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Research on On-line Measurement Accuracy Improvement Technology of Drilling Fluid Rheological Parameters

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Abstract

Drilling fluid plays an irreplaceable role in drilling operations, serving functions such as cuttings transportation, signal transmission, and wellbore stability maintenance. The measurement of drilling fluid rheological parameters is crucial for optimizing hydraulic rock breaking, precisely controlling bottom-hole pressure and wellbore stability, and ensuring wellbore cleanliness. Currently, manual measurement methods such as the Marsh funnel and six-speed rotational viscometer are commonly used on-site, but they suffer from long measurement cycles and significant human interference. The online drilling fluid rheology measurement device enables real-time, automated measurement of drilling fluid rheological properties, offering higher efficiency compared to manual methods. This study addresses errors arising from single measurement methods and proposes a combined approach for measuring drilling fluid rheological parameters, integrating both rotational and tube differential pressure methods, which complement each other. Additionally, techniques for improving the accuracy of rheological parameter measurements in an online drilling fluid measurement system are explored.

Keywords

Drilling Fluid Rheology; Rotation Method Measurement; Tubular Differential Pressure Method.

1. Introduction

Energy resource security is vital to a nation's economy, people's livelihoods, and social stability. As shallow energy reserves become increasingly depleted, the drilling industry is moving toward more challenging deep and complex geological environments. At the same time, the development of green, energy-efficient, and environmentally friendly concepts has set higher requirements for the industry. Digitalization and intelligence are key means to overcoming the challenges of deep and complex geological conditions while ensuring the efficient, safe, and sustainable extraction of underground resources.The properties and functions of drilling fluid are crucial in drilling operations, serving roles such as cleaning the wellbore, transporting rock cuttings, cooling and lubricating the drill pipe and drill string, and controlling and balancing formation pressure. Its rheological and other physicochemical properties significantly impact wellbore conditions and control strategies. Selecting the appropriate drilling fluid system and maintaining optimal drilling fluid performance during operations can effectively reduce overall drilling costs.

Currently, drilling fluid performance data is primarily obtained through manual measurements, and the relevant testing standards have remained largely unchanged since the mid-20th century. Existing online measurement methods for drilling fluid rheology include rotational measurement, vibration-based methods, pipeline flow methods, rheology prediction based on Marsh funnel viscosity, and acoustic-based rheology prediction. However, the measurement

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accuracy has yet to reach the ideal range.Selecting an appropriate technological approach and further improving the accuracy, reliability, and real-time performance of online drilling fluid rheology detection instruments is crucial. Additionally, reducing the cost and size of these instruments will facilitate their widespread adoption and application.

In summary, this study addresses two key aspects: improving the accuracy of online drilling fluid rheology measurement in complex geological environments and optimizing the selection of drilling fluid rheology models for the development of an online measurement instrument with high accuracy, reliability, and real-time performance while maintaining a compact size and low cost. The findings provide new technologies and solutions for enhancing the precision of online drilling fluid rheology detection and parameter measurement during the drilling process.

2. Measurement Principle of Drilling Fluid Rheology Rotation Method

2.1. Measurement Principle of Six-speed Rotary Viscometer

The main components of the six-speed rotational viscometer are shown in Figure 1. Externally, it consists of a flat-bottomed cylindrical cup with a coaxially positioned inner cylinder. A narrow annular gap is formed between two parallel surfaces, where the drilling fluid is contained. The concentric rotating cylinder is suspended by a torsion spring wire, which is connected to a pointer on the dial. The annular gap between the bob and the outer cup is approximately 1 mm. The pointer indicates the rotation angle of the torsion spring wire.When the outer cylinder rotates, the polymer fluid in the annular gap undergoes shear-induced flow. Due to the viscosity of the drilling fluid, it exerts a torque on the inner cylinder, causing it to rotate until the torque is balanced by the restoring force of the torsion spring, at which point the inner cylinder stops rotating. At this equilibrium state, the outer cylinder has rotated by a certain angle. The torque generated in the torsion spring at this moment is equal to the shear strength of the fluid’s plastic structure, satisfying the following relationship:

$$\tau_0 = \frac{T_0}{2\pi R_i^2 h} \tag{1}$$

In the formula : τ_0 is the shear stress, T_0 is the torque at the yield point ; R_i is the radius of the inner cylinder ; h is the effective height of the inner cylinder.

