiency of 91.75%. Moving from speed levels 6 to 10, the effective sieving time gradually decreases from 3 minutes to 2 minutes, while the corresponding sieving efficiency consistently exceeds 96%.

In summary, as the rotation speed increases, the effective sieving time gradually decreases, accompanied by an improvement in sieving efficiency. However, excessively low rotation speeds pose a critical drawback, leading to extremely low sieving efficiency. Nevertheless, a higher rotation speed does not necessarily equate to better performance. An increase in rotation speed does not consistently result in a continuous reduction of effective

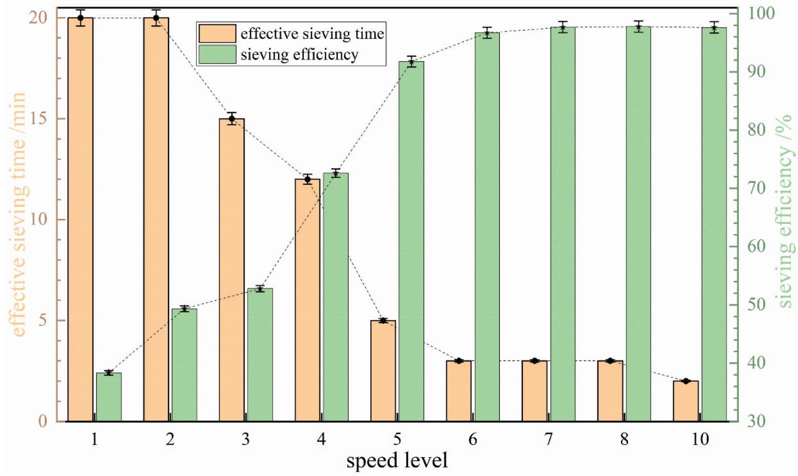

Figure 6. Sieving efficiency corresponding to effective sieving time.

sieving time. In other words, when the rotation speed reaches a certain threshold, further increases may not substantially enhance sieving efficiency; as a result, the reduction in effective sieving time becomes limited. The concept of effective sieving time is an approximation. In practical sieving experiments, it is imperative to avoid both excessively short and excessively long durations. The aim is to approach this critical value as closely as possible for optimal sieving results. Striking a balance is crucial.

Effect of addition mass on sieving

The addition of particle mass is a crucial parameter influencing sieving performance. For the same sample under identical sieving conditions, variations in mass can lead to significant differences in sieving efficiency. Employing the principles of orthogonal experiments, we investigate the sieving performance at different particle masses under speed levels 4, 5, and 6.

The addition of particle mass is a crucial parameter influencing sieving performance. For the same sample under identical sieving conditions, variations in mass can lead to significant differences in sieving efficiency. Employing the principles of orthogonal experiments, we investigate the sieving performance at different particle masses under speed levels 4, 5, and 6.

At a rotation speed of 4, it is observed from Fig. 7 that sieving efficiency decreases with an increase in dosage. Moreover, sieving efficiency improves with prolonged sieving time at each dosage level. The final sieving efficiency at a dosage of M_1 approaches 100%, while at a dosage of M_4, the ultimate sieving efficiency is only approximately 70%.

At a rotation speed of 5 levels, Fig. 7 shows that sieving efficiency does not strictly decrease with an increase in dosage; instead, it follows the pattern (M_1, M_2) > M_3 > M_4. Sieving efficiency at each dosage level demonstrates a rapid initial increase followed by a gradual ascent with prolonged sieving time. Notably, for dosage levels M_1, M_2, and M_3, the differences in sieving efficiency remain within

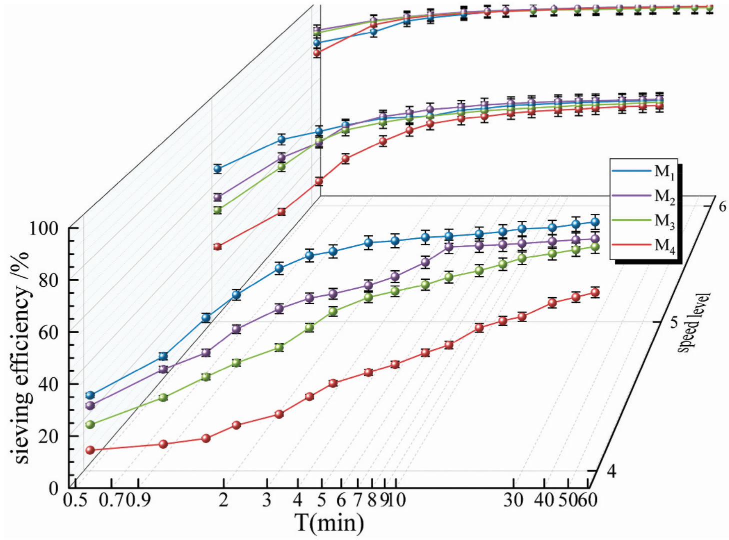

Figure 7. Sieving efficiency at different adding mass.

