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Study on Migration Law of Solid Particles on Sieve Surface of Solid-liquid Separator

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Abstract: Based on the discrete element method and the three-dimensional discrete element analysis software EDEM, simplify the tube net type solid liquid separator model, to explore the net type solid liquid separator inside the cylindrical screen opaque screen the migration law of solid phase particles and different vibration frequency, vibration amplitude, vibration direction Angle, diameter of sieve sieve speed and sieve cylinder is opaque screen the influence of solid phase particles migration rule, In order to provide reference for the selection of structural parameters and vibration parameters of solid-liquid separator in field application. The results show that the motion trajectory of solid particles on the screen is a three-dimensional spiral curve. The larger the vibration frequency and amplitude of the screen box, the higher the particle migration speed. The larger the vibration direction Angle, diameter and speed of sieve box, the smaller the particle migration speed. The research results can be used for reference in the selection of structural parameters and motor vibration parameters that affect the comprehensive performance of the cylinder net solid-liquid separator.

Keywords: Discrete element method, Solid-liquid separator, Solid phase particles, Vibration parameters, Solid phase transport velocity.

1. Introduction

Modern drilling fluid solid control system is mainly composed of drilling shaker, degassing device, demud device, sand device, etc., its role is used to remove the harmful solid phase in drilling fluid, retain useful solid phase. As the first solid control equipment of the solid control system, the main function of the drilling shaker is to remove a large number of large particles of cuttings in the drilling fluid [1]. In order to handle different drilling fluid conditions, the variety of drilling shakers has been gradually increased. Zhang Minghong et al. [2] designed a composite drum-type screen structure for drilling fluid. The screen is made of ordinary flat screen or corrugated conical screen rolled into a tubular structure and can be installed on the existing drilling shaker. When the screen cylinder and screen box vibration together, but also around its axis for slow rotation transport; Trond et al. [3] applied the vacuum filtration system to solid-liquid separation of drilling fluid. Hou Yongjun et al. [4] designed a negative pressure drilling fluid vibrating screen, which used the vacuum system under the screen surface to generate negative pressure and improve the solid-liquid separation efficiency.

During the work of drilling shaker, the migration law of solid particles on the screen surface has a direct impact on the working performance and processing capacity of the shaker. Scholars at home and abroad have done a lot of theoretical research, numerical simulation calculation and test verification on the operation law of solid phase particles on drilling shaker. Zhu Weibing [5] established a theoretical model of solid particle transport on the screen surface of a biaxial inertial vibrating screen. Hou Yongjun [6] studied a kind of vibrating screen with tubular mesh structure and established a theoretical model of solid phase particle migration. Zhou Sizhu et al. [7] simulated the migration process of solid particles on the surface of linear screen by combining the three-dimensional discrete element analysis software EDEM. Under stable working conditions, the migration velocity of particles tends to a stable value, and the smaller the particle size, the smaller the migration velocity. Yang Qianqian et al. [8] studied a new vibrating screen combined with a negative pressure system, and established a mathematical model of the processing capacity and treatment effect of the solid-liquid separator. Zhao et al. [9] used the discrete element method to conduct a mathematical study on the particle flow on the banana sieve plate. Nozali T et al. [10] established a dynamic model of particles in solid-liquid two-phase flow based on the solid-liquid separator of cone drum rotation type, and carried out visual experiments. They found that the drum length, taper Angle, drum speed and particle diameter all affected the migration velocity and migration trajectory of particles. Hou et al. [11] studied the migration law of solid particles on the negative pressure drilling fluid vibrating screen, and analyzed the influence of the negative pressure system on the structural parameters of the vibrating screen. They found that the transport speed of solid particles by the negative pressure vibrating screen was slower than that of the traditional vibrating screen, which was more conducive to liquid-solid separation.

In view of this, the above article mainly studies the solid phase particle migration law of the screen surface of the vibrating screen for the plane screen, and the particle migration law of the drum screen vibrating screen is less mentioned. Therefore, this paper mainly studies the migration law of solid particles on sieve surface of cylinder-mesh solid-liquid separator, establishes the migration velocity model of solid particles in sieve cylinder, and analyzes the influence of different vibration parameters on the migration velocity of solid particles on sieve screen of cylinder-mesh solid-liquid separator.