Laminar flow now begins on the surface of the float and extends outward with continuous transport lines until all the liquid in the annulus becomes laminar flow. At this time :

$$\tau_0 = \frac{T_1}{2\pi R_o^2 h} \tag{2}$$

In the formula : T_1 is the critical torque ; R_o is the inner radius of the outer cylinder. When the outer cylinder rotates at a constant speed, the measured torque value depends on the rheological properties of the liquid.

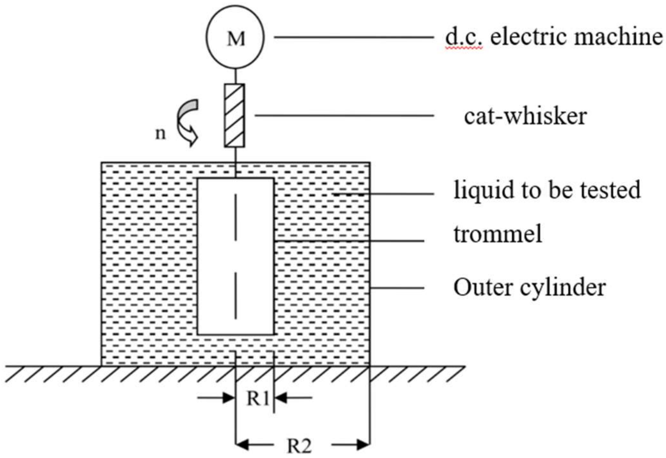

Fig. 1 Torque viscosity represents the intention (the outer cylinder is rotating).

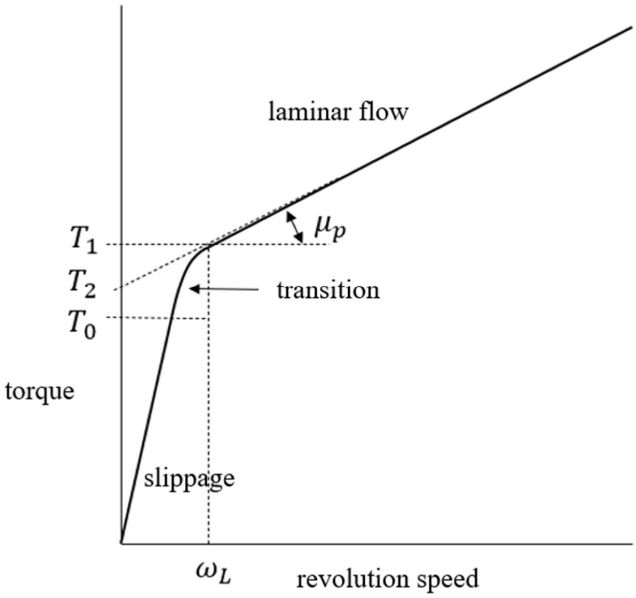

Fig.2 Ribingham plastic consistency curve of viscometer (when the rotational speed is higher than ω_L)

2.2. Torque Sensor Measurement Principle

Torque sensors are widely used in industrial production and other fields. There are many ways to measure torque. Among them, the strain gauge torque sensor has occupied the market for many years by virtue of its mature technology, low price, convenient installation and use. In this paper, in order to change the elastic element connected to the drum into a sensor element that can be converted into a digital quantity, the strain gauge torque sensor is selected as the measuring element. The relationship between the relative change of the resistance of the strain gauge in the torque sensor and the torque is :

$$\frac{dR}{R} = K\varepsilon = K \cdot C_0 M = C_1 M \tag{3}$$

In the formula : R is the strain gauge resistance ; k is a constant related to the material 's Poisson 's ratio, piezoresistive coefficient and elastic modulus E only related to its material.

