Study on Optimization Parameters of Solid-Liquid Separator

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ABSTRACT In order to achieve solid-liquid separation and recycling of drilling fluid during petroleum drilling, a new type of solid-liquid separation device was designed and developed to achieve high-efficiency solid-liquid separation and low cost. The working principle of the equipment was introduced, the mechanical model was established, and the sieve flow of drilling fluid and the movement of wet particles in the real situation were analyzed. The relationship between the processing capacity of the solid-liquid separator and the speed of the solid phase in the drilling fluid and the speed of the excitation motor and the rotary drum were given. Multi-objective evolutionary algorithm was used to solve the multi-objective optimization model. Two typical evolutionary algorithms NSGA-II and MOEA/D were analyzed. An algorithm that solves this problem was selected and improved. A series of optimal solution sets for this problem were obtained by using the improved multi-objective evolutionary algorithm. Finally, based on the experimental prototype of the solid-liquid separator, a functional experiment was performed on the basis of the calculated optimal solution set. The experimental results show the feasibility of the multi-objective optimization model and algorithm.

INDEX TERMS Multi-motor, multi-objective evolutionary algorithm, optimization, solid-liquid separation.

I. INTRODUCTION

During the oil drilling process, drilling fluid will bring out a large number of cuttings from the bottom of the well. In order to recycle the drilling fluid, the drilling fluid and the cuttings need to be separated. The existing separation device mainly uses a shale shaker, which is a vibration separation machine that uses a forced vibration method to generate a periodic motion trajectory. The screen box and the screen are produced in the form of a circle, a straight line, an ellipse, etc. by the exciting force of a motor [1]. Under the action of vibration, the solid phase on the screen is transported along the screen surface from the feed port to the outlet. At the same time, the liquid phase and the solid phase with a particle size is smaller than the size of the screen pass through the screen together to achieve solid-liquid separation of the drilling fluid [2], [3]. In order to effectively carry out solid-liquid separation, this type of shale shaker also needs to add sand removal (mud), centrifuge, etc., so that the required exciting force is large, the power consumption of the motor is large, and the processing capacity and separation efficiency of the shale shaker are relatively low.

In order to improve the separation efficiency and reduce the production cost, a new type of solid-liquid separator is developed [4]. The new screen is made of ordinary flat screen rolled into a drum structure, and is installed on the screen box vertically with the vibrating surface of the screen box. When working, the roller screen vibrates together with the screen box, and at the same time makes a constant-speed rotational movement around its own axis. Relative to the ground, each point on the roller screen is performing space spiral motion, so after the drilling fluid enters the screen cylinder, it no longer performs plane motion like traditional sieve screens, but instead performs spatial motion. After one more dimension of motion, it is beneficial to improve the treatment effect. The solid-liquid separator is mainly composed of two vibration exciters, two synchronous motors, an outer cylinder, a screen cylinder, and a spring support. It is shown in Fig. 1.
The thesis mainly analyzes the working principle and screening mechanism of the new solid-liquid separator, combines the multi-objective optimization theory, selects the easily adjustable exciting motor and rotary drum speed as variables, establishes a multi-objective optimization model, and solves the appropriate speed to make the comprehensive performance of the solid-liquid separator optimal.

II. STUDY ON THE SCREENING MECHANISM OF SOLID-LIQUID SEPARATOR

A. WORKING PRINCIPLE

The vibration exciter of the solid-liquid separator is composed of two exciting motors. The eccentric block massradius-product of the two vibration excitors are different, as shown in Fig. 2 [5], [6]. When the motor starts, the centrifugal inertial force generated by the eccentric block drives the screen box to perform periodic elliptical motion. In normal operation, the two rotary drums rotate at the same speed in the opposite direction, it is shown in Fig. 2 (b).

Coordinate system is shown in Fig. 3, the vibration equations of the centroid of the sieve box in the x and y directions and the pitch vibration equation of the screen box to its centroid can be established [7], [8].

\[
\begin{align*}
(M + m_1 + m_2)\ddot{x} &= (m_1 r_1 - m_2 r_2)\omega^2 \cos \omega t \\
(M + m_1 + m_2)\ddot{y} &= (m_1 r_2 + m_2 r_2)\omega^2 \sin \omega t \\
(J + J_1 + J_2)\ddot{\psi} &= (m_1 r_1 l_3 - m_2 r_2 l_4)\omega^2 \sin \omega t \\
&\quad - (m_1 r_1 l_1 - m_2 r_2 l_2)\omega^2 \cos \omega t
\end{align*}
\]

In the equation, M-the mass of the screen box, Kg; \(m_1,m_2\)-the masses of the eccentric block 1 and the eccentric block 2, respectively, Kg; \(r_1, r_2\)-the eccentric distance of eccentric block 1 and eccentric block 2, m; \(\omega\)-the rotary angular velocity of the vibration exciter eccentric block, rad/s; \(J, J_1, J_2\)-the moment of inertia of the screen box and the eccentric block 1 and the eccentric block 2 relative to the centroid O, Kg-m²; \(x, y\)-the acceleration of solid-liquid separator centroid in x, y directions, m/s²; \(\dot{\psi}\)-the angular acceleration of solid-liquid separator swinging around the centroid rad/s²; \(\dot{x}, \dot{y}\)-the velocity of the solid-liquid separator centroid in the x, y directions, m/s; \(\psi\)-the angular velocity of solid-liquid separator swinging around the centroid rad/s; \(l_1, l_2\)-the distances from O₁ and O₂ to the x-axis, that is, \(l_1 = OA, l_2 = OB\), m; \(l_3, l_4\)-the distances from O₁ and O₂ to the y-axis, that is, \(l_3 = O_1A, l_4 = O_2B\), m.