5% from 2 minutes to the end. Furthermore, the final sieving efficiency for these dosage levels consistently exceeds 95%. In contrast, the results for the M_4 level are significantly worse.

At a rotation speed of 6 levels, sieving efficiency exhibits irregular variations with an increase in dosage, as shown in Fig. 7. In other words, the changing trends are similar and closely aligned. Sieving efficiency at each dosage level undergoes a rapid initial increase, followed by a gradual ascent, and ultimately approaches a consistent level with prolonged sieving time. Approximately 2 minutes later, the differences in sieving efficiency among all dosage levels do not exceed 5%. Moreover, starting from 3 minutes, sieving efficiency remains consistently equal to or greater than 95% for all dosage levels.

Figure 8 illustrates the average sieving rates for various mass additions at different rotation speeds. It is evident that the average sieving rates for different dosages at speed levels 5 and 6 decrease continuously with sieving time, while they fluctuate at speed level 4. Notably, the initial average sieving rates at speed levels 5 and 6 are approximately 10 g/min, whereas at speed level 4, the maximum is around 7 g/min. The average sieving rates at speed levels 5 and 6 both drop below 1 g/min approximately 7 minutes and 2 minutes into the process, respectively.

Table 6 and Fig. 9 present the effective sieving time and corresponding sieving efficiency for various dosages at different rotation speeds. At speed level 4, it is observed that sieving efficiency decreases with an increase in dosage, reaching a minimum of 58%. The effective sieving time fluctuates, with the longest duration being 25 minutes at M_4. At speed level 6, sieving efficiency remains approximately 97% across different dosages, while the effective sieving time is relatively short, averaging around 4 minutes, with a maximum of 5 minutes and a minimum of 3 minutes. At speed level 5, an increase in dosage leads to sieving efficiencies exceeding 92%, with an average effective sieving time of approximately 7 minutes, ranging from 5 to 9 minutes. The results from speed level 6 suggest that further increasing the rotation speed may result in only a limited reduction in effective sieving time.

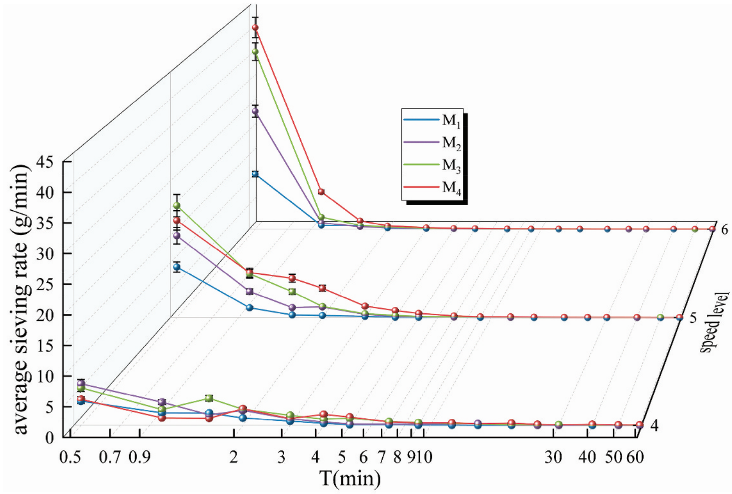

Figure 8. Average sieving rate at different adding mass.

Table 6. Effective sieving time at different adding mass.

Speed level	Final sieving efficiency/%	Adding mass	Effective sieving time/min	Sieving efficiency at Te/%
4	97	M_1	9	90
	90	M_2	20	88
	85	M_3	20	78
	70	M_4	25	58
5	99	M_1	9	95
	99	M_2	7	96
	98	M_3	5	92
	96	M_4	9	92
6	100	M_1	5	98
	100	M_2	4	98
	99	M_3	3	97
	100	M_4	4	97

Table 7. α value at different sieve conditions.