The formula (3) shows that the relative change of the resistance of the strain gauge attached to the surface of the elastic shaft is proportional to the torque of the bearing. Therefore, it can be concluded that the torsion or torque of the elastic shaft can be converted into the resistance of the strain gauge by using the strain gauge for measurement. It is a way to convert mechanical physical quantities into electrical quantities.

The traditional strain gauge placement method is to cross-paste two strain gauges on the surface of the shaft separated by 180 °.One is at an angle of 45 ° with the axis, and the other is at an angle of 135 ° with the axis, so that the four strain gauges at the two positions can sense the stress of the shaft to the greatest extent. In this paper, the patch method is to paste the strain gauge at the four positions of 0 °, 90 °, 180 ° and 270 ° on the axis circumference according to the 45 ° angle and 135 ° angle alternately with the axis. Four leads are extracted from the four strain gauges to facilitate the subsequent measurement of the output. Fig. 3 is the patch diagram of the strain gauge torque sensor.

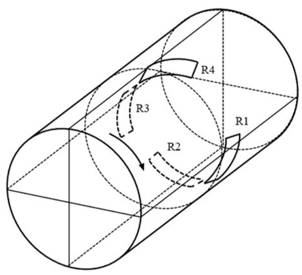

Fig.3 The schematic diagram of strain gauge torque sensor

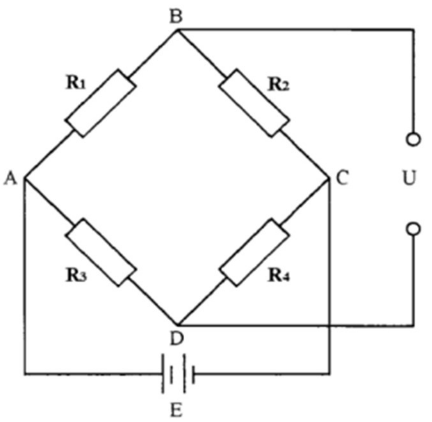

Fig.4 The circuit diagram of strain gauge torque sensor

In Fig.4, the resistance of the bridge arm resistance is the same.$R_1 = R_2 = R_3 = R_4 = R$, The voltage of voltage source is E. The output voltage of the bridge circuit is :

$$U_{BD} = U_{AB} - U_{AD} = \frac{R_1}{R_1+R_2}E - \frac{R_3}{R_3+R_4}E = \frac{R_1R_4-R_2R_3}{(R_1+R_2)(R_3+R_4)}E \quad (4)$$

Because $R_1R_4 = R_2R_3$, the bridge is in equilibrium, $U_{BD} = 0$ The resistance changes of the bridge arm R1, R2, R3 and R4 are R1, R2, R3 and R4, respectively. Because R 1 = R 2 = R 3 = R 4 = R, and the strain gauges connected to the side bridge arm of the bridge have the same mechanical properties, that is, ΔR 1 = R 4 = R, ΔR 2 = R 3 = -ΔR. At this time, the output voltage becomes :

$$U' = \frac{(R+\Delta R)^2-(R-\Delta R)^2}{2R\cdot 2R}E = \frac{\Delta R}{R}E \tag{5}$$

According to the analysis of the torque measurement principle, the relative change of the resistance of the strain gauge Δ R / (R) is proportional to the torque M of the elastic shaft. From the formula (5), it can be seen that the electric signal U output by the bridge circuit is proportional to the relative change of the strain gauge resistance on the bridge arm ΔR / (R). Although the relative change of the resistance can not be measured directly, it can be converted into the voltage signal output by the bridge. From the transmission of the proportional relationship, it can be concluded that theoretically, the output voltage of the bridge circuit has a linear relationship with the torque value of the elastic shaft. By reading the output voltage of the bridge circuit and multiplying a certain proportion, the size of the torque to be measured can be obtained.