2. The Theoretical Model of Solid Phase Particle Transport Velocity of Impenetrable Sieve Was Established

2.1. Brief introduction of cylinder net solid liquid separator

The solid liquid separator is mainly composed of a shaker, a synchronous motor, a screen box, a screen cylinder and a spring bracket. This is shown in Figure 1.The working principle is that the vibrating surface of the roller type screen and screen box is vertically installed in the screen box, and the two vibrators rotate in reverse and synchronously to make the overall trajectory of the screen box translational ellipse.

Figure 1. Structure of solid-liquid separator. 1 Vibration motor, 2 Box, 3 Damping spring, 4 Screen cylinder, 5 Pulley.

2.2. Solid liquid separator screen surface movement track

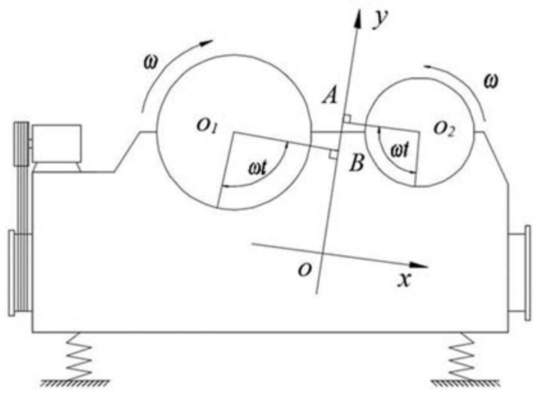


Figure 2. Simplified sieve box model of solid liquid separator.

Ignoring the influence of damping, the dynamic equation of screen box motion is established as follows:

$$\begin{cases}(M+m_1+m_2)\ddot{x}=(m_1r_1-m_2r_2)\omega^2\cos\omega t\\(M+m_1+m_2)\ddot{y}=(m_1r_1+m_2r_2)\omega^2\sin\omega t\\(J+J_1+J_2)\ddot{\theta}=(m_1r_1l_1-m_2r_2l_2)\omega^2\sin\theta\omega t+(m_1r_1l_3+m_2r_2l_4)\omega^2\cos\theta\omega t\end{cases}\tag{1}$$

Then the steady-state response of the solid-liquid separator box is:

$$\begin{cases}x=A_x\cos\omega t\\y=A_y\sin\omega t\\\theta=A_{\theta 1}\cos\omega t+A_{\theta 2}\sin\omega t\end{cases}\tag{2}$$

$$\begin{cases}A_x=\dfrac{m_1r_1-m_2r_2}{m_1+m_2+m_3}\\A_y=\dfrac{m_1r_1+m_2r}{m_1+m_2+m_3}\\A_{\theta 1}=\dfrac{m_1r_1l_1-m_2r_2l_2}{J+J_1+J_2}\\A_{\theta 1}=\dfrac{m_1r_1l_3-m_2r_2l_4}{J+J_1+J_2}\end{cases}\tag{3}$$

Based on the above formula, it can be concluded as follows:

$$\begin{cases}\ddot{x}=-A_x\omega^2\cos\omega t\\\ddot{y}=-A_y\omega^2\sin\omega t\end{cases}\tag{4}$$

In the equation, M -the total mass of mud to be treated in the screen box and the screen cylinder, Kg; m_1- the mass of the large shaker eccentric block, Kg; m_2- the mass of small shaker eccentric block, Kg; r_1- the eccentricity of the large shaker eccentric block, m; r_2- the eccentricity of small shaker eccentric block, m; ω- the speed of the excitation motor, rad/s; J,J_1,J_2-respectively represents the moment of inertia of screen box, large eccentric block, small eccentric block relative to the center of mass, Kg•m^2A; $\ddot{x}$, $\ddot{y}$ -the acceleration of the center of mass of the sieve box along the x and y directions, respectively, m/s^2; $\dot{x}$, $\dot{y}$ - the velocity of the center of mass of the screen box along the x and y directions, m/s; $\ddot{\theta}$ -the angular acceleration of the screen box rotating around the center of mass, rad/s^2; $\dot{\theta}$ -the angular velocity of the screen box rotating around the center of mass, rad/s; l_1,l_2- the distance between the shaker rotation center and the y-axis, m; l_3,l_4- the distance between the shaker rotation center and the x-axis, m;

2.3. The transport velocity model of solid particles in sieve tube was established

Solid liquid separator at run time, the mud from the sieve tube into the mouth, the liquid phase gradually through sieve, solid phase carry forward gradually, has experienced from the submerged condition of solid phased particles to transition state and the submerged condition three phases, solid particles in the solid-liquid separation process always has interaction with liquid, solid phase particles has been in the condition of wet particles. The interaction between solid particles and liquid in the inundation and transition phases is complex and will not be studied here. In this paper, the migration law of solid particles in impenetrable sieve under non-submerged condition is studied.

