Design of Vacuum Pump Control System for Negative Pressure Shale Shaker Based on PLC

Xiangqian Yang¹, Chao Zhou², Hua Guo³ and Qinghua Zheng⁴

CNOOC Research Institute Co., Ltd. Beijing China
¹E-mail:979997829@qq.com;²E-mail:zhouchao@cnooc.com.cn;³E-mail:21346571@qq.com;⁴E-mail: zhengqh@cnooc.com.cn

Abstract. In order to improve the solid-liquid separation effect of drilling fluid in drilling operation, a new type of negative pressure vibrating screen was developed. The vacuum pump is its main component. At present, the degree of vacuum has a significant impact on the screening effect and working efficiency of the negative pressure vibrating screen. The value of the vacuum is based on experience, the setting parameters are not adjustable, or changing via the manual adjustment, and the control precision and the degree of intelligence are low. The system of the negative pressure vibrating screen vacuum pump control was designed with the moisture content of the filter cake as the controlled variable. The mathematical model between the moisture content and the vacuum degree of the filter cake was established. The fuzzy PID was studied by using Siemens S7-300 PLC as the controller. Control the law, build a control system based on the inverter as the actuator, and control the vacuum degree according to the drilling fluid quality in real time. The field application shows that the steady state error of the system is 11.1%, which meets the drilling operation requirements.

1. Introduction

The vibrating screen equipment is a kind of mechanical equipment that uses the vibration principle to perform the screening process. In the oil drilling industry, the shale shaker is the first stage solid control equipment, mainly used to clean the harmful solid particles in the drilling fluid. In order to obtain clean and reusable drilling fluid, secondary and tertiary solids control procedures is often required. The negative pressure shale shaker can meet the requirements of large processing capacity, high screening efficiency and high integration shale shaker. As a component of the apparatus, the vacuum pump has an important influence on the screening efficiency of the negative pressure shale shaker. The important parameter of the vacuum pump is the degree of vacuum. Most enterprises change the vacuum degree by experience, and the value is determined by experience, which make vacuum pump work in low efficiency, high energy consumption, and even unable to meet the work demands.

In order to improve the solid-liquid separation effect and work efficiency, real-time control of the vacuum pump is required. In this paper, moisture content of filter cake is the final control target, the
mathematical model between the solid phase moisture content and the vacuum degree is established, and the vacuum pump vacuum degree control system is designed by using S7-300 PLC and frequency converter. The system intelligently adjusts the vacuum degree of the vacuum pump according to the moisture content of the filter cake, so as to improve the screening efficiency of the negative pressure shale shaker, reduce the energy consumption and the labor cost.

2. Principle of negative pressure shale shaker

The negative pressure shale shaker is mainly composed of frame, circulating screen mechanism, excitation system, negative pressure system, and cleaning mechanism, as shown in figure 1. The flexible screen is detachably attached to a chain, the sprocket drives the chain to circulate under the action of the drive motor, the chain drives the flexible screen fixed on it to circulate together. The excitation system drives the vibration bracket to vibrate through the pneumatic piston reciprocating vibrator, so that the chain transmission device vibrates in the vertical direction and drives the screen to vibrate. When the screen is circulated to the upper side of the chain drive, the drilling fluid is screened, and when the screen is circulated to the underside of the chain drive, the self-cleaning is realized under the action of the vibration and the cleaning mechanism. The negative pressure chamber is located under the upper screen, and a negative pressure is formed under the action of the vacuum pump, so that a pressure difference is formed on the surface of the screen to enhance the screening effect of the drilling fluid.

When the negative pressure vibrating screen is working, the drilling fluid containing cuttings flows from the inlet to the circulation screen. Circulating screen moves forward with drilling fluid and cuttings through chain transmission device. At the same time, under the action of negative pressure and vibration, the liquid phase is recovered by the drainer. The solid phase remains on the screen surface and continues along the screen until the outlet falls into the tank to achieve solid-liquid separation.

![Circulating screen; 2-Vacuum pump; 3-Vibrating bracket; 4-Cleaning system; 5-Motor; 6-Inlet; 7-Outer shell; 8-Outlet](image)

**Figure 1.** Negative pressure shale shaker structure diagram.

Compared with the traditional shale shaker, the negative pressure shale shaker greatly increases the screening efficiency by adding a negative pressure system. The negative pressure system is mainly composed of a vacuum pump and a negative pressure tank. The vacuum pump draws air, so that the pressure of the negative pressure tank under the screen is lower than atmospheric pressure. The solid phase diameter in the drilling fluid is larger than the sieve pore diameter, and is trapped and deposited to form a filter cake. The liquid passes through the screen and the filter cake under pressure difference and gravity to realize solid-liquid separation. At the same time, the suction action of the vacuum pump will cause the gas to pass through the filter cake into the negative pressure tank, take away part of the moisture in the filter cake, and enhance the screening ability of the negative pressure shale shaker.