3. Measurement Principle of Drilling Fluid Rheology Pipe Flow Differential Pressure Method

In the tube viscometer, the viscosity of the fluid is calculated by measuring the volume flow of the fluid through the circular tube and the pressure difference applied at both ends of the circular tube. The more viscous the fluid, the greater the pressure difference applied when passing through the tube, and the smaller the flow rate. At the same time, the rheological properties of the fluid will also affect the volume flow and pressure difference of the fluid through the circular tube. For example, the rheological properties of polymer solutions are affected by the shear rate, so the influence of rheological properties should be considered when measuring polymer solutions by a tube viscometer. In practice, other different types of viscometers such as rotary viscometers are usually used to supplement tubular viscometers to meet the needs of different liquid tests.

The pressure difference parameters measured by the differential pressure sensor at both ends of the measuring tube can obtain the shear stress of the pipe wall :

$$\tau_w = \frac{D}{4}\frac{p}{l} \tag{6}$$

In the formula : τ_w is the shear stress at the pipe wall, Pa ; D is the inner diameter of the measuring tube, m ; p is the pressure difference in the measuring section of the measuring tube, Pa ; l is the length of the measuring section of the measuring tube, m.

For the pipe, the shear rate at the pipe wall is :

$$\gamma_w = \frac{1}{4}\left[3 + \frac{d\left(\ln\frac{8v}{D}\right)}{d(\ln\tau_w)}\right]\frac{8v}{D} \tag{7}$$

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$$N = \frac{d(\ln \tau_w)}{d\left(\ln\frac{8v}{D}\right)} \tag{8}$$

There is:

$$\gamma_w = \frac{3N+1}{4N}\frac{8v}{D} \tag{9}$$

In the formula : γ_w is the wall shear rate, s^{-1} ; v is the velocity of fluid flow, m/s ; n is a dimensionless parameter. According to the measured value, N can be obtained in the velocity gradient curve of ln $\ln \tau_w$- $\ln\frac{8v}{D}$. After the N value is determined, the rheological parameter values of each rheological model can be obtained.

