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Research Article
Dynamical Model and Simulation on Variable Linear Shale Shaker

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Abstract

Through analyzing the disadvantages of traditional linear shale shaker, the variable linear shale shaker is proposed to improve the working performance of shale shaker. The trajectory equation is deduced based on the oscillatory differential equation. Through theoretical research and Discrete Element Method (DEM) simulation, the changing rules of trajectory gradient, throwing index and throwing velocity along the screen deck are obtained, which are in good agreement with each other. The results show that the excitation position $l_0<0$ is conducive to solid and drilling liquid separation and solid particles conveyance. In addition, on the base of distribution of throwing index at the inlet and outlet, the proper value ranges of excitation position and direction are decided, which are -0.5 m$<l_0<$-0.35 m, 35°$<\beta_0<$45°.

Key words: Shale shaker, moving track, throwing index, DEM

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Shale shaker as the first stage solid control equipment is an indispensable equipment in petroleum industry, the working performance of which has a direct influence on circulating mud (Bouse and Carrasqero, 1992; Li and Chen, 2000). As the most prevalently used solid control equipment, linear shale shakers and elliptical shale shaker have a same disadvantage that the moving track and throwing index are all the same along the screen deck, which is not fit for separating solid particles from drilling liquid. The ideal working way of a shale shaker used in petroleum industry is that the throwing index is bigger around the inlet to accelerate solid-liquid separation and smaller around the outlet to accelerate the conveyance of solid particles (Yan, 2007).

Figure 1a shown is an actual structure of shale shaker. In this study, the focus point is the conveyance process of particles on the screen deck, so the structure have nothing to do with it are neglected, such as supporting beam, wedgeblock and stiffener. The schematic diagram of the shale shaker is shown as Fig. 1b. The excitation shaft equipped with two motors forces the screen box vibrating in both vertical and horizontal directions, while the particle inlet stands still. Particles fall to the screen deck from the particle inlet and then move forwardly and upwardly as the vibration of screen. Usually the x-velocity component of particles is called conveyance velocity v_x, which is an important parameter to evaluate the transport efficiency of shale shaker.

For Linear shale shaker, the excitation force of which passes through the mass center, but for variable linear shale shaker, the excitation force doesn't. So the screen deck of variable linear shale shaker has a pitching motion around the mass center, which leads to the moving track of every points in the screen deck being different. Furthermore, if the angle of pitching motion is proper, the ideal moving track of shale shaker can be achieved.

The conception of variable linear shale shaker was first proposed by Hou *et al.* (2003). In their study, they deduced the trajectory equation and simulated the moving track of some points on the screen deck by ADAMS. But in the coordinate system they create, x-axis is perpendicular to the direction of excitation force, which is not suitable for researching the conveyance velocity of particles. In 2013, the professor Du Changlong of China University of Mining and Technology proposed a kind of variable linear vibration screen used in coal industry (Du *et al.*, 2013). But the structure and working conditions of mining vibrating screen are completely different from the shale shaker used in the petroleum industry. So the conclusions they obtained are unable to be applied to the petroleum shale shaker directly. In addition, both of these researches don't study the velocity of particles, which is a vital factor of shale shaker.

As the complicate interactions between particles, the study on particle conveyance of vibrating equipment for a long time is confined to one particle, namely the interactions are neglected, which is far from the actual working conditions. In 1970s the Discrete Element Method (DEM) was proposed and provide a new solution to research the particles movement, which is used widely in the vibrating equipment. Zhao *et al.* (2011) applied this method into the study on a circularly vibrating screen, while Dong and Yu (2012) research the bend/low head screen. Chen and Tong (2010) and Wang and Tong (2011) focused on the screening efficiency of linear vibrating screen. Xiao and Tong (2012) study the stratification appearance of particles during the screening process. However, all these researches are aim to the vibrating screen used in mining industry or agriculture industry, which are different greatly from the petroleum shale shaker. So these

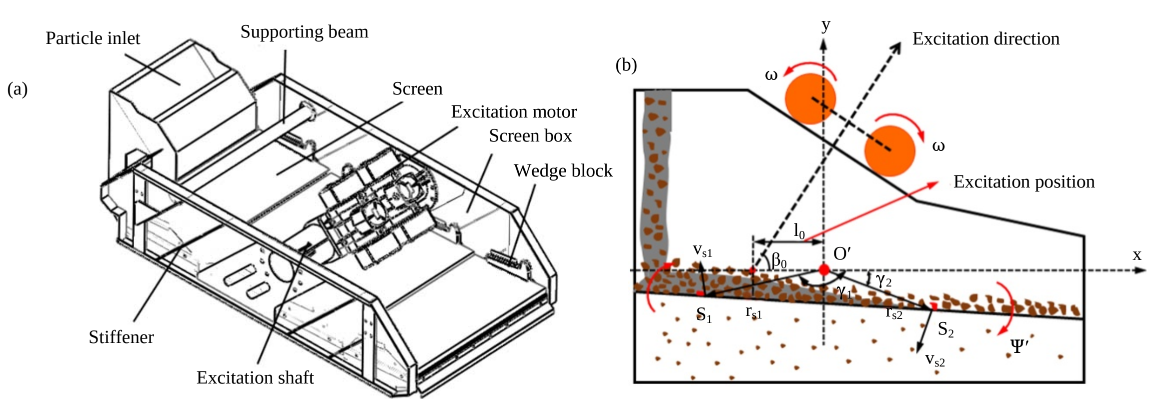


Fig. 1(a-b): Motion analysis diagram of screenbox system, (a) Actual structure of shale shaker and (b) Schematic diagram of shale shaker researches built a solid foundation for our research, but the research results cannot be used in petroleum shale shaker directly.