Stationary solutions can be obtained by solving the above equations:

\[
\begin{align*}
x &= A_x \cos \omega t \\
y &= A_y \sin \omega t \\
\psi &= A_{\psi 1} \sin \omega t - A_{\psi 2} \cos \omega t \\
\end{align*}
\]

Among them

\[
\begin{align*}
A_x &= -\frac{m_1 r_1 - m_2 r_2}{M + m_1 + m_2} \\
A_y &= -\frac{m_1 r_2 + m_2 r_2}{M + m_1 + m_2} \\
A_{\psi 1} &= -\frac{(m_1 r_1 l_3 - m_2 r_2 l_4)}{(J + J_1 + J_2)} \\
A_{\psi 2} &= \frac{(m_1 r_1 l_1 - m_2 r_2 l_2)}{(J + J_1 + J_2)} \\
A_\psi &= \sqrt{A_{\psi 1}^2 + A_{\psi 2}^2} \\
\chi &= \arccos(A_{\psi 1}/A_\psi)
\end{align*}
\]

B. FORCE ANALYSIS OF PARTICLES ON A ROLLER SCREEN

Take out a part of the roller screen as the research object, establish a coordinate system as shown in Fig. 4, and decompose the received gravity, inertia force, screen support force,
and friction force along the radial direction \( r \), axis direction \( z \), and tangential direction \([9],[10]\). Then the force of the particles in the three coordinate directions is

\[
\begin{aligned}
P_f &= P_{f\tau} - G_r - m(a_r + \Delta \ddot{r}) \quad (7) \\
F_r &= G_r + F_r - m(a_r + \Delta \ddot{r}) - N \\
P_z &= P_{fz} - G_z - m(a_z + \Delta \ddot{z})
\end{aligned}
\]

In the equation, \( N \)-The supporting force of the screen against the particles, N; \( m \)-mass of particles, Kg; \( r_T \)-the screen cylinder radius, m; \( \omega \)-rotating angular speed of screen cylinder, rad/s; \( F_r \)-centrifugal inertia forces on particles, N; \( P_f \), \( P_r \), \( P_z \)-tangential resultant force, radial resultant force, and axial resultant force, N; \( P_{f\tau} \), \( P_f \), \( P_{fz} \)-tangential friction and axial friction, N; \( G_r \), \( G_f \), \( G_z \)-tangential, radial, and axial components of gravity, N; \( a_r \), \( a_z \), \( a_z \)-the acceleration components of vibration acceleration in tangential, radial and axial directions, m/s\(^2\); \( \Delta \ddot{r} \), \( \Delta \ddot{z} \)-the relative acceleration of the particles along the screen surface in the tangential, radial and axial directions, m/s\(^2\).

Some parameters in equation (7) are expressed as follows:

\[G_r = G \cos \alpha \cos \theta = mg \cos \alpha \cos \theta \quad (8)\]

The vibration acceleration component in the three directions of \( r \), \( r \), \( z \) is

\[
\begin{aligned}
a_r &= B_1 \sin(\omega t - \beta_1) \omega^2 \sin \theta \quad (9) \\
a_r &= -B_1 \sin(\omega t - \beta_1) \omega^2 \cos \theta \\
a_z &= B_2 \sin(\omega t + \beta_2) \omega^2 
\end{aligned}
\]

Among them

\[
\begin{aligned}
B_1 &= \sqrt{(A_y \sin \delta)^2 + (A_x \cos \delta)^2} \quad (12) \\
B_2 &= \sqrt{(A_y \cos \delta)^2 + (A_x \sin \delta)^2} \quad (13) \\
\beta_1 &= \arccos(A_y \sin \delta / B_1) \quad (14) \\
\beta_2 &= \arccos(A_x \cos \delta / B_2) \quad (15)
\end{aligned}
\]

In the equation, \( \theta \)-the angle between the radial and vertical directions of the particles at a point on the screen, rad; \( \delta \)-angle between ellipse long axis direction and screen axis, rad; Where \( a_r \) is negative, because we select the upward direction as the positive direction \([10]-[13]\).

**C. THROWING INDEX**

On the roller screen, when the particles are relatively sliding on the screen surface, according to Newton’s second law, it can be obtained that the relative acceleration and relative displacement between the particles and the screen are zero, and in the direction perpendicular to the relative sliding, the resultant force is zero, that is, the resultant force in the radial direction \([14]-[17]\). According to equation (7), it can be obtained that the supporting force of the screen against particles is

\[N = G_r - m(a_r - r_T \omega^2) \quad (16)\]

In the equation, \( r_T \)-the radius of the rotary drum, m; \( \omega \)-the rotational angular velocity of the rotary drum, rad/s.

Finishing the above equations, we can get

\[D(\theta) = \frac{B_1 \omega^2 \cos \theta}{g \cos \alpha \cos \theta + r_T \omega^2} \quad (17)\]

\(D(\theta)\) is called the throwing index of the solid-liquid separator at position \( \theta \), and the value is the ratio of the radial component of the vibration acceleration of the particle to the sum of the radial component of gravity acceleration and centrifugal acceleration, which is actually the ratio of the driving force and resistance of the particle on the screen surface \([18]\).

The relationship between the throwing index and the speed of the exciting motor and the speed of the rotary drum motor is simulated and analyzed. The results are shown in Fig. 5 and Fig. 6.

**FIGURE 5.** Fluid unit for roller screen material.

Comparing Fig. 5 with Fig. 6, it can be seen that the throwing index \( D \) of the solid-liquid separator is positively related to the speed of the exciting motor \( n_1 \) and negatively related to the speed of the rotary drum motor \( n_2 \).
D. ANALYSIS OF SOLID MIGRATION SPEED

The solid migration speed reflects the ability of the shale shaker to remove unused solid phases from the material.

If the vibrating screen has good processing capacity and the solid phase migration speed is slow, it will cause solid phase accumulation phenomenon, which will reduce the shale shaker processing capacity. The solid migration speed is also an important index parameter to measure the performance of the shale shaker.