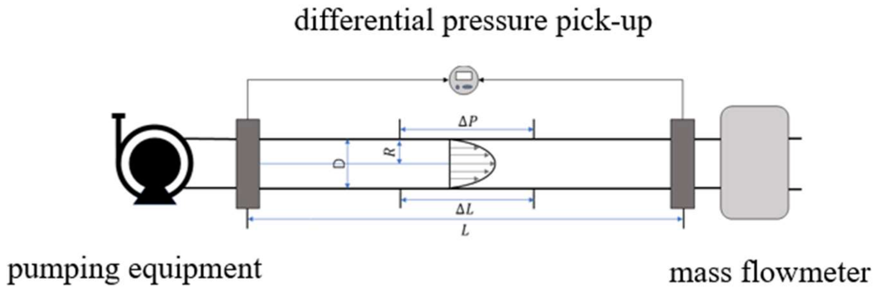

Fig.5 Measurement principle of tube viscometer

4. On-line Measurement Method of Drilling Fluid Rheology

The tubular differential pressure measurement method for online drilling fluid rheology measurement operates as follows:First, a diaphragm pump continuously pumps a controlled volume of drilling fluid from the mud tank into the measurement pipeline. The fluid passes through a filter to remove impurities and then flows through an air damper to reduce flow pulsation. Afterward, it enters a mass flowmeter, which measures the drilling fluid's density, volumetric flow rate, and mass flow rate in real time and transmits the data to the host control center.The host system determines whether the flow is stable based on the measured flow data. If necessary, it adjusts the diaphragm pump's flow rate to ensure a constant output flow. The drilling fluid then passes through the measurement tube, where a differential pressure sensor records the pressure difference between the two ends of the tube and transmits the acquired signal to the host system. The system then solves the model online to obtain the corresponding rheological parameters of the drilling fluid.The measured drilling fluid is subsequently returned to the mud tank, completing the measurement cycle. Since the dimensions of the measurement tube are known, the flow rate of the drilling fluid can be calculated from the mass flow rate and density provided by the mass flowmeter. By adjusting the diaphragm pump's driving frequency, the drilling fluid flow rate can be varied, allowing the system to record corresponding differential pressure data at different flow rates. These measurements enable the construction of flow curves for the drilling fluid, facilitating real-time and accurate online measurement of rheological parameters such as plastic viscosity, apparent viscosity, funnel viscosity, and yield stress.A schematic diagram of the working principle of the tubular drilling fluid performance measurement device is shown in Fig. 6.

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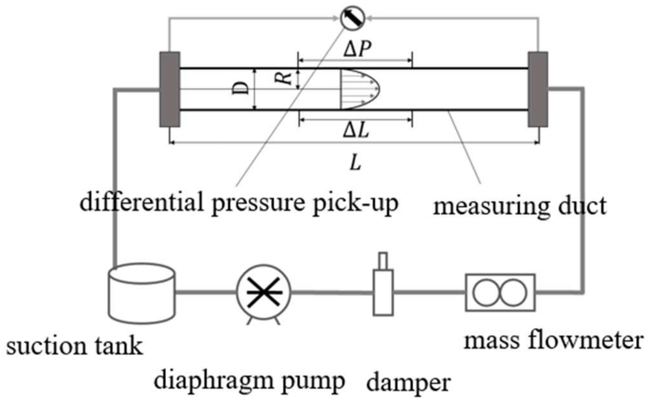

Fig.6 Scheme diagram of on-line measuring device for drilling fluid pipe rheology

The most important thing of drilling fluid tube measurement is to draw the flow curve of drilling fluid, obtain the pressure difference data at both ends of the measuring tube at different flow rates, calculate the wall shear rate and wall shear stress of drilling fluid through the flow rate and pressure difference data, draw multiple data points, and then fit the drilling fluid flow curve.

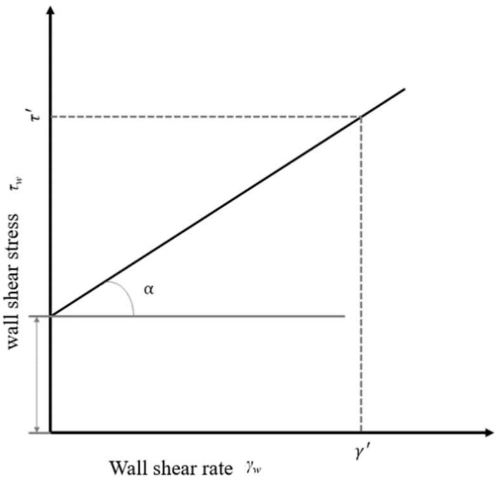

Fig. 7 Flow curve of Bingham rheological model

As shown in Fig.7, where the x-axis is the wall shear rate γw, the y-axis is the wall shear stress τw, and the intercept between the flow curve and the y-axis is the dynamic shear force τy. The slope of the flow curve represents the plastic viscosity μ _ p of the drilling fluid, and the apparent viscosity μ of the drilling fluid refers to the ratio of the wall shear rate to the corresponding wall shear stress, which is expressed as :

$$\eta_a = \frac{\tau'}{\gamma'} \tag{10}$$

The funnel viscosity T is usually expressed as :

$$T = \frac{\eta_a}{\rho} + 25 \tag{11}$$

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In the above two formulas, $\gamma' = 1022$, η_a unit is mPa · s, and T unit is s.