Sieve size/mm	Adding mass/g	A value/g	α/%	$\bar{\alpha}$
0.5	10	6.79	67.9	67.58
	20	13.49	67.45	
	30	20.61	68.7	
	40	26.50	66.25	
0.3	10	5.36	53.6	52.73
	20	10.67	53.35	
	30	15.86	52.86	
	40	20.44	51.1	
0.1	10	2.52	25.2	24.9
	20	5.04	25.2	
	30	7.50	25	
	40	9.71	24.2	

The variation in dosage primarily manifests as the thickness of coal particles on the sieve surface. Generally, excessive thickness may impede the material's ability to loosen and stratify, leading to reduced sieving efficiency and increased sieving time. In theory, both insufficient and excessive dosages are suboptimal. Insufficient dosages result in decreased

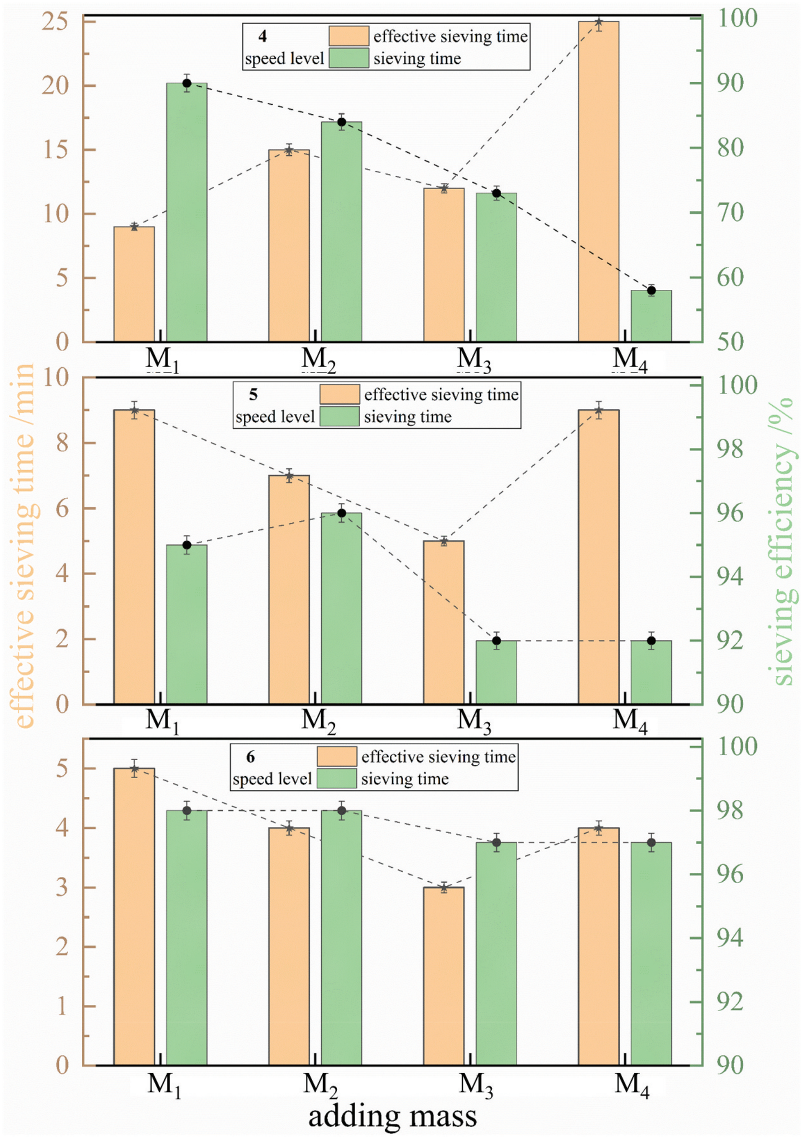

Figure 9. Effective sieving time corresponding to sieving efficiency at different adding mass.

contact between the raw particles and the sieve surface, while excessive dosages can lead to sieving congestion. Identifying an optimal dosage is crucial for achieving superior sieving performance.

Based on the above analysis, it is evident that the impact of dosage on sieving effectiveness is contingent upon rotation speed. When the rotation speed is set at 4, the screening effect deteriorates with an increase in dosage. In contrast, at rotation speeds of 5 or 6, the differences in screening effectiveness under varying dosages are less pronounced, and the overall performance is improved. In general, regardless of dosage, a higher rotation speed is recommended. When the rotation speed is low, careful consideration must be given to dosage selection, as an excessive amount may prolong effective sieving time. For particles with a low firmness coefficient, it is advisable to opt for a lower rotation speed to mitigate the risk of abrasion during the sieving process.