Since the particles are not in contact with the screen surface after being thrown off the screen surface, the supporting force N = 0 is affected only by gravity. The equation of motion of the particles after being thrown off the screen surface can be established according to Newton’s second law.

\[
\begin{align*}
    m(a_r + \Delta \vec{r}) &= -mg \cos \alpha \sin \theta \\
    m(a_r - r_T \omega_z^2 + \Delta \vec{r}) &= mg \cos \alpha \cos \theta \\
    m(a_z + \Delta \vec{z}) &= -mg \sin \alpha
\end{align*}
\]

(18)

It can be obtained by solving the above equations:

\[
\begin{align*}
    \Delta \vec{r} &= -B_1 \omega^2 \sin(\omega t - \beta_1) \sin \theta - g \cos \alpha \sin \theta \\
    \Delta \vec{\dot{r}} &= g \cos \alpha \cos \theta + r_T \omega_z^2 + B_1 \omega^2 \sin(\omega t - \beta_1) \cos \theta \\
    \Delta \vec{\ddot{z}} &= -g \sin \alpha - B_2 \omega^2 \sin(\omega t + \beta_2)
\end{align*}
\]

(19)

When analyzing the movement of particles, the main purpose is to obtain the movement of particles in the axial direction, therefore, the movement of particles in the axial direction is mainly calculated in the next step. By integrating equation (19) from time \( t_0 \) to time \( t \), we can obtain the particle’s radial and axial velocity.

\[
\begin{align*}
    \Delta r &= \int_{t_0}^{t} \Delta \vec{r} dt = \int_{t_0}^{t} [g \cos \alpha \cos \theta + r_T \omega_z^2 \\
    & \quad + B_1 \omega^2 \sin(\omega t - \beta_1) \cos \theta] dt \\
    \Delta \vec{\dot{z}} &= \int_{t_0}^{t} \Delta \vec{\ddot{z}} dt = -\int_{t_0}^{t} [g \sin \alpha + B_2 \omega^2 \sin(\omega t + \beta_2)] dt
\end{align*}
\]

(20)

Let \( \varphi = \omega t - \beta_1 \), then \( \varphi_0 = \omega t_0 - \beta_1 \), and then integrate equation (20) from time \( t_0 \) to time \( t \) to obtain the particle displacement in the radial and axial directions.

\[
\begin{align*}
    \Delta r &= \frac{g \cos \alpha \cos \theta + r_T \omega_z^2}{2\omega^2} (\varphi - \varphi_0)^2 - B_1 \cos \theta \\
    & \times [\sin \phi - \sin \varphi_0 - (\varphi - \varphi_0) \cos \phi_0] \\
    \Delta \vec{\dot{z}} &= -\frac{g \sin \alpha}{2\omega^2} (\varphi - \varphi_0)^2 + B_2 [\sin(\varphi + \beta_1 + \beta_2) \\
    & - \sin(\varphi_0 + \beta_1 + \beta_2) - (\varphi - \varphi_0) \cos(\varphi_0 + \beta_1 + \beta_2)] \quad (21)
\end{align*}
\]

When the particles complete a throwing motion cycle, they will contact the roller screen again. Currently, the relative displacement of the particle in the radial direction is 0. That \( \Delta r = 0 \), which can be obtained from equation (21)

\[
\frac{g \cos \alpha \cos \theta + r_T \omega_z^2}{2\omega^2} (\varphi - \varphi_0)^2 - B_1 \cos \theta \\
\times [\sin \phi - \sin \varphi_0 - (\varphi - \varphi_0) \cos \phi_0] = 0 \quad (23)
\]

From equation (23), \( \phi_0 \) and \( \varphi_0 \) can be obtained. \( \varphi_0 \) is the vibration phase angle at the end of the particle throwing motion, referred to as the throw angle, rad; \( \varphi_0 \) is the difference between the throw angle and the throw angle of the particle, referred to as the kick-off angle, expressed by \( \theta_p \), rad.

In order to fully reflect the migration of particles in the cylindrical network, it is necessary to calculate the average migration velocity. The average throwing speed at position \( \theta \) is

\[
V_p(\theta) = \frac{\Delta \vec{\dot{z}}}{T} \quad (24)
\]

\( T \) is the vibration period of the solid-liquid separator

\[
T = \frac{2\pi}{\omega} \quad (25)
\]

Let \( \beta = \beta_1 + \beta_2 \) and take equations (22) and (25) into equation (24), and get

\[
V_p(\theta) = \frac{\omega}{2\omega} \left\{ -\frac{g \sin \alpha}{2\omega^2} (\varphi - \varphi_0)^2 + B_2 [\sin(\varphi + \beta) \\
- \sin(\varphi_0 + \beta) - (\varphi - \varphi_0) \cos(\varphi_0 + \beta)] \right\} \\
= -\frac{g \sin \alpha (\varphi - \varphi_0)^2}{4\pi \omega} \\
+ \frac{B_2 \omega [\sin(\varphi + \beta) - \sin(\varphi_0 + \beta) - (\varphi - \varphi_0) \cos(\varphi_0 + \beta)]}{2\pi} \quad (26)
\]

Considering that the particles are in any allowed position, the total average throwing and moving speed of the roller screen is

\[
V_p = \frac{1}{2\theta_0} \int_{-\theta_0}^{\theta_0} V_p(\theta) d\theta \quad (27)
\]
E. PROCESSING CAPACITY ANALYSIS

The processing capacity of the shale shaker is one of the main indicators for measuring the performance of the shale shaker. It mainly reflects the penetration efficiency of the shale shaker to the drilling fluid. It can be characterized by the screen flow rate of the material on the screen.

The screen flow of the material on the flat screen is perpendicular to the screen surface. The roller screen is rolled up by a flat screen. From the perspective of microelements, the screen flow of the material is always perpendicular to the screen surface. From the perspective of the roller screen, it is along the normal direction of the screen.