From the above analysis, it can be seen that only by ensuring the accurate measurement of differential pressure and flow rate data can the wall shear rate and wall shear stress of drilling fluid be accurately calculated, and then the accurate data positioning point can be obtained. Through the data positioning point, the drilling fluid flow curve can be accurately drawn, and the accurate rheological performance parameters of drilling fluid can be obtained. Therefore, the accurate measurement of pressure difference and flow rate is the key to ensure the measurement accuracy of rheological properties of drilling fluid.

5. Design and Experimental Verification of Combined On-line Measurement Experimental Platform for Drilling Fluid Rheology

5.1. Process Design

The overall structure of the combined on-line measuring device for drilling fluid rheology is shown in Fig.5-1.It consists of the following main devices : automatic rotation measuring device, tubular differential pressure measuring straight pipe, diaphragm pump, three-way ball valve, Coriolis mass flowmeter and differential pressure sensor.

The torque data generated by the automatic rotary viscometer and the pressure difference data generated by the straight pipe are measured to facilitate the calculation of the rheological parameters of the drilling fluid. Coriolis mass flowmeter is used to collect and measure drilling fluid density and mass flow data. The electric diaphragm pump is used to pump drilling fluid and water from the mud tank and water tank to the circulating measurement pipeline ; the air damper is used to reduce the fluid pulsation generated by the electric variable frequency diaphragm pump.

The drilling fluid tube rheological measurement experiment is to continuously change the output power of the electric variable frequency diaphragm pump through the host computer, measure the pressure difference data generated when the drilling fluid flows through the two ends of the measuring tube at different flow rates, measure the mass flow and density of the drilling fluid by the mass flowmeter, and display the data collected by each sensor on the screen of the industrial computer, and then analyze, process and store the data. The rapid measurement of drilling fluid rheological parameters is realized.

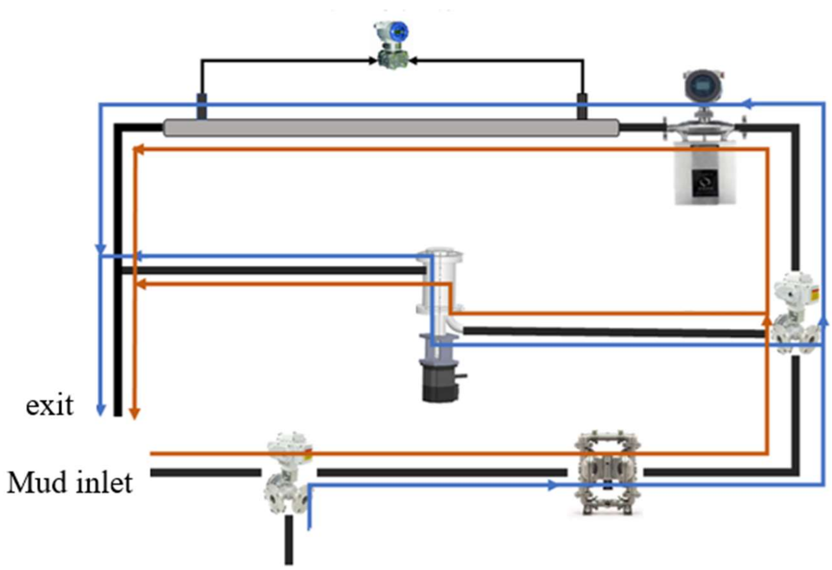

Fig.8 Equipment measurement and cleaning flow chart

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As shown in Figure 8, the measurement process is shown by the brown-yellow arrow : start the three-way ball valve straight through, the diaphragm pump draws the mud from the inlet, until the flow is stable, the diaphragm pump after the three-way ball valve becomes bypass, the mud is pumped into the rotating torque device, after a certain period of time, it is stationary, and the rotation method is measured. After the measurement is completed, the ball valve becomes straight through, through the mass flowmeter and the measuring tube, the pipe flow method is measured, and finally discharged from the mud outlet, which is the measurement process.