In this study, the dynamical theoretical model is built and the changing laws of trajectory, throwing index and conveyance velocity are obtained, the theoretical results are proved by simulation as well. Furthermore, the screening process of variable linear shale shaker is firstly simulated by the discrete element method in this research.

MATERIALS AND METHODS

Dynamical model and theretical analysis

Deduction of trajectory equation: During the working process of shale shaker, what matters is the movement of particles in x direction, the movement across the width direction is not the focus point. So the structure of shale shaker is simplified into two-dimensions (Zhang and Deng, 2013). The simple kinetic model of variable shale shaker is shown as Fig. 1. The original point of this coordinate system is set at the mass center O'. The movement of screen deck is consisted of reciprocal rectilinear motion and pitching motion around the mass center. Neglecting the influence of spring stiffness, the vibration differential equation of variable linear shale shaker can be expressed as following Eq. 1:

$$\begin{aligned} M\ddot{x} &= 2m_0\omega^2 r\cos\beta_0 \sin\omega t \\ M\ddot{y} &= 2m_0\omega^2 r\sin\beta_0 \sin\omega t \\ J\ddot{\psi} &= 2m_0\omega^2 r l_0 \sin\beta_0 \sin\omega t \end{aligned} \tag{1}$$

where, ω is the angular frequency of excitation motor, rad sec^{-1}, M is the mass of screen box kg, m_0 is the mass of eccentric block kg, r is the gyration radius of eccentric block m, β_0 is the excitation direction degree, J is the rotational inertia of shale shaker and screen box kg m^2, ψ, $\ddot{\psi}$ are the angular velocity and angular acceleration respectively, rad, rad sec^{-2} and l_0, which is also called excitation position, represents the x-value of the intersection point of excitation force and x-axis, m.

Solving the Eq. 1, the x, y, ψ can be expressed as Eq. 2:

$$\begin{cases} x = A_x \sin\omega t = -\dfrac{2m_0 r\cos\delta}{M}\sin\omega t \\ y = A_y \sin\omega t = -\dfrac{2m_0 r\sin\delta}{M}\sin\omega t \\ \psi = \theta\sin\omega t = -\dfrac{2m_0 r l_0 \sin\delta}{J}\sin\omega t \end{cases} \tag{2}$$

where, $\lambda_0 = \sqrt{A_x^2 + A_y^2}$ is the amplitude at mass center is also called excitation amplitude, which is decided by the structure of shale shaker and mass of eccentric block.

Consuming the relative coordinate value of any point S on the screen deck is (s_x, s_y), then the velocity of it can be expressed as follows, which is decomposed into x and y direction:

$$\begin{cases} v_{sx} = v_{Mx} + \omega_{sM} r_{sM} \sin\gamma \\ v_{sy} = v_{My} + \omega_{sM} r_{sM} \cos\gamma \end{cases} \tag{3}$$

Through integral calculation of Eq. 3, the displacement can thus be obtained and expressed as in Eq. 4:

$$\begin{cases} x_s = x + \psi s_y \\ y_s = y + \psi s_x \end{cases} \tag{4}$$

Substituting the Eq. 2 into Eq. 4 can be expressed as Eq. 5:

$$\begin{cases} x_s = A_x \sin\omega t + s_y \theta \sin\omega t \\ y_s = A_y \sin\omega t + s_x \theta \sin\omega t \end{cases} \tag{5}$$

Eliminating the parameter t in Eq. 5, the y_s can be expressed as Eq. 6:

$$y_s = \frac{A_y + \theta s_x}{A_x + \theta s_y} x_s = k x_s \tag{6}$$

where, k is the angle between direction of vibration and horizon. In practice, the trajectory slope is usually recognized as the angle between direction of vibration and screen deck, which can be expressed as Eq. 7:

$$ks = \tan(\arctan k - \alpha_0) \tag{7}$$

where, α_0 is the screen deck slope, degree.

Equation 6 shows, the trajectory slope of point s is related to its position (s_x, s_y). In other words, points with different position have different trajectory slopes. Calculating the trajectory slope of some key points on the screen deck by Eq. 6 with respect to parameters in Table 1, the results are shown as Fig. 2, where, Fig. 2a is the linear shale shaker with the same trajectory slope along the screen deck. Fig. 2b is the variable linear shale shaker with variable trajectory slope.

Changing law of trajectory slope: Substituting the Eq. 2 into Eq. 6, then the trajectory slope can be expressed as Eq. 8:

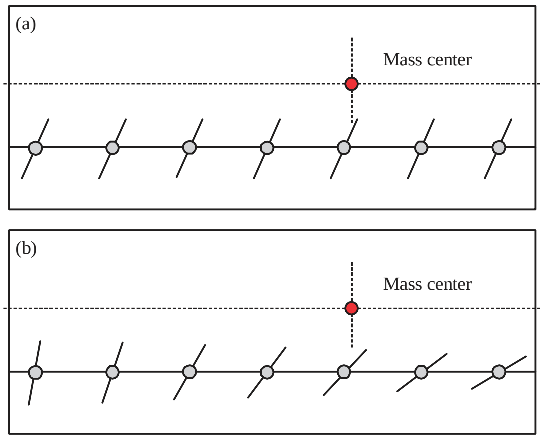


Fig. 2(a-b): Motion trajectory of key points on screen deck, (a) Linear trajectory and (b) Variable linear trajectory

Table 1: Main parameters of variable linear shale shaker

Parameters						Value
Screen pole a (mm)						0.83
Screen deck slope α_0 (Degree)						0
Excitation amplitude λ_0 (mm)						4
Excitation direction δ (Degree)						45
Excitation frequency f (Hz)						18.5
Excitation position l_0 (m)						-0.04
Surface adhesion per unit mass of particles, R_m (N kg^{-1})						15
Particle type	d/a = 0.5~0.7		d/a = 0.7~1		d/a = 1~3	
Diameter (mm)	0.3	0.5	0.6	0.8	1.6	2
Generate rate (Particles/s)	400	800	1200	800	2400	2400

$$k=\frac{A_y+\theta s_x}{A_x+\theta s_y}=\frac{J+Ml_0s_x}{J\cot\beta_0+Ml_0s_y} \tag{8}$$