The cylindrical coordinate system shown in Fig. 5 is established, the microelements in the material are selected, and according to Newton’s second law, the microelement radial motion equation is established.

\[
prd\theta dz + dG \cos \alpha \cos \theta + 2pdr \sin(\frac{d\theta}{2})
\]

\[
\frac{dp}{d\theta} d\theta dr \sin(\frac{d\theta}{2}) - \left(p + \frac{\partial p}{\partial r} dr\right)
\]

\[
\times (r + dr) d\theta dz = \rho dr d\theta dz (R + \frac{dV_r}{dt}) (28)
\]

Finishing the above equations, we can get it can be obtained by omitting the high-order trace:

\[
\rho dr \cos \alpha \cos \theta - \frac{\partial p}{\partial r} dr = \rho dr (\frac{dV_r}{dt}) (29)
\]

And

\[
\frac{dV_r}{dt} = \frac{\partial V_r}{\partial r} V_r + \frac{\partial V_r}{\partial \theta} V_\theta + \frac{\partial V_r}{\partial z} V_z + \frac{\partial V_r}{\partial t} (30)
\]

Substitute equation (30) into equation (29) to get

\[
\frac{dV_r}{dt} = \frac{\partial V_r}{\partial r} V_r + \frac{\partial V_r}{\partial \theta} V_\theta + \frac{\partial V_r}{\partial z} V_z + \frac{\partial V_r}{\partial t} (31)
\]

In the case that \( \theta \) and \( z \) are constant, take the two positions of \( r \) and integrate the upper and lower limits of the integral with equation (31) to obtain

\[-(p_2 - p_1) - \frac{V_r^2 - V_{r1}^2}{2} = \rho (a_r - r_T \omega^2 - g \cos \alpha \cos \theta)
\]

\[\times (r_2 - r_1) + H_{ri} (32)\]

In the equation, \( p_1, p_2 \) — the pressures at the position \( r_1 \) and \( r_2 \), \( Pa; V_{r1}, V_{r2} \) — the radial velocity at the position \( r_1 \) and \( r_2 \), m/s; \( \rho \) — the drilling fluid density, kg/m3; \( H_{ri} \) — the relative inertia head.

\[H_{ri} = \int_{r_1}^{r_2} \rho \left( \frac{\partial V_r}{\partial \theta} V_\theta + \frac{\partial V_r}{\partial z} V_z + \frac{\partial V_r}{\partial t} dV_r \right) (33)\]

The drilling fluid always flows along the radial direction of the screen, so the permeation flow rate of the drilling fluid can be expressed by the radial flow velocity of the drilling fluid on the screen surface.

When the free fluid level of the drilling fluid is \( h \), the distance from the fluid level to the axis at position \( \theta \) is \((r_T - h) / \cos \theta \). Let \( r(h) = (r_T - h) / \cos \theta \).

Finishing the above equations, we can get

\[
\frac{V_r^2}{2} = \rho [B_1 \omega^2 \sin(\alpha_1 - \beta_1) \cos \theta + r_T \omega^2 + g \cos \alpha \cos \theta]
\]

\[\times [r_T - r(h)] - H_{ri} (34)\]

In the equation, \( V_r \) — Screening flow rate of drilling fluid at the roller screen circumferential position \( \theta \), m/s.

It is seen from equation (34) that in order to have a solution to this equation, or to have the screen flow through the roller screen, the equation on the right side must be greater than 0, that

\[
\rho [B_1 \omega^2 \sin(\alpha_1 - \beta_1) \cos \theta + r_T \omega^2 + g \cos \alpha \cos \theta] - [r_T - r(h)] - H_{ri} > 0 (35)
\]

If the relative inertia head is not considered temporarily, finishing the above equations, we can get

\[
r_T \omega^2 + g \cos \alpha \cos \theta > -B_1 \omega^2 \sin(\alpha_1 - \beta_1) \cos \theta (36)
\]

It is seen from equation (36) that when the radial acceleration component is opposite to the centrifugal force and the gravity acceleration radial component, as long as the radial component of the centrifugal force and the acceleration of gravity is greater than the radial component of the vibration acceleration, there will be a flow.

The key factor for equation (36) to be true is that equation (36) can be written as

\[
\sin(\alpha_1 - \beta_1) > -\frac{g \cos \alpha \cos \theta + r_T \omega^2}{B_1 \omega^2 \cos \theta} (37)
\]

Finishing the above equations, we can get

\[
\frac{\phi_0(\theta) + \beta_1}{\omega} < t < \frac{\pi - \phi_0(\theta) + \beta_1}{\omega} (38)
\]

Equation (38) is the time that can pass through the screen in a period \( T \).

Because the vibration of the solid-liquid separator is periodic, the flow rate of the screen also changes periodically. In order to reflect its comprehensive performance, the average flow rate of drilling fluid through the screen per unit time is required:

\[
\bar{V_r} = \frac{1}{T} \int_{t_1}^{t_2} V_r dt (39)
\]

In the equation, \( \bar{V_r} \) — the average permeate flow rate of the material per unit time at the roller screen circumferential position \( \theta \).

\( t_1, t_2 \) — the range of integration, determined by equation (38), \( t_1 = \frac{\phi_0(\theta) + \beta_1}{\omega}, t_2 = \frac{\pi - \phi_0(\theta) + \beta_1}{\omega} \).
Equation (39) is the expression of the average flow rate of material passing through the roller screen per unit time. From the equation, it is known that the average flow rate depends largely on the velocity of $V_y$. From the analysis of the actual situation, the direction is always perpendicular to the screen surface, so the direction of the average screen flow rate $V_f$ is also perpendicular to the screen surface, and the factors affecting $V_f$ are basically the same as the factors affecting $V_y$. That is, the average sieve flow rate $V_f$ increases as the parameters $r_T$ and $ω_z$ of the screen cylinder increase.

**F. POWER ANALYSIS**

It is assumed that the rigidity of the screen box and the screen frame is very large, that is, the power consumed by the deformation of the screen box and the screen frame is not considered when calculating the motor power. When the solid-liquid separator is vibrating, the motor power is being consumed by vibration and friction. The motor power can be expressed as

$$P' = \frac{1}{η}(P_1 + P_2)$$  \hspace{1cm} (40)

In the equation, $η$—the transmission efficiency; $P_1$—the power consumed by vibration, kW; $P_2$—the power consumed by friction, kW.