The cleaning process is shown by the blue arrow : two three-way ball valves become bypassed, the pneumatic diaphragm pump draws water from the inlet and flushes the rotary measuring device. After a certain time of cleaning, the three-way ball valve after the diaphragm pump becomes straight through, and the water is passed through the mass flowmeter and the measuring tube, and finally discharged by the mud outlet. This is the flushing process.

In this section, the accuracy and repeatability of the drilling fluid rheology on-line monitoring device built in this paper were tested in a good indoor environment, and its flow rate and wall shear rate were analyzed to verify the rationality of the frequency setting. One of the 10 groups of drilling fluids was measured and analyzed. The rheological parameters of drilling fluids without combined measurement were compared with those with combined measurement.

5.2. Analysis of Experimental Data

Table 1. Pipe flow differential pressure method measurement

Tube pressure difference method measurement				Rotary viscometer measurement				deviation			
AV	PV	YP	FV	AV	PV	YP	FV	AV	PV	YP	FV
45.6	43.8	1.8	48.7	40	35	5	1.9	5.6	8.8	-3.2	2.7
44.0	38.6	5.4	47.8					4.0	3.6	0.4	1.8
44.4	38.0	6.4	48.1					4.4	3.0	1.4	2.1
43.7	41.2	2.5	47.8					3.7	6.2	-2.5	1.8
42.0	38.6	3.5	46.8					2.0	3.6	-1.5	0.8
44.2	34.7	9.5	48.2					4.2	-0.3	4.5	2.2
44.9	36.7	8.3	48.6					4.9	1.7	3.3	2.6
47.0	37.3	9.7	49.3					7.0	2.3	4.7	3.3
48.5	35.0	5.3	50.2					8.5	0.0	8.3	4.2
43.9	35.8	8.1	47.7					3.9	0.8	3.1	1.7

Table 2. Combined measurement

Tube pressure difference method measurement				Rotary viscometer measurement				deviation			
AV	PV	YP	FV	AV	PV	YP	FV	AV	PV	YP	FV
41.1	35.5	5.2	46.3	40	35	5	1.9	1.1	0.5	0.2	0.3
40.6	35.5	5.1	46.1					0.6	0.5	0.1	0.1
40.2	34.2	5.3	45.9					0.2	-0.8	0.3	-0.1
39.9	33.9	5.1	45.7					-0.1	-1.1	0.1	-0.3
39.8	33.3	4.9	45.6					-0.2	-1.7	-0.1	-0.4
41.5	34.6	5.3	46.5					1.5	-0.4	0.3	0.5
41.2	33.5	5.2	47.0					1.2	-1.5	0.2	1.0
41.4	34.7	4.8	46.5					1.4	-0.3	-0.2	0.5
41.5	35.5	5.1	46.5					1.5	0.5	0.1	0.5
41.5	36.3	5.2	46.7					1.5	1.3	0.2	0.7