Taking a derivative of β_0 and l_0 respectively based on Eq. 8, then the differential equation can be expressed as Eq. 9:

$$\begin{cases}\dfrac{\partial k}{\partial l_0}=\dfrac{JM\left(s_x\cot\beta_0-s_y\right)}{\left(J\cot\beta_0+Ml_0s_y\right)^2}\\[2ex]\dfrac{\partial k}{\partial\beta_0}=\dfrac{J\left(J+Ml_0s_x\right)}{\sin^2\beta_0\left(J\cot\beta_0+Ml_0s_y\right)^2}\end{cases} \tag{9}$$

When the structure of shale shaker is determined, J and M are constant values. So the trajectory slope is mainly decided by excitation direction β_0 and excitation position l_0.

Set the first formula of Eq. 9 is zero, then it can be translated into Eq. 10 as:

$$s_x\cot\beta_0 - s_y = 0 \tag{10}$$

The relationship between s_x and s_y is shown as Eq. 11:

$$s_y \tan\alpha s_x+b \tag{11}$$

where, b is the y-value of intersection point of screen deck and y-axis, m.

Substituting the Eq. 11 into Eq. 10, which can be expressed as Eq. 12:

$$s_x = b/(1-\tan\alpha) \tag{12}$$

So, it can be concluded that the trajectory slope of point P(b/(1-tanα), b/(1-tanα)) is tan β_0, which is only related to excitation direction β_0 and has nothing to do with excitation position l_0.

Keeping $\beta_0 = 45°$ unchanged, set l_0 is -0.2, -0.1, 0, 0.1 and 0.2 m, respectively. The changing laws of trajectory slope correspondin l_0 are shown as Fig. 3. No matter how the l_0 changes, the lines go through a same point, marked as point P.

When $l_0 = 0$, the trajectory slope is a constant value along the screen deck, in this case the variable linear shale shaker is transformed into linear shale shaker. Due to the screen deck has a slope itself, according to Eq. 7, ks≠1. When $l_0>0$, the intersection point of excitation force and x-axis is on the right of mass center. In this case, the trajectory slope is smaller around the inlet and increases gradually towards the outlet, which can't improve the conveyance ability of shale shaker. On the contrary, when $l_0<0$, the trajectory slope is bigger around the inlet and decreases gradually towards the outlet, which is benefit to improve the throwing index around the inlet and decrease the accumulation of particles. So in order to ensure the working performance of variable shale shaker, the excitation position should satisfy the condition: $l_0<0$.

Changing law of throwing index: Throwing motion is the mainly action of particles to move forwardly. Therefore, throwing index is a very important parameter to evaluate the working performance of shale shaker. For variable linear shale shaker, the throwing index of particles can be expressed as following Eq. 13 (Zhang and Deng, 2013):

$$D=\frac{\lambda\omega^2\sin\delta}{g\cos\alpha_0}\times\frac{1}{1+\dfrac{R_m}{g\cos\alpha_0}} \tag{13}$$

where, R_m is the surface adhesion per unit mass of particles, which is 15 N/kg (Hoberock, 1980, 1981) and λ is the single amplitude in the excitation direction, which can be expressed as Eq. 14:

$$\lambda=\sqrt{\left(A_x+s_y\theta\right)^2+\left(A_y+s_x\theta\right)^2} \tag{14}$$