Among them, the power consumed by vibration is

$$P_1 = \frac{MA^2n_1^3C}{1740480}$$  \hspace{1cm} (41)

In the equation, $M$—the vibration mass, kg; $A$—the maximum single amplitude, m; $n_1$—the speed of exciting motor, r/min; $C$—the damping coefficient.

The power consumed by friction is

$$P_2 = \frac{MAN_1^3f_m}{1740480}$$  \hspace{1cm} (42)

In the equation, $f_m$—the rolling friction coefficient, $f_m = 0.0045 \sim 0.005$; $d$—the journal diameter, m.

Equation (41) and equation (42) can be substituted into equation (40)

$$P' = \frac{MAN_1^3A^2C + Af_md}{1740480}$$  \hspace{1cm} (43)

When the rotary drum rotates at the rotational speed (the number of revolutions per minute), some materials will be raised to a certain height due to the friction force and the viscosity of the liquid phase, and the material weight will generate a torque opposite to the rotation direction of the rotary drum. The rotary drum must overcome this torque to lift the material to a certain height, and the power consumed in this process is the effective power consumed by the rotary drum motor.

Assuming that the solid phase cuttings are evenly distributed in the material, and that the solid phase cuttings are also evenly distributed in the non-submerged area. Then a simplified rotary drum model as shown in Fig. 6 can be established.

Then the effective power $P_e$ of the lifting material is

$$P_e = \frac{1000G \cdot V_y}{102}$$  \hspace{1cm} (44)

In the equation, $G$—the material weight, kg; $V_y$—the vertical velocity of material at center of gravity, m/s.

$$V_y = r_o\omega_z \sin γ = \frac{2πn_2r_s \sin γ}{60}$$  \hspace{1cm} (45)

In the equation, $r_o$—the distance from the center of gravity of the submerged area to the center of the rotary drum, m; $ω_z$—the angular velocity of rotary drum, rad/s; $n_2$—the rotary drum speed, r/min; $γ$—the angle between material surface and horizontal plane, rad.

Because the density and weight of the material are significantly different in the submerged area and the non-submerged area, they are calculated separately. In the submerged area, the density of the material increases with the increase of the axial distance. In the non-submerged area, it can be approximated as no screen flow. If the flow at the feed end is stable, when the solid-liquid separator is vibrating normally, the solid-phase cuttings in each axial position of the non-submerged area are regarded as equal.

In the submerged area, when the rotary drum speed is zero, the liquid surface height at the axial position $z$ is $h(z)$, and the material density is $ρ(z)$. Then, the microgravity $dG$ at the axial position $z$ is

$$dG = ρ(z) \left[ \frac{\arccos \frac{r_T - h(z)}{r_T}}{180} - \sqrt{1 - \frac{h(z)}{r_T}} \cdot [r_T - h(z)] \right] dz$$  \hspace{1cm} (46)

The effective power of the rotary drum motor at the location $z$ of the submerged area is

$$P_{e1}(z) = \frac{1000G}{102} dG$$  \hspace{1cm} (47)

Finishing the above equations, we can get

$$P_{e1}(z) = \frac{1000G}{306} πn_2 \left[ \frac{h(z)}{2} \right] \sin γ dG$$  \hspace{1cm} (48)

The effective power of the rotary drum motor in the submerged area is

$$P_{e1} = \int_{z_1}^{z_2} P_{e1}(z) dz$$  \hspace{1cm} (49)

In the equation, $z_1$ is the axial position of the end point of the submerged area, m.

In the non-submerged area, if the solid phase is uniformly distributed, and the height of the solid phase cuttings is $h$ and the density of the solid phase cuttings is $ρ$, the weight of the solid phase is

$$G' = \left[ \frac{\arccos \frac{r_T - h}{r_T}}{180} - \sqrt{1 - \frac{h}{r_T}} \cdot (r_T - h) \right] ρ(z_0 - z_1)$$  \hspace{1cm} (50)

where $z_0$ is the effective screening length of the screen cylinder, m.
The effective power of the rotary drum motor in the non-submerged area is

\[ P_{e2} = \frac{1000G'}{102} \cdot \frac{\pi n2r_s \sin \gamma}{30} = \frac{100G' \pi n2 \sin \gamma}{306} (r_T - \frac{h}{2}) \]

(51)

The effective power of the rotary drum motor can be obtained from equations (49) and (51).

\[ P'' = P_e + P_{e2} \]

(52)

It can be obtained that the total power consumption of the solid-liquid separator is

\[ P = P' + P'' \]

(53)

### III. MULTI-OBJECTIVE OPTIMAL SOLUTION

How to coordinately control the two groups of motors to achieve the best overall performance of the solid-liquid separator is an important issue. To solve this problem, we need to introduce multi-objective optimization theory, treat each performance evaluation index as a target, establish a multi-objective optimization model function by combining these three performance evaluation indexes, and theoretically find the optimization solution set of the model.

#### A. CONSTRAINT ANALYSIS

In practical terms, the motor has its rated speed. The rated speed is regarded as the maximum speed of the motor. The rated speed of the exciting motor currently used is 1140r/min. For the rotary drum, because it has a certain cleaning function, the rotary drum speed cannot be zero. At present, it is considered to set the minimum rotary drum speed to 10r/min.