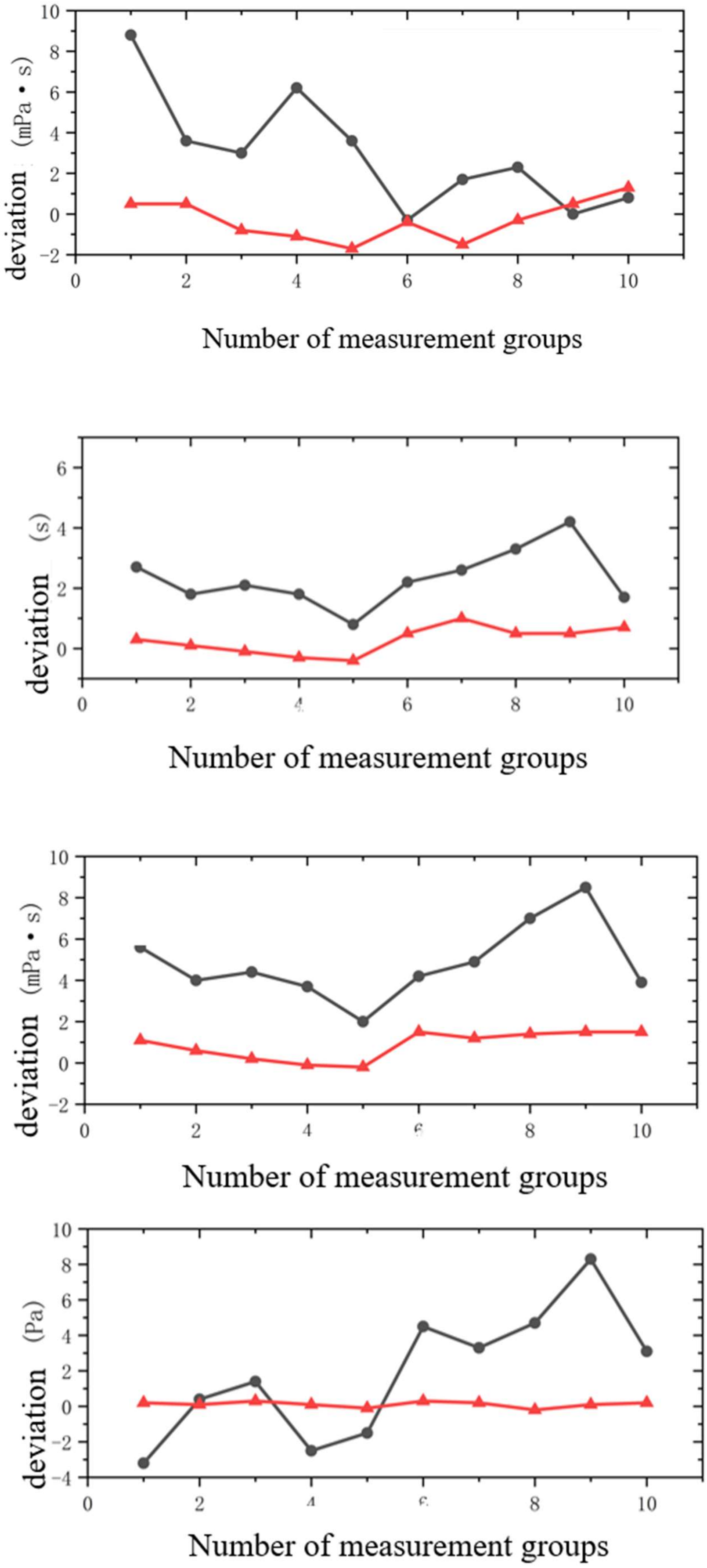

Fig.9 Comparison of rheological parameter deviation

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As shown in Fig.9, based on the measurement data of 6-speed rotary viscometer and funnel viscometer, the rheological parameters measured by the combined measurement method are better than those measured by the tube pressure difference method without the combined measurement method. The error of combined measurement is within the allowable range on site. Therefore, the combined measurement method is used to improve the accuracy of on-line measurement of drilling fluid rheological parameters.

6. Conclusion

In this paper, through in-depth study of the principle of on-line measurement of drilling fluid rheology, the common on-line measurement techniques of drilling fluid rheology are studied and compared. The method of predicting drilling fluid rheology based on Markov funnel viscosity still requires manual detection of Markov funnel viscosity. The theory of detecting drilling fluid rheology based on acoustic technology is complex. The attenuation of acoustic wave will be affected by many factors such as density, rheology and solid content, and it is difficult to apply. Therefore, the most practical and effective rotation method measurement and tube pressure difference method measurement were selected for research. Due to the influence of common fluid pulsation and mechanical vibration on the measurement of tubular differential pressure method, the measurement accuracy of the sensor is reduced. According to the domestic research status, on the basis of tubular differential pressure measurement, a combined method for measuring rheological parameters of drilling fluid is proposed. This method combines the rotation method and the tubular differential pressure method, which complement each other and effectively solves the problem of large measurement error of drilling fluid rheological parameters caused by a single measurement method.

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