Effect of sieve size on sieving

The proportion of particles within the material that can pass through the sieve and be classified as undersized varies with different sieve sizes. In practical sieving processes, coal samples with varying particle sizes require corresponding sieve mesh sizes. Sieve sizes of 0.5 mm, 0.3 mm, and 0.1 mm are used in comparative tests to explore the impact of differences in screen size on the sieving effect.

Figure 10 illustrates the sieving efficiency of three sieve meshes at speed level 6 and varying dosages. The graph shows that, at speed level 6, the final sieving efficiencies for the 0.5 mm, 0.3 mm, and 0.1 mm sieves are approximately 97%, 96%, and 90%, respectively. Furthermore, the graph indicates that the trend in sieving efficiency is remarkably similar between the 0.3 mm and 0.5 mm sieve meshes. Across the different dosage levels depicted in the figure, it is evident that sieving efficiency decreases with a reduction in sieve size.

Figures 11 and 12 present the sieving efficiency at speeds 5 and 4, respectively, for different sieve mesh sizes. Both figures indicate a decrease in sieving efficiency with a reduction in sieve mesh size. In Fig. 11, it is observed that, under speed level 5, the final sieving efficiencies for the 0.5 mm, 0.3 mm, and 0.1 mm sieves are approximately 97%, 93%, and 40%, respectively. Meanwhile, Fig. 12 illustrates that, at speed level 4, the final sieving efficiencies for the 0.5 mm, 0.3 mm, and 0.1 mm sieve meshes are approximately 85%, 52%, and 35%, respectively.

According to the conclusions in Section 4.1, lower rotation speeds correspond to decreased sieving efficiency. Therefore, as the sieve mesh size decreases, the sieving

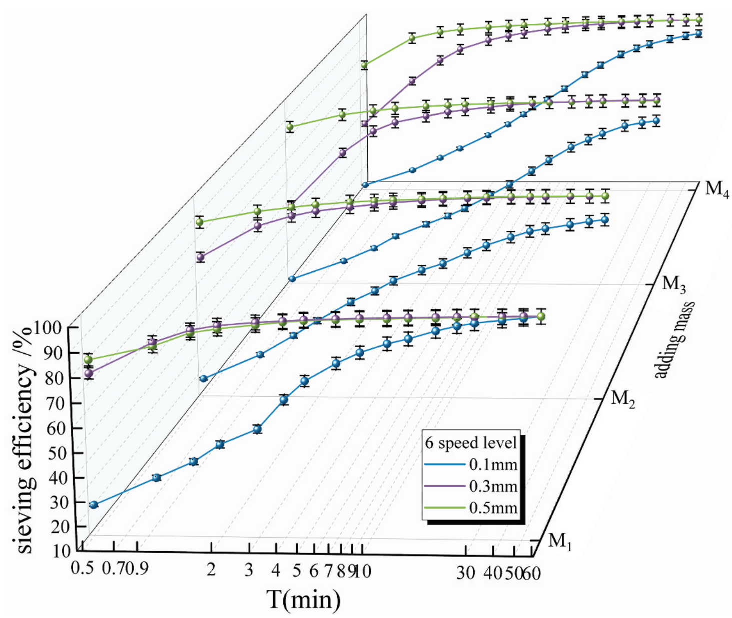

Figure 10. Sieving efficiency of different sieve sizes at 6th speed level.