The condition that the particle can produce a throwing motion is that the throwing index is greater than 1, that is,

\[ D(\theta) > 1 \]

(54)

Then the area range and angular velocity limit of the particles that can be thrown on the roller network can be obtained.

\[ < \theta < \arccos \frac{r_T \omega_2^2}{B_1 \omega_2^2 - g \cos \alpha} \]

(55)

\[ \omega_{min} = \sqrt{\frac{g \cos \alpha \cos \theta_0 + r_T \omega_2^2}{B_1 \cos \theta_0}} \]

(56)

\[ \omega_{max} = \pm \sqrt{\frac{B_1 \omega_2^2 - g \cos \alpha}{r_T}} \]

(57)

Therefore, the constraints of the multi-objective model are

\[
\begin{align*}
\text{s.t. } & \omega \leq 38\pi \\
& \omega \geq \sqrt{\frac{g \cos \alpha \cos \theta_0 + r_T \omega_2^2}{B_1 \cos \theta_0}} \\
& \frac{\pi}{3} \leq \omega \leq \sqrt{\frac{B_1 \omega_2^2 - g \cos \alpha}{r_T}} 
\end{align*}
\]

(58)

### B. ESTABLISHING A MULTI-OBJECTIVE OPTIMIZATION MODEL

At present, there are only two variables that can be adjusted conveniently, namely, the speed of the exciting motor and the speed of the rotary drum. At present, there are only two variables that can be easily adjusted, namely the speed of the exciting motor and the speed of the rotary drum. After analyzing the impact of the rotational speed of the exciting motor and the rotary drum on the three performance evaluation indicators of the processing capacity, processing efficiency and power consumption of the solid-liquid separator. Through the coordinated control of the speed of the exciting motor and the speed of the rotary drum, the overall performance of the solid-liquid separator is optimized (large processing capacity, high processing efficiency, low power consumption).

The mathematical expressions of the multi-objective optimization model can be written as follows: (58), (59).

\[
\begin{align*}
\max & \quad \tilde{V}_l(\omega, \omega_2) \\
\max & \quad V_p(\omega, \omega_2) \\
\min & \quad P(\omega, \omega_2) \\
\text{s.t. } & \frac{\pi}{3} \leq \omega \leq \sqrt{\frac{B_1 \omega_2^2 - g \cos \alpha}{r_T}} \\
& \omega \leq 38\pi \\
& \omega \geq \sqrt{\frac{g \cos \alpha \cos \theta_0 + r_T \omega_2^2}{B_1 \cos \theta_0}}
\end{align*}
\]

(59)

### IV. SOLUTION OF MULTI-OBJECTIVE OPTIMIZATION MODEL

In order to solve the multi-objective optimization model, an evolutionary algorithm needs to be introduced. Evolutionary algorithm (EA) is a type of random search algorithm that simulates natural selection and evolution of living things. This algorithm has been widely used because it shows great advantages in solving more complex problems.

Among evolutionary algorithms, MOEA/D is one of the most widely studied and widely used evolutionary multi-objective optimization frameworks. MOEA/D is a multi-objective optimization algorithm based on decomposition. There are three main decomposition methods: weighted sum method, Chebyshev method and boundary intersection method. Among them, the most widely used method is the Chebyshev method.

Using the Chebyshev method, MOEA/D decomposes a multi-objective optimization problem into N sub-problems, and the k-th sub-problem has the following form:

\[
\begin{align*}
\min & \quad g^{\omega}(\mathbf{x} | \mathbf{w}^k, \mathbf{z}_*) = \max_{1 \leq j \leq m} \left\{ w_j^k f_j(\mathbf{x}) - z_j^* \right\} \\
\text{s.t. } & \mathbf{x} \in \Omega
\end{align*}
\]

(60)

where, \( \mathbf{w}^k (k = 1, \ldots, N) \)-the k-th weight vector, and \( \sum_{j=1}^{m} w_j^k = 1; \Omega \)-the feasible region; \( z_j^* \)-reference point of the k-th sub-problem, and \( z_j^* = \min \{ f_j(\mathbf{x}) | \mathbf{x} \in \Omega \} \) (j = 1, ⋯, m).
The idea of the Chebyshev method is that during each iteration, the algorithm will select a set of current optimal solutions and compare each mutated solution to select a better solution to replace it. In this way, continuous evolution, choosing the set of solutions that are closest to the Pareto optimal solution.

The main steps of the MOEA/D algorithm are as follows:
1. Setting parameters: parameters including population size and DE operator;
2. Generating weight vector and initializing population;
3. Evaluating the objective function of each solution and update the reference point;
4. Generating a new solution using the DE operator and evaluate and update the reference point;
5. Updating the external population according to the Chebyshev method;
6. Ending the judgment or returning to step (4).

![The basic framework of the MOEA/D algorithm.](image)

The basic framework of the MOEA/D algorithm is shown in Fig. 7.

### A. IMPROVED EVOLUTIONARY ALGORITHM

The improvement part is mainly divided into two aspects: the way to generate new solutions (mutation strategy) and the decomposition method for multi-objective problems (also known as fitness function or evaluation function).

The mutation strategy used by the MOEA/D algorithm is the DE operator. The DE operator is a new evolutionary operator. This operator has advantages in solving continuous problems, so it is widely used.

The mutation strategy used in the MOEA/D algorithm is a very common DE operator “DE/rand/1”. The operation of the operator to generate a new solution can be expressed by the following equation:

\[ V_{i}(t+1) = X_{r1}(t) + F[X_{r2}(t) - X_{r3}(t)] \] (61)

In the equation, \( V_{i}(t+1) \) is a new solution generated in \( t+1 \) iterations, \( F \) is a scale factor, and \( X_{r1}(t), X_{r2}(t), X_{r3}(t) \) is the mutually different individuals in the external population after the \( t \)-th iteration.

With the continuous development of the DE algorithm, some new mutation strategies have been proposed. Among them, the typical mutation strategy is “DE/best/1”. The operation of “DE/best/1” can be expressed by the following equation:

\[ V_{i}(t+1) = X_{\text{best}}(t) + F[X_{r1}(t) - X_{r2}(t)] \] (62)

where, \( X_{\text{best}}(t) \) is the better individual after the \( t \)-th iteration.

The strategy “DE/rand/1” is not constrained by the search mode, so the search range is wider, the diversity is greater, and it is easier to globally optimize. But precisely because of its wide search range, the resulting new solutions are not conducive to evolution along the optimization direction, so this strategy makes the algorithm’s convergence rate not fast in the early stages of evolution.

The strategy “DE/best/1” adds the optimal individuals, which is equivalent to guiding the search direction, which greatly increases the convergence speed of the algorithm and makes it easier to obtain the optimal solution. However, since the initial solutions are randomly generated, the optimal solution selected from them is likely to deviate from the global optimal, and coupled with the decrease in diversity, it may fall into a local optimal. Both have their own advantages and disadvantages. Only by combining the advantages of the two can achieve better results.