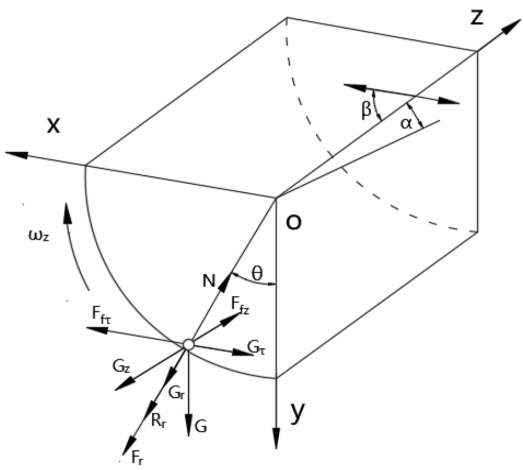


Figure 3. The force of solid particles on the screen cylinder

In actual working conditions, the shape of solid particles in the screen cylinder is random. When analyzing the stress of solid particles in the screen cylinder, the shape of particles is simplified to spherical equivalent particles for analysis [1]. Take part of the cylindrical screen as the research object, the establishment of the submerged condition of cylindrical screen of the cylindrical coordinates, as shown in Figure 3, the particles will be influenced by gravity, inertia, screen upward force, friction force, residual mud the cohesive force of the direction where the radius of the cylindrical screen r, z axis direction of cylindrical screen, the tangent direction of cylindrical screen, decomposition and composition of the particles in these three directions are:

$$\begin{cases} F_\tau = F_{f\tau} - G_\tau - m\left(a_\tau + \Delta\ddot{\tau}\right) \\ F_r = R_r + G_r - m\left(a_r - r\omega_z^2 + \Delta\ddot{r}\right) - N \\ F_z = F_{fz} - G_z - m\left(a_z + \Delta\ddot{z}\right) \end{cases} \quad (5)$$

In the equation, F_r, F_z, F_τ - the radial, axial and tangential components of the resultant force on the particle, N; G_r, G_z, G_τ -the radial, axial and tangential forces of gravity on the particle, N; a_r, a_z, a_τ -the radial, axial and tangential components of the screen cylinder acceleration, m/s; N -the supporting force of the screen on particles, N; r- the radius of screen cylinder, m; R-the component force of the bonding force between particles along the radius direction, N[8]; $\Delta\ddot{r}, \Delta\ddot{z}, \Delta\ddot{\tau}$ - the acceleration components of the particle along the radial, axial and tangential directions respectively.; ω_z – the Screen cylinder angular velocity, rad/s.

$$R_r = \left(\frac{\pi d_s \tau_0}{2} + \alpha_m \pi d_s\right) cos\,\theta\, cos\,\alpha \quad (6)$$

In the equation, τ_0 - the dynamic shear stress of mud, N/m; α_m - the surface tension of mud, N/m. α - screen barrel inclination Angle, rad; θ -the position of particles in the screen, rad; d_s - the diameter of two adjacent bonding particles, m.

Solid liquid separator in the process of operation, the solid phase particles on the surface of the screen are relatively static, relative sliding, throwing movement three movement forms, studies have shown that throwing motion is cylindrical screen within the solid state of ideal gas migration, in throwing motion not only has faster conveyance speed of solid phased particles and particles increased drilling fluid during cast to sieve sieve area [6].

According to Newton's second law, at the moment of throwing motion between particles and screen, the radial relative acceleration between particles and screen surface is $\Delta\ddot{r} = 0$, the supporting force of screen on particles isN=0, and the force of particles on screen is F_r =0. Then the equilibrium equation of particles in radial direction is as follows:

$$N = R + G_r - m\left(a_r - r\omega_z^2\right) = 0 \quad (7)$$

The throwing exponent is an index to measure the throwing motion of solid particles. The throwing exponent in the process of throwing motion reflects the throwing exponent and the ability of solid particles to have throwing motion. The value of the throwing index $D(\theta)$ is the ratio of the radial component of the vibration acceleration value of the particle, the radial component of the gravity acceleration and the centrifugal acceleration, that is, the ratio of the driving force and the resistance of the particle on the screen surface.