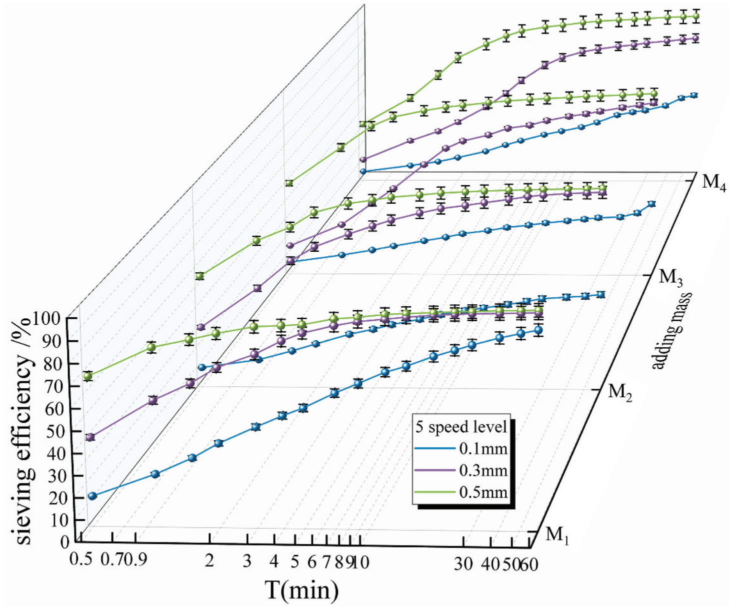

Figure 11. Sieving efficiency of different sieve sizes at 5th speed level.

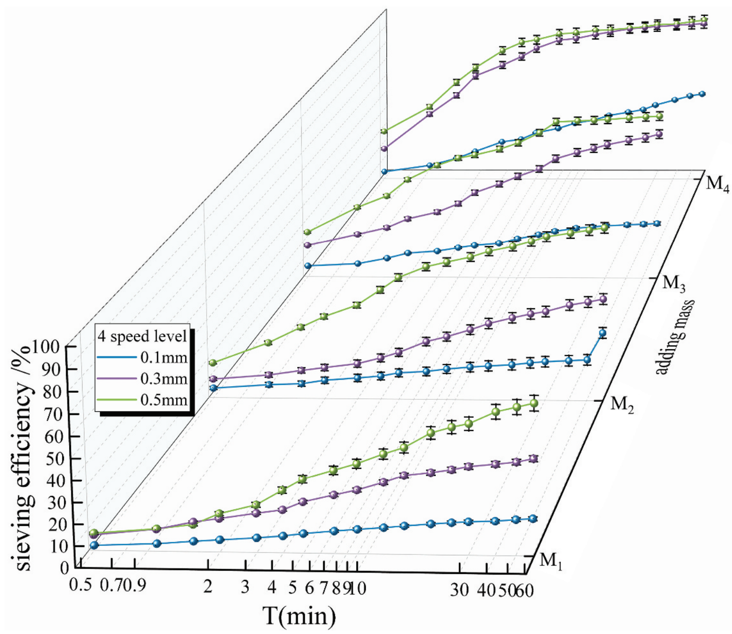

Figure 12. Sieving efficiency of different sieve sizes at 4th speed level.

efficiency diminishes further. As evident from Figs. 11 and 12, the sieving efficiencies for the 0.1 mm sieve mesh at speeds 4 and 5 are approximately 35% and 40%, respectively. Consequently, when the sieving efficiency is excessively low, the numerical value of effective sieving time loses its practical significance. Therefore, based on the average sieving rate, the effective sieving time and related data (refer to Tables 7 and 8) are determined. The effective sieving times for the 0.5 mm, 0.3 mm, and 0.1 mm sieve meshes at speed level 6 are 3, 7, and 25 minutes, respectively, indicating that smaller sieve mesh sizes require longer effective sieving times.

Utilizing the insights derived from the impact of rotation speed and dosage on screening efficiency, as discussed in Sections 4.1 and 4.2, and consolidating the pertinent data within this section, we opted for specific effective screening time for each sieve at 6th speed level, culminating in the generation of Fig. 13 effective sieving time and the corresponding sieving efficiency for different sieve sizes under 6th speed level.

Figure 13 illustrates the sieving efficiency of three sieve mesh at various dosages under six speed level. The trends across the four conditions exhibit remarkable

Table 8. Relevant data at different sieve sizes.

Adding mass	Speed level	Sieve size/ mm	Final sieving efficiency/ %	Effective sieving time/ min	Sieving efficiency at Te/ %
M_1	4	0.1	52	20	41
		0.3	95	9	86
		0.5	97	9	90
	5	0.1	90	15	74
		0.3	98	9	93
		0.5	99	9	95
	6	0.1	100	15	91
		0.3	100	4	98
		0.5	100	5	98
M_2	4	0.1	31	12	24
		0.3	81	20	70
		0.5	90	20	88
	5	0.1	47	12	39
		0.3	97	12	91
		0.5	99	7	96
	6	0.1	90	20	82
		0.3	100	5	97
		0.5	100	4	98
M_3	4	0.1	35	7	14
		0.3	52	20	42
		0.5	85	20	78
	5	0.1	39	7	24
		0.3	93	12	81
		0.5	98	5	92
	6	0.1	90	25	81
		0.3	100	7	96
		0.5	99	3	97
M_4	4	0.1	17	7	13
		0.3	45	25	39
		0.5	70	25	58
	5	0.1	51	12	32
		0.3	84	15	78
		0.5	96	9	92
	6	0.1	93	25	85
		0.3	100	7	95
		0.5	100	4	97