Therefore, in this paper, the strategy for generating new solutions of the MOEA/D algorithm is improved. In order to obtain the global optimal solution, the strategy “DE/rand/1” is undoubtedly more advantageous, but there are too many directions, which leads to a slower speed to reach the optimal solution. The strategy “DE/best/1” can just guide the direction. Therefore, by alternately using the two strategies and letting the strategy “DE/best/1” timely guide the direction of “DE/rand/1”, the convergence speed of MOEA/D algorithm can be increased and the ability to approach the optimal solution can be improved.

The fitness function of the MOEA/D algorithm usually uses the Chebyshev method, which is determined by equation (60). Because the fitness function finally obtains a scalar value, when the value of an objective function is too large...
compared to other objective functions, it may cause the algorithm using the Chebyshev method as the fitness function to fall into a local optimum. Since the result of fitness function is a scalar, when the value of an objective function is too large compared with other objective functions, the algorithm using Chebyshev method as fitness function may fall into local optimization.

This is the case for the multi-objective mathematical model to be solved in this paper. In order to reduce the situation of falling into the local optimum, the Chebyshev method was improved. The improved Chebyshev method can be expressed by

\[
\min g^k(x) = \max_{1 \leq j \leq m} \left\{ w_j^k \left[ f_j(x) / z_j^* \right] \right\} + k \sum_{i=1}^{m} \left| f_i(x) - z_i^* \right| \quad (63)
\]

s.t. \( x \in \Omega \)

In the equation, \( k \) is a very small constant. Generally speaking, \( k \) is very small to limit the contribution of the second term to the objective function. This method combines the characteristics of fast convergence of weight sum method and good distribution of Chebyshev method. According to the actual situation, the effect of the two methods on the objective function can be balanced by adjusting the size of \( k \), so that the MOEA/D algorithm has better performance in solving practical problems.

### B. SOLUTION OF MULTI-OBJECTIVE OPTIMIZATION MODEL

In the MATLAB environment, the multi-objective optimization model was solved by using the modified MOEA/D algorithm before and after. The result was in the form of an optimal solution set consisting of three objective functions: sieving flow velocity, solid phase migration speed, and power. It appears, as shown in Fig. 8 and Fig. 9.

It is seen from Fig. 8 (b) that most individuals (solutions) meet along a certain direction, and the sieve flow rate and the solid phase migration speed increase, but some individuals do not meet this rule. These individuals are called locally optimal or non-convergent solutions. It is seen from Fig. 8 (c) that most solutions satisfy that when the power consumption increases, the screen flow rate also increases; From Fig. 8 (d) that it can be seen that most solutions satisfy that when the power consumption increases, the solid migration speed increases, some individuals do not meet this rule; And it is seen from Fig. 8 (a) that, except for a few solutions, the rest of the solutions satisfy that when the power consumption increases, the screen flow rate and the solid migration speed increase. These individuals cannot compare the advantages and disadvantages of the overall objective function. Therefore, these solutions are called non-dominated solutions or Pareto optimal solutions, that is, these individuals can be called the optimal solution set of the optimization model. Specific speed individual is shown in Fig. 9.

From Fig. 10 (b), most individuals (solutions) meet along a certain direction, and the screen flow rate and solid migration speed increase, but some individuals do not meet this rule. These individuals are called local optimal solutions or non-convergent solutions. Compared with the results obtained by the improved algorithm, the number of non-convergent solutions decreases. From Fig. 10 (c) that most solutions satisfy that when the power increases, the screen flow rate also increases; From Fig. 10 (d) that most solutions satisfy that when the power consumption increases, the solid migration speed increases, some individuals do not meet this rule; It is seen from Fig. 10 (a) that, except for a few solutions, the rest of the solutions satisfy that when the power consumption increases, the screen flow rate and the solid migration speed increase, which doesn’t meet the rule. That is, the number of non-convergent solutions is significantly reduced compared to the number of non-convergent solutions in the solution set obtained by the improved algorithm. Specific speed individual is shown in Fig. 11.

By comparing the results obtained by the original and improved algorithm, the solution set obtained by the MOEA/D algorithm is poorly distributed, and more individuals are locally optimal; the solution obtained by the improved MOEA/D algorithm has better distribution and convergence, which shows that the improved MOEA/D algorithm has more advantages in solving the problems faced by this subject.

Part of the model parameters of the improved MOEA/D algorithm are: population size \( N \) is 70, number of iterations \( \text{Gen} \) is 500, number of weight vectors \( W \) in the domain is 30, scale factor \( F \) is 0.5, and mutation rate \( \text{CR} \) is 0.5. The parameters of the improved MOEA/D algorithm remain unchanged, and the parameter used to limit the weight summation method to the fitness function is 0.001.

### V. EXPERIMENT

The prototype used in this experiment is a GIGYJ-1 double-cylinder solid-liquid separator. The physical device is shown in Fig. 12.

### A. CONTRAST EXPERIMENT

In this experiment, yellow mud mixed with mud and water is used as the processing material, and the density is 1.18g/cm3. As shown in Fig. 13, under the relevant conditions, three measurements are performed for each group of data, and the average of the three measurements is calculated, through measurement and calculation, three types of data such as the effect of solid-liquid separator on material processing, solid migration speed and power consumption are obtained. The experiment results are shown in Table 1, Table 2, and Table 3.

The material processed by the solid-liquid separator becomes a dry spherical pellet, as shown in Fig. 14. It is seen from Fig. 14 that the mud after solid-liquid separation is basically fully separated due to moisture, and formed into a spherical shape, and there is no adhesion between each other, which indicates that the separation effect is good.
The liquid medium (water) has been separated from the screen before half of the process (half of the total axial length of the screen cylinder). In the process of the second half of the screen drum, the remaining solid phase particles are mainly kneaded into a block shape, which is extremely beneficial for subsequent further processing.
B. OPTIMAL EXPERIMENT

Select individuals in the optimal solution set for experiments. In order to facilitate comparison, one of the variables is selected to be as consistent as possible for the experiment. Because the exciting motor provides the main power, the speed of the exciting motor is given priority when...
selecting the appropriate speed, so individuals with similar speeds of the exciting motor are selected for comparative analysis. The experiment results are shown in Table 4, Table 5, and Table 6.