The particle throwing index $D(\theta)$ at position θ on the screen is [6] :

$$D(\theta) = \frac{-A_y \omega^2 \sin\omega t \sin\beta \cos\theta}{R_m + g\cos\alpha\cos\theta + r\omega_z^2} \quad (8)$$

Among them:

$$R_m = \frac{R}{m} \quad (9)$$

For solid particles to undergo throwing motion, the throwing index must meet the following conditions:

$$D(\theta) > 1 \quad (10)$$

Therefore, the range of throwing motion of particles in the sieve cylinder is as follows:

$$-\theta_0 < \theta < \theta_0 \quad (11)$$

In the equation:

$$\theta_0 = \arccos \frac{R_m + r\omega_z^2}{-\left(\lambda\omega^2 \sin\delta + g\cos\alpha\right)} \quad (12)$$

The average migration rate of particles on the whole screen is:

$$\bar{v} = \frac{1}{2\theta_0}\int_{-\theta_0}^{\theta_0} \bar{v}(\theta)\,d\theta \quad (19)$$

Among them:

$$\bar{v}(\theta) = \frac{\omega}{2\pi}\left\{\frac{1}{2\omega^2} g\sin\alpha(\phi_2-\phi_1)^2 - A_x\cos\beta\left[\sin\phi_2 - \sin\phi_1 - (\phi_2-\phi_1)\cos\phi_1\right]\right\} \quad (20)$$

In the above equation, ϕ_1 -the initial phase Angle of the projectile motion, rad; ϕ_2 - the phase Angle of the end of the projectile motion, rad.

3. Establishment of Discrete Element Method and EDEM model

EDEM is a multipurpose modeling software, the discrete element method is often used in the industrial production in grain processing and manufacturing equipment of the production process of the simulation and analysis, the user can use EDEM quickly and easily create particles parameterized model of entity, thus acquiring the trajectories of particles in mechanical equipment, migration velocity, particle force data such as [12]. The combination of discrete element method (DEM) and EDEM software can accurately reflect the motion state of the solid particles in the sieve cylinder of the solid-liquid separator, and reproduce the motion law of the sieve particles on the sieve surface.

The simplified sieve tube model is shown in Figure 4. Due to the limitation of computer capacity, the size of the sieve tube is reduced to 1/4 of the conventional size, and the diameter of the sieve tube remains unchanged. As the main research object of this paper is the migration law of sieve particles, the sieve tube model will not be opened. When the mesh number is 25 mesh, the particle size parameter of the impenetrable screen is taken as the size parameter of the simulation particle.

3.1. Selection of particle contact model

In EDEM software, the Hertz-Mindlin and Hertz-Mindlin with JKR Cohesion models are suitable for particle contact in the sieve cylinder. The Hertz-Mindlin contact model is mainly used to study the contact between particles without bonding effect. Hertz-mindlin with JKR Cohesion was established based on the JKR theory, which mainly considered the effect of Cohesion between wet particles on particle motion based on Hertz theory. The actual working area of the drum screen is only in the lower part of the screen cylinder, and the contact probability between wet particles is large, so the bonding between particles should be considered. JKR model was selected as the contact model between particles. The interaction force between particles in the JKR model can be obtained according to the empirical formula (21) [13].

$$F = \frac{1}{3}\pi\gamma d \quad (21)$$

Among them:

$$\frac{1}{d} = \frac{1}{d_1} + \frac{1}{d_2} \quad (22)$$

In the equation, F -the interaction force between particles,N; γ - the density of particles,rad; d - the equivalent diameter of the bonded particles,m ; d_1, d_2 - the diameters of the two bonded particles, m.