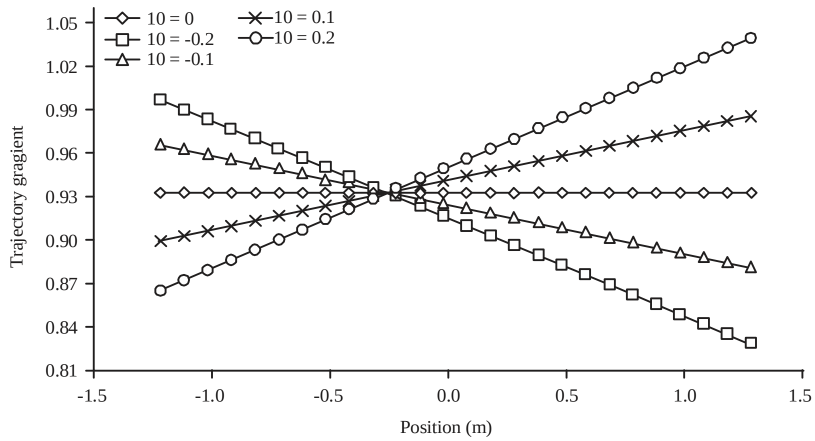


Fig. 3: Relationship between l_0 and gradient

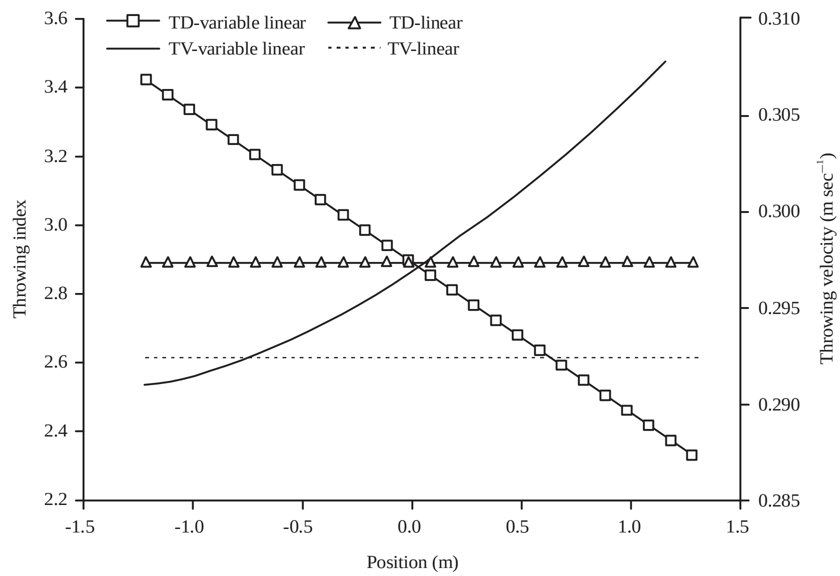


Fig. 4: Varying pattern of throwing index and velocity

Equation 14 shown, λ is related to the specific position (s_x, s_y) of point. Namely, different points on the screen deck have different amplitude value. Furthermore, when $s_x = s_y = 0$, $\lambda = \lambda_0$. When $l_0<0$, the changing law of throwing index can be calculated by Eq. 13 as Fig. 4 shown.

Figure 4 shown, the throwing index of linear shale shaker are all the same along the screen deck, while that of variable linear shale shaker decreases gradually. Around the inlet, the drilling mud layer is thick, high throwing index generating a high throwing height is good for separating the solid particles from th drilling liquid. After the liquid end point, on the most of the fluid passes through the screen pole, only particles left this deck and keep on conveying forwardly. In situation, high throwing index is not necessary and may increase the probability of particle breakage.

Changing law of throwing velocity: Throwing motion is the most important movement of particles. The throwing velocity of particles, which is expressed as following Eq. 15, has a direct impact on the speed of solid conveyance.

$$v_d = \omega\lambda\cos\delta\frac{\pi i^2}{D}(1+\tan\alpha\tan\delta) \quad (15)$$

where, $i = \frac{\varphi_z - \varphi_d}{2\pi}$ ϕ_d and ϕ_z is the angle between throwing track and screen deck when one round of throwing motion begins and accomplishes, respectively.

Based on Eq. 15 with respect to parameters in Table 1, the throwing velocity can be calculated as Fig. 4 shown. For linear shale shaker, the change law of throwing velocity is the same with throwing index, both of which keep unchanged along the screen deck, while for the variable linear shale shaker, the throwing velocity increases gradually from inlet to outlet, which is inversely proportional to the throwing index. Therefore, combining the characteristics of variable linear shale shaker, higher throwing index around the inlet is good for solid-liquid separation and higher throwing velocity around outlet can accelerate the speed of solid conveyance.

Value ranges of excitation position and direction: Equation 8 expressed once the structure of shale shaker is fixed, the track slope related with throwing index and velocity is mainly affected by excitation position l_0 and excitation direction β_0. Consequently, these two key parameters have a great meaning on the working performance of shale shaker. In this context, the concrete proper value ranges of l_0 and β_0 are determined according the distribution of throwing index.

In general, the throwing motion of particles can be achieved only with the throwing index D satisfied the condition D>1. At the inlet of shale shaker, drilling fluid just falls down to the deck and the mud layer is very thick, so the throwing index should be big enough to separate the particles from mud layer. However, too big throwing index can result to the particles broken easily and decrease the conveyance velocity. So around inlet the throwing index ranges from 3-6, namely, $3<D_{in}<6$. At the outlet, there is no much drilling fluid, the throwing index only need to satisfy the fundamental throwing condition D>1. So the throwing index at the outlet ranges from 1-3, namely $1<D_{out}<3$ (Zhao and Hua, 1988; Lal and Hoberock, 1988). When the l_0 and β_0 take different values, the distribution of throwing index at inlet is shown as Fig. 5. Where, Fig. 5a is the distribution of throwing index, Fig. 5b is the projection figure at xy-palne of contour line. The different color of the contour line in Fig. 5b represents the different value of throwing index. To keep the throwing index satisfying $3<D_{in}<6$ all the time, the proper value ranges of l_0 and β_0 shown as the shaded section in Fig. 5b, are approximate to Eq. 16:

$$-0.5\text{ m}<l_0<-0.1\text{ m},\ 35°<\beta_0<70° \qquad (16)$$

The distribution of throwing index at the outlet is shown as Fig. 6. Similarly, the value ranges of l_0 and β_0 are approximate to Eq. 17:

$$-0.7\text{ m}<l_0<-0.35\text{ m},\ 20°<\beta_0<45° \qquad (17)$$

Combining the Eq. 16 and 17, the proper value ranges of l_0 and β_0 of variable linear shale shaker can be determined as: $-0.5\text{ m}<l_0<-0.35\text{ m}$, $35°<\beta_0<45°$. When the excitation position and direction value in this range, the variable linear shale shaker is able to work in an ideal condition: Particles jump higher without broken around the inlet and convey faster around the outlet.

Simulation setup

Simulation model: Discrete Element Method (DEM) as a rising technology to analyze the powder and particles has been intensively developed in recent years, which has been applied into many fields successfully, such as coal-mining industry, geotechnical mechanics, mix and agitation, lapping technology and so on (Cundall and Strack, 1979; Cleary and Sawley, 2002; Di Renzo and Di Maio, 2004; Xiao and Tong, 2012). However, it is rarely applied to the petroleum industry, especially to the shale shaker. In this section, a discrete element model has been implemented to validate the theoretical results derived from previous research. The main parameters of this model are shown in Table 1.

The down-scale model is selected to research the working process of variable linear shale shaker. The size in x and y dimension is reduced to one tenth of their original shape. Due to the movement of particles in z direction is not the focus point in this research, which is reduced to one twentieth. The screen pole affect the solid-conveyance directly, which keeps as the same size as actual one. Twenty meshes screen with square hole is selected as the research object, the screen pole size is a = 0.83 mm and opening rate is 42.71%.