3. Mathematical model of vacuum degree and moisture content of filter cake
The solid phase moisture content after solid-liquid separation is often used to evaluate the treatment effect. The moisture content of the filter cake is the mass ratio of the moisture in the filter cake to the solid content after drying, the lower the moisture content, the better the treatment effect is.

The moisture content of the filter cake is related to the flow speed of the drilling fluid. To simplify the study, it is assumed that the drilling fluid has no lateral flow along the width of the screen, the flow rate of the drilling fluid in the x direction is consistent with the screen surface and the effects of entrained gases in the drilling fluid is ignored. That is, only the flow through the screen is studied. Establish the coordinate system shown in figure 2, Dong’s discrete element method is used to select the unit body $d_x, d_y$ as the research object.

![Figure 2. Screen unsteady flow and fluid unit.](image)

When considering the application of negative pressure, there is a pressure difference between the upper and under surfaces of the drilling fluid, in the y direction, according to Newton’s second law:

$$p \, dx - (p + \frac{\partial p}{\partial y} \, dy) \, dx - \gamma \, dy \, dx = \frac{\gamma}{g} \, dx \, dy \, (\ddot{y} + \frac{d v_y}{dt})$$

(1)

Where $p$ is the pressure, $\ddot{y} = -\sigma_0^2 \lambda \sin \omega t$ is the acceleration of the screen along the y direction, $\gamma$ is the gravity density of the drilling fluid.

Introducing the relative inertia head $H_{yi}$ and the flow loss $H_{wy}$. After calculation, it can be obtained that:

$$\frac{p_1 - p_2}{g} + \frac{v_y^2 - v_{y0}^2}{2g} = \frac{1}{g} (\ddot{y} + g)(y_2 - y_1) + H_{yi} + H_{wy}$$

(2)

In the above formula, $H_{yi} = \int_{y_1}^{y_2} \left( \frac{\partial v_y}{\partial t} + \frac{\partial v_y}{\partial x} v_x \right) \frac{dy}{g}$ is the relative inertia head, $H_{wy} = \frac{\eta}{\gamma c} u_y + \beta \frac{\rho B}{\gamma c} u_y^2 + \frac{c_0}{\gamma} \sigma_0$ is the flow loss, $p_1$ is the pressure at the top of the microelement, $p_2$ is the pressure at the negative pressure tank, $c$ is the screen liquid passing rate, $\sigma_0$ is static shear stress of drilling fluid, $\epsilon$, $B$, $D$ are respectively the porosity, thickness and size of the mesh, $\beta$, $c_0$ are experimental constant.

At $y_1 = h$, because the vertical flow rate of the drilling fluid is small, assuming its velocity is 0; then equation (2) can be simplified as:

$$\frac{u_v^2}{2g} - \frac{h}{g} (\ddot{y} + g) - H_{yi} - H_{wy}$$

(3)
When $\ddot{y} > -g$, the drilling fluid passes through the screen, and the flow rate of the sieve is $u_y$; when $\ddot{y} < -g$, there is no drilling fluid through the screen, and the drilling fluid movement equation is:

$$\begin{cases}
\frac{u_y^2}{2g} - p = h(\ddot{y} + g) - H_{wy} - H_{wy}, \ddot{y} > -g \\
u_y = 0, \ddot{y} \leq -g
\end{cases}$$  \hspace{1cm} (4)

The vibration of the negative pressure vibrating screen is periodic, and the flow rate of the through-screen is also cyclically changed. In order to reflect its comprehensive performance, the average flow rate of the drilling fluid through the screen per unit time is required.

$$\bar{u_y} = \frac{1}{T} \int_{t_1}^{t_2} u_y \, dt$$  \hspace{1cm} (5)

Where $t_1$ and $t_2$ are the upper and under limit of integration, they are determined by equation (4),

$$t_1 = -\frac{\arcsin \frac{g}{\lambda \omega^2} - \pi}{\omega}, t_2 = -\frac{\arcsin \frac{g}{\lambda \omega^2}}{\omega}.$$

The amount of treatment of the negative pressure shale shaker in unit time is expressed as :

$$Q_s = \frac{C_s}{C + C_s} \int_0^{\xi_1} k \, dz \int_0^{\xi_1} u_y \, dx$$  \hspace{1cm} (6)

In the formula, $k$ is the proportion of screen perforation relative to the screen area, $x$, is the length of the drilling fluid can effectively pass through the screen, $z$, is the width of the drilling fluid can effectively pass through the screen, $c_s$ is the liquid passing rate conductivity of the cuttings layer at position $x$, $I$ is the solid phase interference coefficient of the screen which is determined by experiment. The inlet flow of the negative pressure shale shaker vibrating screen is set to $G$. The density of unscreened debris-containing drilling fluid can be measured as $\rho_l$, the mass percentage $\lambda$ of solids in the drilling fluid can be obtained by experiment, and the volume percentage $\delta$ of fine particles passing through the screen relative to the through-screen drilling fluid is also obtained by experiment. So the moisture content $H$ of the filter cake is

$$H = \frac{\rho_l G (1 - \lambda) - \rho_s (1 - \delta) Q_s}{\rho_s \lambda G - \delta \rho_s Q_s}$$  \hspace{1cm} (7)

Mathematical model of vacuum degree and moisture content of filter cake can be obtained from equations (5), (6) and (7).