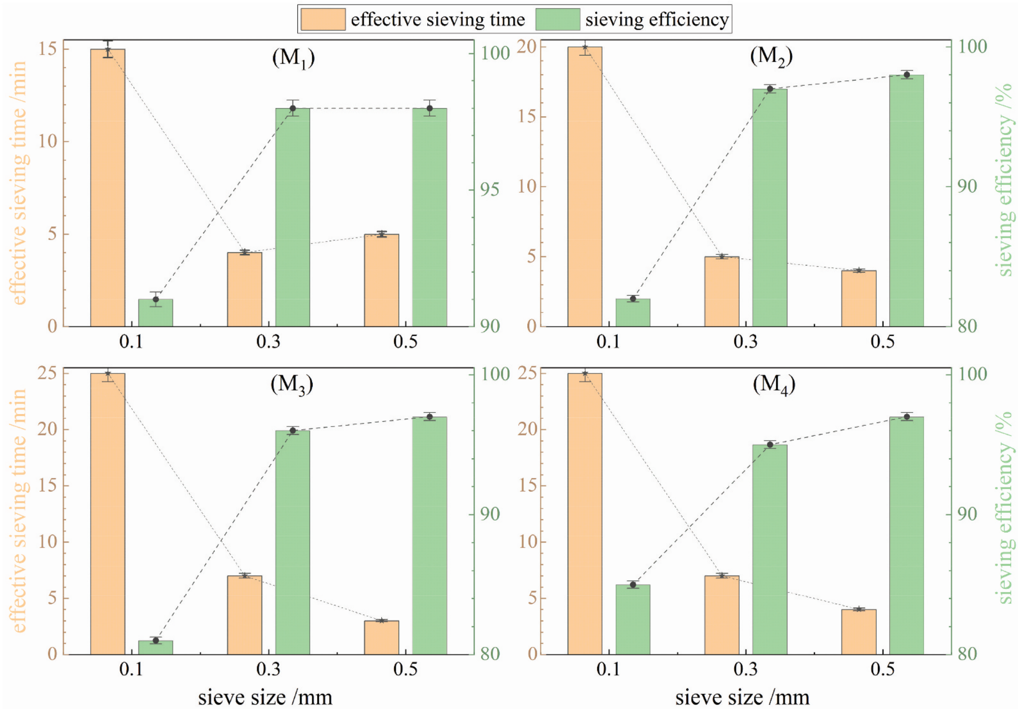

Figure 13. Effective sieving time and the corresponding sieving efficiency for different sieve sizes under 6th speed level.

similarity: as the sieve mesh size increases, the sieving efficiency improves while the effective sieving time decreases. Within Fig. 13, the sieving efficiency and effective sieving time for sieve mesh sizes of 0.3 mm and 0.5 mm are quite comparable, displaying a substantial contrast when compared to the 0.1 mm mesh size. At 0.1 mm, the sieving efficiency ranges between 81% to 91%, with effective sieving time spanning from 15 to 25 minutes. For 0.3 mm and 0.5 mm meshes under M_1 and M_2, the sieving results are analogous, with a sieving efficiency of approximately 98% and an average effective sieving time of around 4.5 minutes. Under M_3 and M_4, the sieving results for these meshes are similar, yielding a sieving efficiency of approximately 96%, with respective effective sieving times of approximately 7 minutes and 3.5 minutes.

Table 8 presents the data under various operating conditions. The data indicate that the sieving efficiency of the 0.1 mm sieve mesh at speed level 4 is consistently low, reaching a maximum of approximately 52%. Under certain conditions, the short sieving time is attributed to weak sieving capability, which causes the sieving rate to fall below the critical threshold prematurely, thus creating the illusion of a brief effective sieving time. At speed level 5, except for dosage M_1, the sieving efficiency remains generally low, with a maximum of approximately 51%. At speed level 6, the sieving efficiency is relatively high, ranging from a minimum of 90%. For the 0.3 mm sieve mesh, at lower speeds (speed level 4) and higher dosages (M_3, M_4), the sieving efficiency is lower, around 50%. However, under other conditions, the sieving efficiency is notably higher, with a minimum of 81%. This highlights the importance of considering both rotation speed and dosage when evaluating the impact of sieve mesh size on sieving effectiveness.