JKR contact model: As an important foundation of DEM model, contact model decides directly the contact force between particles. The JKR (Johnson-Kendall-Roberts) contact model is based on the JKR theory, which not only takes the energy loss generated by collision into account, but also considers the effect of adhesion between wet particles. In view of the working condition of shale shaker, the viscous force between particles cannot be neglected, so JKR contact model is applied to this simulation.

A JKR theory, the normal contact force can be calculated as Eq. 18 (Hayashi and Koguchi, 2015; Dong *et al*., 2013):

$$F_{JKR} = -4\sqrt{\pi\gamma E^*}\, r_c^{3/2} + \frac{4E^*}{3R^*} r_c^3 \qquad (18)$$

where, γ is the surface energy, which is decided by particle size and surface adhesion, E* is the equivalent elastic modulus,

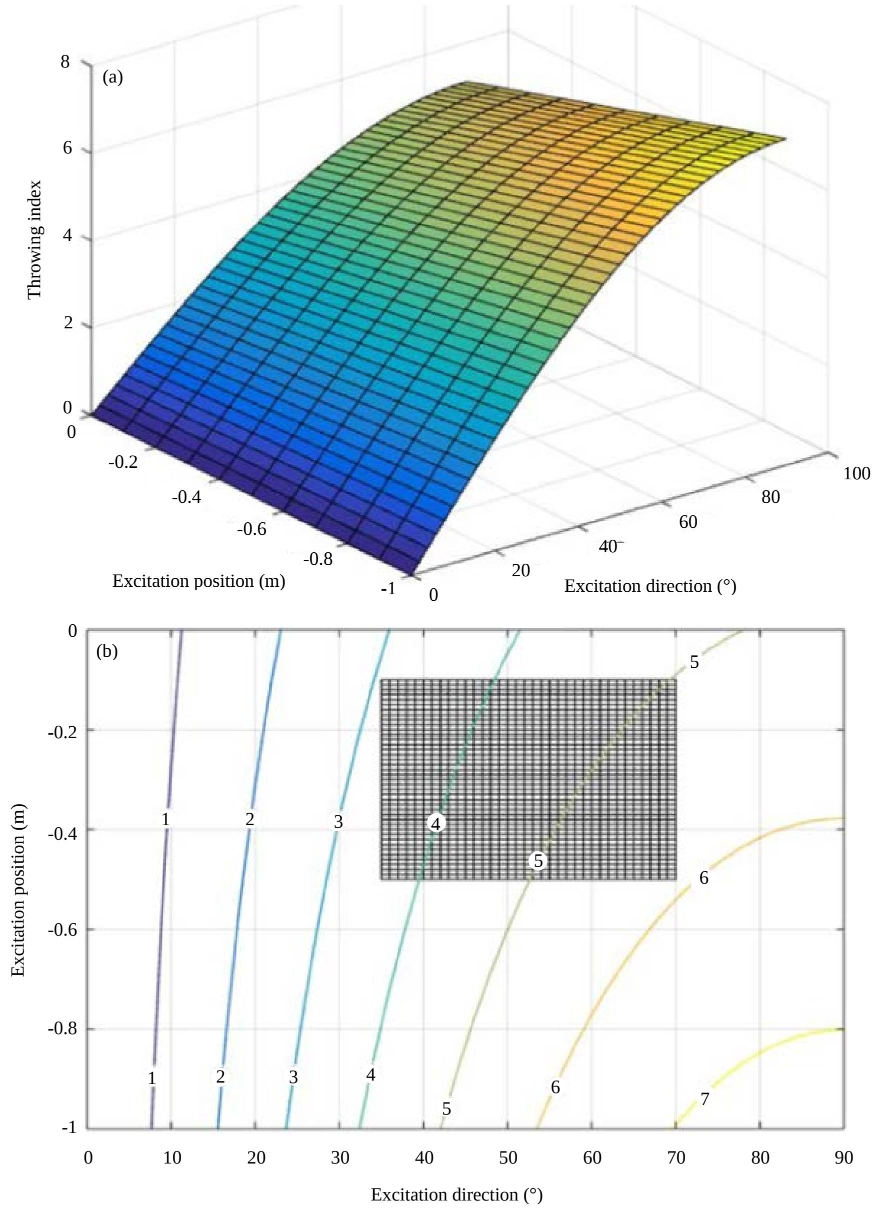


Fig. 5(a-b): Distribution of throwing index at inlet, (a) Distribution of throwing index and (b) Projection figure of contour line

R^* is the equivalent particle radius and r_c is the radius of contact surface. They can be calculated by Eq. 19-21:

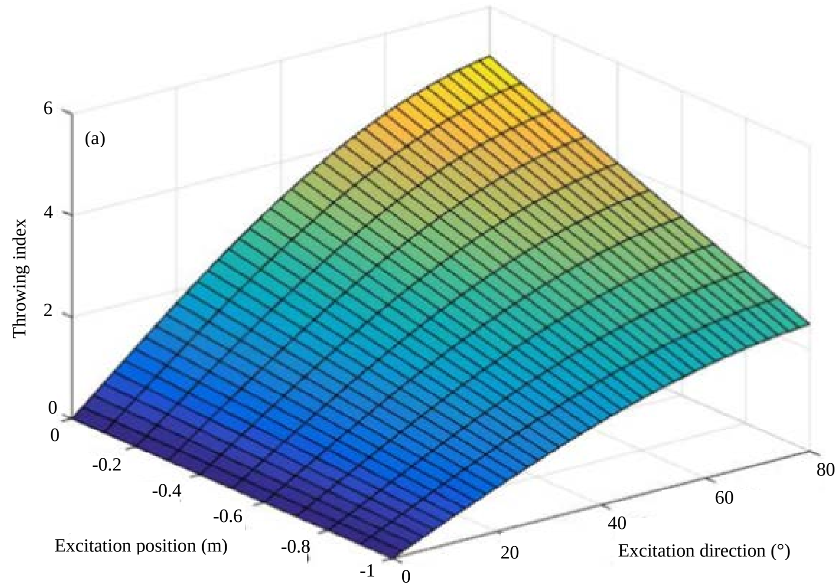
$$\frac{1}{E^*} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_j^2}{E_j} \tag{19}$$

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j} \tag{20}$$

$$\delta_{overlap} = \frac{r_c^2}{R^*} - \sqrt{\frac{4\pi\gamma r_c}{E^*}} \tag{21}$$

where, E_i, E_j are the elastic modulus of particles i and j respectively, v_i and v_j are the Poisson's ratio and $\delta_{overlap}$ is the overlap length of two contact particles.