4. Design of control system

Negative pressure shale shaker vacuum degree control system is shown in figure 3. Part of the system parameters are determined by experiment, which makes the mathematical model is not accurate enough, it needs to change the control parameters with time, so the control system uses fuzzy PID control.
Figure 3. The block diagram of moisture content control program.

In practice, the density of drilling fluid is 1.015 kg/m³, funnel viscosity is 48.8 s, the density of pure drilling fluid is 1.009 kg/m³, the density of filter cake is 2.34 kg/m³, the vibration frequency is 96 Hz. The transfer function established according to the mathematical model of the degree of vacuum and the moisture content of the filter cake is

\[
G(s) = 1 - \frac{0.08 e^{-4.02t}}{(0.5s^2 + s)(2s + 1)(0.4s + 1)}
\] (8)

The simulation result of the filter cake moisture content fuzzy PID control process based on the transfer function formula (8) is shown in figure 4.

Figure 4. The simulation curve of Water content control process.

The set value of moisture content is 0.9, as can be seen from the figure, after 15 s, the moisture content of the filter cake reaches the set value. The system has some overshoot, but the duration is short, and the system has almost no oscillation, which can meet the requirements of negative pressure shale shaker.

The system uses Siemens S7-300 PLC as controller to realize the real-time control of moisture content. When the system is working, the moisture content sensor feeds back the detected moisture content to the PLC, PLC compares the real-time moisture content returned from the feedback with the set value. The program uses fuzzy PID control algorithm to calculate and output the required amount of control. PLC converts the control amount into a voltage value, the frequency of converter is changed through the RS485 communication protocol. The PLC control flow is shown in figure 5.
5. Experimental verification
Experiment is implemented to verify the rationality of the system, the moisture content control process can be expressed as the distribution of drilling fluid on the screen surface, as shown in figure 6.
Figure 6. Distribution of drilling fluid on the screen surface.

The set value of moisture content is 0.9, figure 6 (a) shows the distribution of drilling fluid on the screen surface when the moisture content is 2.4, figure 6 (b) shows the distribution of drilling fluid in the final stable condition, the adjustment time of the system is 16.5s, which is almost identical to the simulation result. The moisture content collected by the sensor is 0.8, and there is an error of 11.1% from the set value, it can meet the working needs of negative pressure shale shaker. The actual moisture content control process curve is shown in figure 7.

Figure 7. The curve of control.

6. Conclusion
The negative pressure shale shaker vacuum pump control system of this design is based on PLC, and the vacuum pump motor speed is changed by means of fuzzy PID control. The vacuum of the vacuum pump is adjusted. A mathematical model of vacuum and moisture content of the filter cake is established, automatic control of the moisture content of the filter cake is achieved. The experimental results show that the response time of the system is short and the steady-state error is 11.1%, which can meet the working requirements of the negative pressure shale shaker.

7. References
[1] M.H. Zhang, R. Deng and Q. Xu 2013 WORKING THEORY AND TESTING TECHNOLOGY OF DRILLING VIBRATING SCREEN (Petroleum industry press)
[2] Q.Y. Shi and J.H. Zhang 2019 Design of intelligent control system for negative pressure casting process based on PLC Thermal processing technology vol 13 67-69+73
[3] Q. Zeng 2017 Analysis on dehydration mechanism of vacuum belt micro-vibrating mud screen (Yangtze university)

[4] Dong K J and Yu A B 2012 Numerical simulation of the particle flow and sieving behavior on sieve bend/low Head Screen Combination Minerals Engineering, vol 31 pp 2-9

[5] Hoberock L L 1980 A Study of Vibratory Screening of Drilling Fluids Journal of Petroleum Technology vol 32(11) pp 1889-1902

[6] W.X. Li 2018 Research on the theory of negative pressure vibrating screen(Southwest petroleum university)

[7] S. Guo 2019 Study on coordinated control strategy of multiple motors of solid liquid separator (Southwest petroleum university)

[8] A.W. Wen 2016 Development of fuzzy control algorithm based on SIEMENS s7-300 PLC (North China electric power university)

[9] M.M. Fang 2019 Application of PLC automatic control technology in frequency converter Electronic technology and software engineering vol 13 p 120