The individuals with similar exciting motor speed in the experimental group and the optimal individuals are selected for comparative analysis. The contrast results are shown in Table 7.

Table 7 selects four groups of individuals with similar motor speeds for comparison and analysis, and analyzes the changes in water content, solid migration speed, and power consumption of the individuals in the comparative analysis.
experimental group and the optimal individual. It is seen from Table 7:

1. The optimal individual in the second group reduced the processing effect of the solid-liquid separator by 2.2%, which indicating that compared with the individual in the comparative experimental group, this individual can’t make the overall performance of the solid-liquid separator better.

2. Although the best individuals in the first group fail to make the solid-liquid separator process better, the processing effect only decrease by 0.5%, while the solid migration speed is optimized by 12.7%, the power consumption is optimized by 4.5%. Compared with the individuals in the comparison experimental group, the comprehensive performance of the solid-liquid separator can be optimized to a certain extent.

3. The data in the second group and the fourth group show that the optimal individual doesn’t weaken any other performance when improving one performance of the solid-liquid separator, which shows that the optimal individual makes the
overall performance of the solid-liquid separator better, compared with the individuals in the comparative experimental group. It is summarized from the experiment results that in the four groups of comparative experiments, the three groups of optimal individuals can achieve better overall performance of the solid-liquid separator.

**TABLE 5.** Experimental results of solid migration speed of individuals in the optimal solution set.

| Test number | Column number | Measurement calculation results |
|-------------|---------------|--------------------------------|
| 1 | 2 | n1 (r/min) | n2 (r/min) | 1 | 2 | 3 | Average value | Theoretical value |
| 1 | 728 | 10 | 0.1766 | 0.1721 | 0.1708 | 0.1732 | 0.1892 |
| 2 | 790 | 14 | 0.2073 | 0.2127 | 0.2083 | 0.2094 | 0.2267 |
| 3 | 826 | 17 | 0.2308 | 0.2273 | 0.2345 | 0.2309 | 0.2444 |
| 4 | 847 | 19 | 0.2391 | 0.2370 | 0.2327 | 0.2363 | 0.2537 |

**TABLE 6.** Experimental results of individual power consumption in the optimal solution set.

| Test number | Column number | Measurement calculation results |
|-------------|---------------|--------------------------------|
| 1 | 2 | n1 (r/min) | n | Power consumption (kW) |
| 1 | 728 | 10 | 1.4 | 0.6 | 0.1 | 2.1 | 1.9183 |
| 2 | 790 | 14 | 1.7 | 0.8 | 0.1 | 2.6 | 2.4599 |
| 3 | 826 | 17 | 2.1 | 1.1 | 0.1 | 3.3 | 2.8188 |
| 4 | 847 | 19 | 2.2 | 1.1 | 0.1 | 3.4 | 3.0440 |

**TABLE 7.** Comparative analysis of experimental results.

| Serial number | Exciting motor speed n1 (r/min) | Screen cylinder speed n2 (r/min) | Moisture content (%) | Solid migration speed (m/s) | Power consumption (kW) | Optimization judgment |
|---------------|---------------------------------|---------------------------------|----------------------|---------------------------|-----------------------|----------------------|
| 1             | 720                             | 30                              | 16.62                | 0.1536                    | 2.2                   | Optimize overall performance to some extent |
| 2             | 728                             | 10                              | 16.71                | 0.1732                    | 2.1                   | Optimize the overall performance of solid-liquid separator |
| 3             | 728                             | 10                              | Increase 0.5%        | Increase 12.7%            | Decrease 4%           | Cannot optimize the overall performance of solid-liquid separator |
| 4             | 790                             | 30                              | 15.76                | 0.1877                    | 2.7                   | Optimize the overall performance of solid-liquid separator |
| 5             | 790                             | 14                              | Decrease 0.1%        | Increase 11.6%            | Decrease 3.7%         | Optimize the overall performance of solid-liquid separator |
| 6             | 840                             | 30                              | 14.39                | 0.2242                    | 3.4                   | Optimize the overall performance of solid-liquid separator |
| 7             | 840                             | 17                              | 14.71                | 0.2309                    | 3.3                   | Optimize the overall performance of solid-liquid separator |
| 8             | 840                             | 17                              | Increase 2.2%        | Increase 3.0%             | Decrease 2.9%         | Optimize the overall performance of solid-liquid separator |
| 9             | 847                             | 30                              | 14.39                | 0.2242                    | 3.4                   | Optimize the overall performance of solid-liquid separator |
| 10            | 847                             | 19                              | 14.28                | 0.2363                    | 3.4                   | Optimize the overall performance of solid-liquid separator |

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VI. CONCLUSION

Through the research and design of the solid-liquid separator, the following conclusions are obtained:

(1) The force of a single particle on a new screen is established, and the throwing capacity of the solid-liquid separator is analyzed. By analyzing the single particles thrown off the screen, the average moving speed of the single particles in the axial direction of the screen is calculated. The influence of exciting motor and rotary drum motor on the axial velocity of solid particles is explained theoretically.

(2) According to the basic principles of fluid mechanics, the selected fluid unit is subjected to a force analysis, the screen flow speed of the solid-liquid separator for cuttings-containing drilling fluid is calculated, and the influence of the rotating speed of the exciting motor and the rotary drum on the drilling fluid screen flow rate is analyzed. Based on the analysis of the single particle migration, the force of the wet particles on the roller screen is established, the throwing index of wet particles by solid-liquid separator and the migration speed of wet particles in the axial direction are given.

(3) Based on the optimization theory, a multi-objective optimization model of the solid-liquid separator is established and solved. After experimental verification, the migration speed is increased by 12.7% and the power consumption is reduced by 4.5%.

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