Verification of DEM model: The DEM simulation model is examined here using the experimental data available in the literature (Zhang and Deng, 2013; Hoberock, 1980). To compare with the experimental data, all the working parameters of shale shaker are as the same as experiment conditions, which are shown in Table 1 except the excitation position $l_0 = 0$. The results are shown in Table 2.



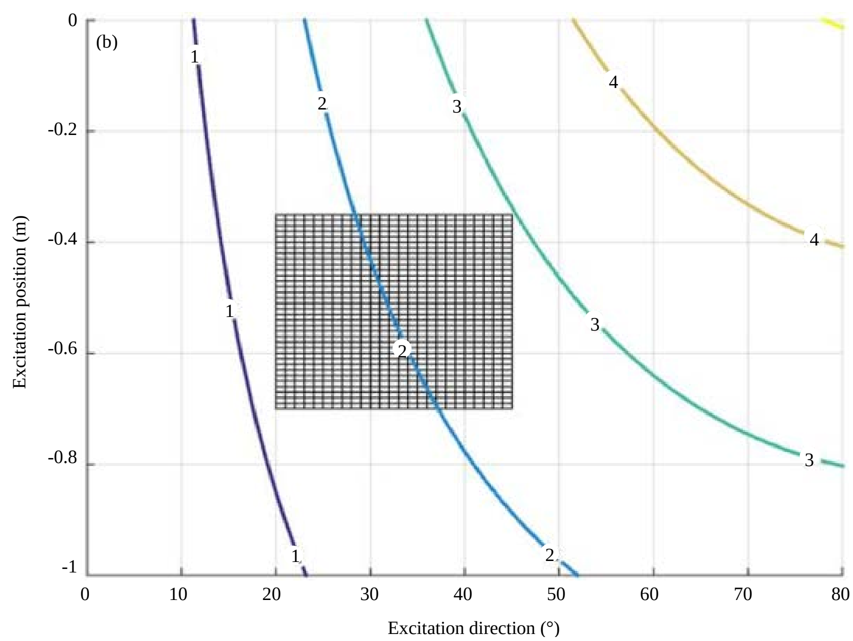


Fig. 6(a-b): Distribution of throwing index at outlet, (a) Distribution of throwing index and (b) Projection figure of contour line

Table 2: Comparison between DEM simulation and experiment

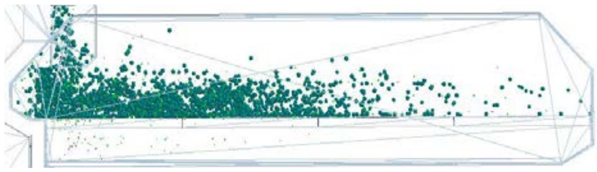
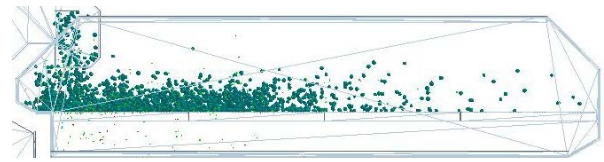
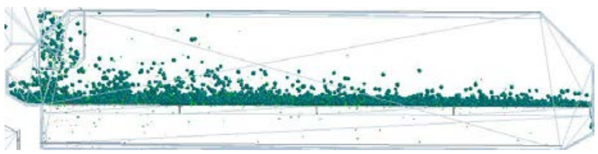
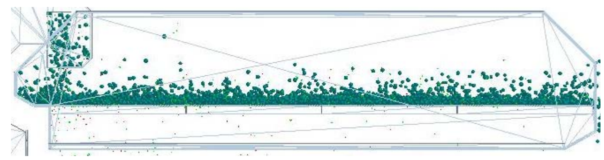
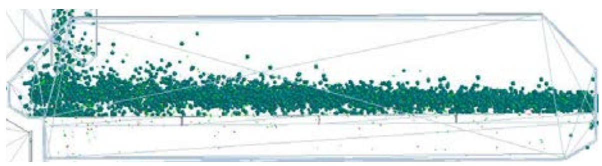
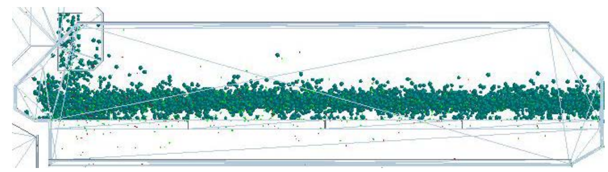
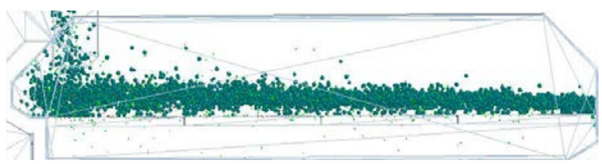
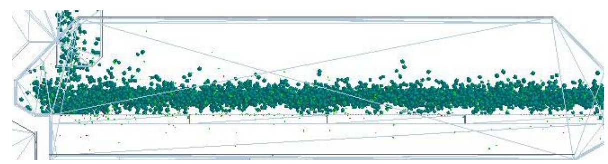
Parameters	DEM simulation	Experiment
Conveyance velocity (m sec^{-1})	0.256	0.27
Error (%)	5.2	

Table 2 shown, comparing with experiment data, the error of DEM simulation is 5.2% within permissible error rang. Therefore, the DEM model built in this study is reasonable and accurate. When the excitation position is not zero, the basic DEM simulation model and parameters of particles are unchanged, the alteration of working parameters of shale shaker will not affect the accuracy of discrete element method. Therefore, in this case the DEM model is also suitable.