3.2. Particle parameter Settings

The types of drilling fluids are mainly divided into oil-based and water-based drilling fluids, and water-based drilling fluids are selected as the treatment object carrier. The particle shape is simplified as ball type, and the particle diameter is selected from the 25 mesh screen. The diameter size of the impermeable sieve particles is 0.8mm~2.0mm. Specific dimensions are shown in Table 1:

Table 1. Grain size comparison table

Numble	1	2	3	4	5	6	7
Particle diameter /mm	0.8	1.0	1.2	1.4	1.6	1.8	2.0

The number of particles and the generation rate are shown in Table 2:

Table 2. Generate particle parameter table

Numble	1	2	3	4	5	6	7
Number of particles	200	400	500	600	500	400	200
Generation rate(s-1)	40	80	100	120	100	80	50
Initial velocity(m/s)	0.15	0.15	0.15	0.15	0.15	0.15	0.15

After studying the basic properties of particles in drilling fluid and referring to the particle parameter recommendation in the Open GEMM Wizard particle library in EDEM software, the accumulation Angle of particles was input [14].

The material parameters of particles and screen screen selected were shown in Table 3, and the contact parameters between particles and particles and between particles and materials were shown in Table 4.

Table 3. Material parameters

Parameter	Solid phase particles	Screen box and screen mesh
Poisson's ratio	0.2	0.3
Density(Kg/m3)	2600	7800
Shear modulus(Pa)	5e+07	7e+10

Table 4. Contact parameters

Parameter	Particle - Particle	Particle - Screen mesh
Coefficient of restitution	0.003	0.4
Coefficient of rolling friction	0.4	0.5
Coefficient of static friction	0.15	0.01

The particle factory in the EDEM model is set at the feed inlet of the screen cylinder as shown in FIG. 4. In order to simulate the real operating conditions, the shape of the particle factory is set as a 12-sided type (approximately a circle) with a diameter of 120mm, and the initial velocity of the particle is set as 0.1m /s, with the direction along the gravity direction.

Figure 4. The model of cylindrical screen

3.3. Case Verification

The post-processing function of EDEM software was used to calculate the velocity change trend chart of solid phase particles in the stable process from generation to migration, as shown in Figure 5.

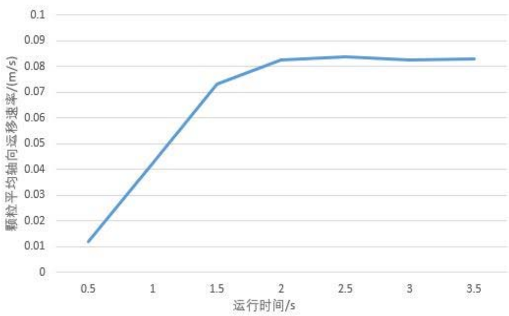


Figure 5. Transport velocity of solid particles on screen surface

The broken lines in the figure represent the changes of the actual migration velocity of dry solid particles on the screen surface. It can be seen from the figure that the migration velocity of particles on the screen surface gradually tends to a stable value, that is, 0.0826m/s, with time. It was compared with the measured and calculated values of the solid phase particle migration velocity on the screen surface of the drum solid-liquid separator with the same parameters [6]. The results showed that the theoretical, measured and EDEM simulation values of the migration velocity were 0.0891m/s, 0.071 m/s and 0.0826 m/s, respectively. The errors of theoretical values and EDEM simulation values are 25% and 16%, respectively.

According to the analysis, the simulation error value of EDEM is smaller than the theoretical error value, and the error sources are mainly the following factors:

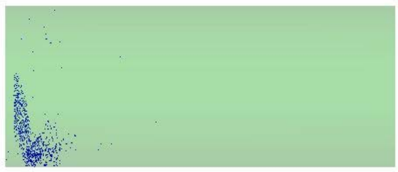
(1) In the theoretical calculation of particle velocity, only the force and operation of a single particle are considered, and the energy loss caused by the collision between particles is ignored, resulting in a large calculation result.

(2) In the theoretical study, the influence of the roughness of the screen on particle migration is not considered, so that the theoretical calculation results are too large.

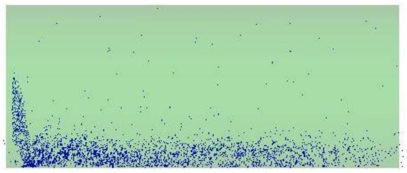
4. Simulation of Particle Migration Trajectory

4.1. Analysis of solid particle migration process in sieve tube

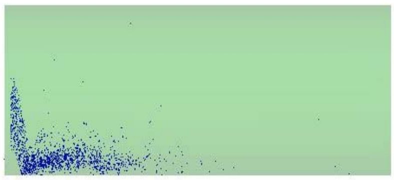
EDEM software was used to simulate the migration trajectory of particles. The simulation results of particle trajectory are shown in Figure 6:



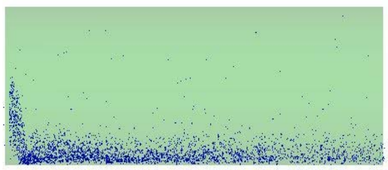
(a).t=0.3s



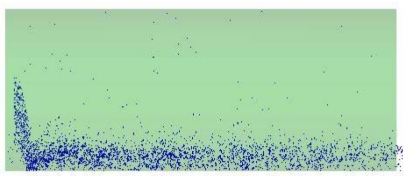
(c).t=2.0s



(b).t=0.7s



(d).t=2.6s



(e).t=3.0s

Figure 6. Particle transport process on the screen surface

In Figure 6 a, t=0.3s, particles with axial initial velocity fall from the particle factory to the screen, and some particles have been thrown along with the screen cylinder.

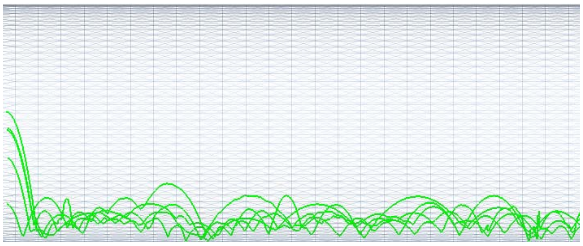
In Figure 6 b, t=0.7s, the solid particles falling off the screen begin to be transported forward with the vibration of the screen cylinder. It can be seen from the figure that at this moment, the particle group is in the state of upcasting and the particles are relatively dispersed.

In Figure 6 c, t=2.0s, the particles on the screen are thrown up with the sieve cylinder, and the particles are spread all over the sieve cylinder. The particles that initially flow into the sieve cylinder have been thrown out from the outlet of the sieve cylinder. Some of the larger particles are thrown higher and fall back after colliding with the upper part of the sieve cylinder. Therefore, compared with the traditional plane screen, the advantages of drum screen are reflected.

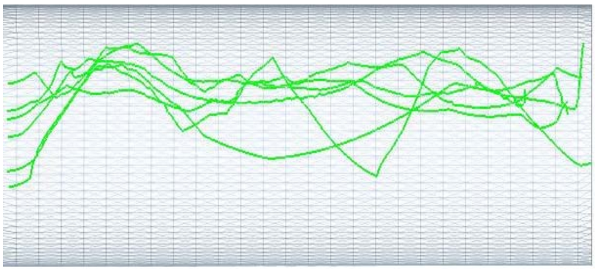
In Figure 6 d, t=2.6s, the particles on the screen surface fall down with the screen, and most of the particles gather at the bottom of the screen cylinder.

In Figure 6 e, t=3.0s, the screen moves upward. Compared with Figure 6 c, the particle distribution is more uniform, and the particle migration is gradually in a stable state.

4.2. Trajectories of particles on the screen surface



(a). The trajectory of a particle in the x-y plane



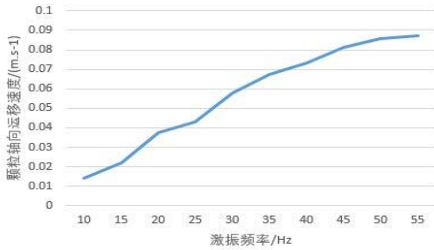
(b). The trajectory of a particle in the x-z plane

Figure 7. Particle transport track

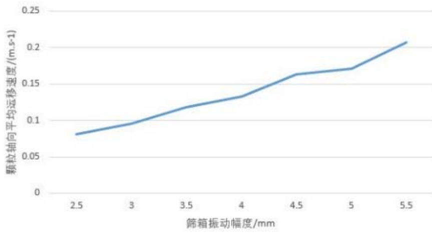
From the Figure 7, it can be seen that the solid rock debris particles in drilling fluid make translational elliptic vibration (associated motion) with the sieve box, and rotate with constant axis (relative motion) around the axis of the sieve box. Under the action of related motion and relative motion, the solid rock particles move in a three-dimensional spiral curve (absolute motion). Under the dual action of throwing and centrifugation, it not only increases the processing capacity of drilling fluid, but also promotes the efficient separation of solid and liquid.