Based on the aforementioned data, it can be deduced that the effective sieving time for the 0.1 mm sieve mesh is no less than 15 minutes. This duration is approximately twice that of the 0.3 mm sieve mesh and three times that of the 0.5 mm sieve mesh. Furthermore, as the dosage increases, this discrepancy is expected to widen even further.

In general, there exists a lower limit to the particle size of material particles. As the sieve mesh size decreases, two primary factors come into play: first, the proportion of particles capable of passing through the sieve diminishes; second, the particle size of those particles that do pass through the sieve becomes closer to the sieve mesh size. Specifically, the particles that successfully pass through the sieve are predominantly smaller than the sieve mesh size but closely approximate it. Consequently, this proximity poses challenges to the sieving process, potentially resulting in reduced sieving efficiency and increased sieving time.

Conversely, as the sieve mesh size increases, the proportion of particles passing through the sieve also increases. Simultaneously, the difference between the particle size of those passing through and the sieve mesh size becomes more pronounced. Therefore, when the sieve mesh size is larger, the proportion of particles that can pass through is higher, and the disparity between the particle size of these particles and the sieve mesh size is greater. Consequently, for a given material, selecting a smaller sieve mesh size theoretically makes the sieving process more challenging.

Conclusion

Effective sieving time is a pivotal factor influencing particle sieving and is essential for particle separation. The determination of this critical time parameter concurrently indicates associated parameters, such as vibration frequency and feed rate. The concept of effective sieving time arises in response to the consequences of excessively short or prolonged sieving durations, serving as a vital evaluative metric in the sieving process. The primary conclusions drawn from this study are as follows:

(1) Examination of rotation speed reveals a gradual increase in sieving efficiency at each speed level as the speed is elevated up to level 6. Beyond level 6, further improvement in speed results in a rapid, cliff-like improvement in sieving efficiency at each speed level, followed by a gradual stabilization. This suggests that sieving efficiency exhibits distinct variations with rotation speed. Concerning effective sieving time, an increase in rotation speed leads to a notable reduction in effective sieving time. However, after reaching a certain threshold, the effective sieving time stabilizes around a specific value. So the rotation speed is not the higher the better.

(2) In the study of dosage, it is found that the screening efficiency will vary greatly with the dosage based on different rotating speeds. At low rotating speed, the screening efficiency at the same time increased with the increase of dosage; When the rotating speed increases, the screening efficiency at the same time does not strictly increase with the increase of dosage; The higher the rotating speed, the closer the screening efficiency at the same time under different dosage. The higher the rotating speed, the

shorter and similar the effective screening time under different dosages, and the effective screening time under different dosages is about 4 min at 6-step speed. It can be seen that the influence of dosage should also refer to the speed.

(3) The influence of screen size on the screening process is primarily reflected in the control of the proportion of particles passing through the screen. The smaller the screen size, the fewer particles pass through it. At a 6-step speed, a smaller screen size results in a longer effective screening time. The effective screening time for a 0.1 mm screen under M_1 is approximately 15 minutes, which is two to three times that of the 0.3 mm and 0.5 mm screens, respectively. With an increase in dosage, the multiple gap becomes larger. For the screening of smaller screens, the dosage should not be excessive; otherwise, the effective screening time will be significantly increased.

(4) This study conducted tests on a specific apparatus using coal particles with particular characteristics, yielding research findings regarding effective sieving time. The proposal of effective sieving time not only avoids the low sieving efficiency caused by insufficient screening time but also mitigates the impact of prolonged sieving time on coal particle breakage. It is essential to note that insights from this study can be extrapolated to different devices and particles with diverse characteristics.

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CRediT authorship contribution statement

Peizhuang Han: Conceptualization, Resources, Supervision, Writing original draft, Methodology. **Xiaodong Lu**: Conceptualization, Resources, Supervision, Writing – review & editing, Methodology. **Qingquan Liu**: Methodology, Investigation, Formal analysis, Funding acquisition. **Kunsang Lee**: Methodology, Investigation, Formal analysis. **Liang Wang**: Data curation. **Yuanping Cheng**: Validation.

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