RESULTS

Screening process: Based on the DEM simulation model with respect to parameters in Table 1, the screening processes of linear and variable linear shale shaker are obtained, as the Table 3 shown.

Table 3: Comparison on screening process between variable linear and linear shale shakers

Variable linear	Linear
	
t = 0.5 sec	
	
t = 1 sec	
	
t = 1.4 sec	
	
t = 2 sec	

At the beginning t = 0.5 sec, the particles just move to the middle of screen deck. Under the interactions between particles, mostly particles are transported forward by the vibrating screen, but some of the particles which the diameter is smaller than the screening size are passing through the screen deck under the interactions between particles. At this time, particles have not yet come into the steady moving stage, so the differences between these two type shale shakers are not very obvious. When t = 1 sec, the screen deck vibrates downward, mostly particles fall down to the screen deck after one throwing motion. And without the exciting force of screen deck, particles are unable to achieve a new round of throwing motion. So for both of the shale shakers, most particles stay on the screen deck keep relative static to it. When t = 1.4 and t = 2 sec, screen deck vibrates upward, particles jump up under the exciting force from screen deck. Most particles move forward by throwing motion. Compared with the beginning time, the particles have come into a steady moving stage, the differences on particles distribution between the two type shale shakers are increasingly obvious. As the figure shown, for variable linear shale shaker, particles jump higher around the inlet and lower around the outlet, while for the linear shale shaker particles almost keep the same height.

Variety of throwing height: Throwing index as an important parameter of screening equipment, which is a parameter calculated by exciting amplitude, frequency and direction. It cannot be obtained directly in discrete element simulation. But throwing height, which increases as the throwing index, can be easily obtained. So the changing law of throwing index is obtained by analyzing the throwing height of particles. To research the changing law of throwing index in the longitude direction of screen deck, which is divided into eight parts and marked as D1~D8, respectively, as Fig. 7 shown.

The change law of throwing height, which is characterized in terms of the position of particles in y direction, denoted as y-position, is shown as Fig. 8. In D1 section, particles fall to the screen deck from the inlet, which locates a higher place than the screen deck, so the average y-position of particles is higher than the other sections obviously. From D2-D8, namely from the inlet to outlet of screen deck in longitude direction, the screen deck do the reciprocating motion in a fixed direction and every point on the screen deck has the same moving track for the linear shale shaker, so the throwing height (throwing index) of particles almost keeps the same from inlet to the outlet. For the variable linear shale shaker, the screen deck rotates around the mass center clockwise while vibrating upward, which changes the moving tracks of point on the screen deck. Around the inlet,

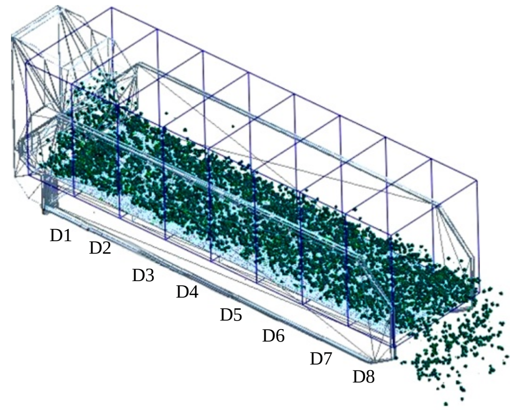


Fig. 7: Divisions of screen box

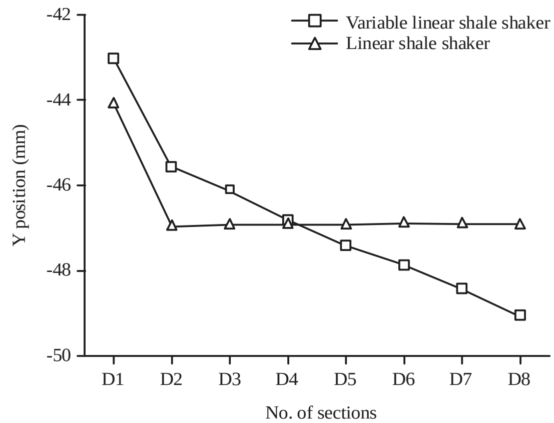


Fig. 8: Influence of excitation position on throwing height

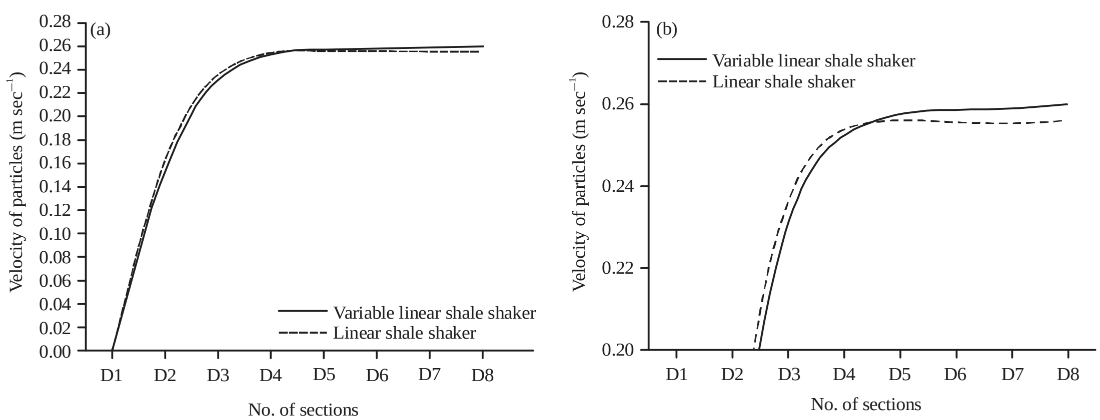


Fig. 9(a-b): Conveyance velocity of particles at different sections of the screen, particles at every section and (b) Velocity of particles at main section

the trajectory slope is bigger, so the exciting force in the y component is bigger and particles can jump higher, which increase the throwing height (throwing index) of particles. On the contrary, around the outlet, the trajectory slope is smaller, which results to throwing index is smaller.