5. Simulation Analysis of Influencing Factors of Particle Migration Law

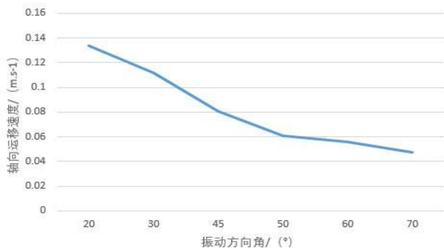
The processing capacity and treatment effect of the solid-liquid separator are the main indexes to evaluate its performance, which are mainly related to the solid phase transport speed and the sifting flow rate [8]. The main factors affecting the transport speed of solid particles are vibration frequency, amplitude, vibration direction Angle, screen speed and screen diameter. Control variable method is used to explore the influence of each parameter on the transport velocity of solid particles. The basic parameters are: vibration frequency 47Hz, amplitude: 2.32mm, vibration direction Angle: 45°, screen tube diameter 220mm, screen tube axial length: 500mm, screen tube speed: 20rpm, screen tube inclination: 0°.



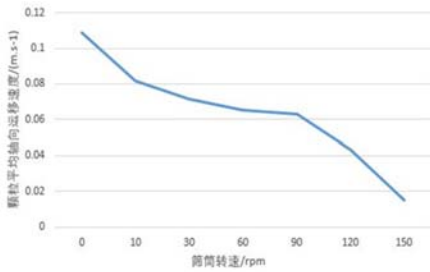
a. Effect of excitation frequency on axial migration rate



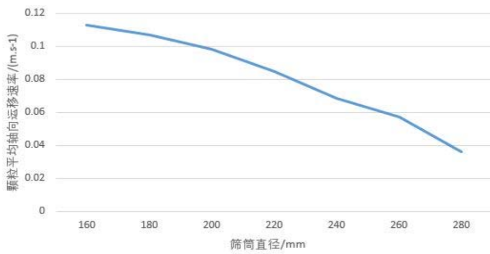
b. Effect of vibration amplitude on axial migration rate



c. Effect of vibration direction Angle on axial migration rate



d. Effect of sieve cylinder speed on axial migration rate



e. Effect of sieve tube diameter on axial migration rate

Figure 7. Plot of influence of each factor on particle axial migration rate

Can be seen from the above, the vibration frequency and vibration amplitude of screen box is proportional to the particle axial transport speed, increase the screen box can improve the vibration frequency and vibration amplitude conveyance speed of solid phased particles so as to improve the processing efficiency of solid liquid separator, but high particle migration velocity can reduce sludge retention time on screen, lead to after processing of solid phase fluid rate is too high and run slurry occur.

The vibration direction Angle of the screen box, the diameter of the screen box and the speed of the screen box are inversely proportional to the migration speed of the particles. Increasing the vibration direction Angle of the screen box, the diameter of the screen box, and the speed of the screen box will reduce the migration speed of particles, and the solid particles in the screen box will accumulate and block the screen, thus reducing the processing efficiency of the solid-liquid separator. Therefore, the parameters of the solid-liquid separator should be selected according to the type of mud to be processed, the volume fraction of solid phase and the mud flow.

6. Conclusion

Through the above research and analysis, the following conclusions are drawn:

(1) Based on the theoretical mechanics and kinematics, the kinematic equation of the sieve box and the mathematical model of the transport velocity of the solid particles in the sieve box were established

(3) The migration law of solid phase particles in the sieve tube of the translational elliptical vibration cylinder type solid-liquid separator was explored. The migration speed of particles on the sieve surface was taken as the index, and the influencing factors of the migration speed of particles in the sieve were explored by simulation.

(2) The results show that the motion trajectory of the solid particles on the screen of the cylinder-mesh solid-liquid separator is a three-dimensional helical curve, and the solid particles rotate around the axis of the sieve cylinder while making translational elliptic vibration with the sieve box. After the solid-liquid separator runs stably, the particle migration speed gradually approaches a stable value. The vibration frequency, amplitude, vibration direction Angle, diameter and speed of the sieve box all have an impact on the particle migration speed. The larger the vibration frequency and amplitude of the sieve box, the larger the particle migration speed. The larger the vibration direction Angle, diameter and speed of sieve box, the smaller the particle migration speed. The results can be used as a reference for the selection of parameters for the field use of the cylinder net solid-liquid separator.

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