Variety of velocity: In this context, in order to compare the change law of conveyance velocity in the longitude direction of screen deck between the two type shale shakers, the screen deck is divided into 8 sections just as the Fig. 7 shown. So the average velocity in each section can be obtained, as Fig. 9

shown. In D1 section, particles just fall to the screen deck from the inlet with gravity acting on them, so particles only have the velocity in y direction and the conveyance velocity (x direction) in this section is near to zero. Then in D2~D3 section, under the interactions between particles and exciting force from screen deck, particles can get energy to jump up and move forward. At these sections, the relative velocity between particles and screen deck are significant, so the relative acceleration is big, the velocity of particles can increases rapidly from zero. In D3~D8 parts, the movement of particles has reached to a stable stage, the velocity of particles are closer to the screen deck. For linear shale shaker, the exciting force in x-direction is all the same along the screen deck. Once the movement reached to a stable stage, the conveyance velocity of particles almost keeps the same. For the variable linear shale shaker, the exciting force in x-direction increase along the deck, which will improve the velocity in x direction, so in these sections, the velocity of particles can still increases slowly.

DISCUSSION

At present, the discrete element simulation on screening equipment is mainly aim to the linear vibrate mode and circular mode (Dong *et al*., 2013; Zhao *et al*., 2010, 2011), the mode of variable linear is first researched by this method. Compared with the results, the different diameters particles follow the same moving mode that particles are moving forward by throwing motion under the exciting force of screen deck. When the screen deck vibrate downward, particles fall down to the screen deck and move with it to prepare for the next round of throwing motion. When the screen deck vibrate upward, particles jump up and move forward by throwing motion. But compared with the linear vibrating screen, the variable linear shale shaker change the moving track of screen deck and consequently change the distribution of particles.

The throwing index has been studied in many manuscripts (Dong *et al*., 2013; Elskamp and Kruggel-Emden, 2015), but all of these studies are aim to linear mode vibrating and the throwing index is taken as constant value along the screen deck. A comparison between the linear mode and variable linear shale shaker on throwing height is shown in Fig. 8. For the linear shale shaker, the throwing index almost keeps unchanged. It reveals that in the study of linear shale shaker, it is proper to consider it as a constant value. However, for the variable linear shale shaker, the throwing index decrease gradually along the screen deck, which agrees well with the theoretical results shown in Fig. 4.

In the study of Dong *et al*. (2013) the results confirm that particle velocity along a screen plays an important role in governing the sieving performance. In their case, when on the sieve bend, particles velocities keep increasing from the feed end to the discharge end under the effect of gravity. But for linear shale shaker in this study, the screen deck is horizontal. So the gravity acted on particles is the same along the screen deck, which results to the particles velocities almost keep the same from the inlet to outlet.

Comparing the simulation results with the theoretical analysis, the change laws of velocity have the same trend, but the theoretical velocity is bigger and increase tendency is more obvious. Because in the theoretical analysis, the results are based on the stable state of solid-conveyance, the interactions between particles, viscous resistance and different kinds of movement conditions are neglected. Usually the collisions between particles generating energy losses which inevitably decreases the moving velocity of particles. For variable linear shale shaker, the exciting force in x-direction is bigger around the outlet, which is conducive to improve the conveyance velocity. But the accumulation of particles is also obvious, which will produce more collisions between particles and decrease the velocity to some degree. So combined the two factors, the simulation results are more reliable, namely the velocity of particles of variable linear shale shaker will increase, but it will not be so obvious.

Combining all the above discussion, the variable linear shale shaker is unable to change the conveyance velocity to a great degree comparing with the linear mode, but the most important meaning of it lies in that it can change the distribution of velocity in the longitude direction of screen deck and accomplish the redistribution in an ideal way. In other words, it has higher throwing index around inlet and higher conveyance velocity around the outlet, which is the perfect working way of petroleum shale shakers.

CONCLUSION

In this study, the kinematical equation of variable liner shale shaker is built and trajectory equation is deduced. Based on that, the trajectory gradient, throwing index and throwing velocity of particles are studied. In addition, the suitable value ranges of l_0 and β_0 are determined. The following conclusions can be achieved.

- Based on the trajectory equation of variable linear shale shaker, the changing laws of trajectory gradient, throwing index and throwing velocity in the longitude direction of screen deck are achieved. When excitation position $l_0<0$, throwing index is bigger around the inlet and conveyance velocity is bigger around the outlet, which is conducive to solid-liquid separation and solid conveyance
- Through analyzing the distribution of throwing index at the inlet and outlet, respectively, the suitable value ranges of excitation position and direction are determined: $-0.5\ m<l_0<-0.35\ m$, $35°<\beta_0<45°$
- The DEM simulation model of variable linear shale shaker is built based on JKR contact model, which is validated by experimental data. The simulation results and theoretical research are well consistent with each other. Although, the variable linear shale shaker is unable to change the conveyance velocity and the filter ratio to a great degree, the significant advantage of it lies in the fact that it can change the distribution of velocity in the longitude direction of screen deck and accomplish the redistribution in an ideal way

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