The Successful Application of MPD Technology in Drilling Ultra Deep and Ultra-high Pressure Saltwater Formation to Mitigate Drilling Hazards: A Case Study in Tarim Basin

Dezhi Liu, Hongjun Jia, Ming Lei, Weixiong Feng, Hui Feng, and Jiwei Jiang

Abstract The ultra-high pressure saltwater formation coupled with high permeability sand intercalation makes the ultra-deep salt and gypsum formation (6670–7700 m TVD) drilling of the 9–1/2″ hole section particularly challenging in the piedmont area in Tarim Basin. Drilling strategy is usually oriented to the use of high density OBM with densities normally ranging between 2.32 and 2.60 g/cm^3. High density mud causes losses and sticking events. To overcome the challenges mentioned, the application of MPD technology with the constant liquid volume during the drilling of the 9–1/2″ hole section enables utilizing the balance between formation pressure and downhole pressure. The technology involves keeping constant circulation fluid volume during drilling, and pipe connection under shut-in, shut-in during trip and keeping fluid in wellbore constant by squeezing in and releasing liquid, so as to keep pressure in wellbore balanced. This paper summarizes the key points of field implementation and related calculation method of the constant liquid volume MPD technology. Comparing with conventional drilling methods, the constant liquid volume MPD technology can enhance drilling efficiency and mitigate drilling hazards such as losses and differential sticking. As a result 325 m of salt and gypsum formation were drilled in only 29 days while field average is around 97 days. The successful application of MPD technology will provide a new approach for safe drilling of ultra-high pressure saltwater and narrow density window formation.

Keywords Ultra-high deep · Saltwater formation · MPD technology · Salt and gypsum formation · Narrow density window · Ultra-high pressure

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1 Introduction

The K field is located in the Tarim Basin, Xinjiang Uyghur autonomous region of Northwest China (Fig. 1). The ultra-thick salt and gypsum formation is generally developed, with a buried depth of 6670–7700 m. K salt intervals are considered "dirty" in that they are interbedded with mudstone, gypsum, dolomite, and siltstone. So there are issues with those types of salts, their behavior is unpredictable and they have much tendency to deform or "squeeze". There are many sets of ultra-high pressure salt-water layer with equivalent drilling fluid density greater than 2.32 g/cm^3 and thin tensile mudstone with weak tensile strength in the salt layer, resulting in narrow safety drilling window of the formation.

The main operational issues while drilling those wells are related to ultra-thick salt and gypsum formation crossed in the 9 1/2″ section [1]: salt water influxes, stuck pipe and mud losses. The vicious cycle conditions frequently occur, and it is difficult to drill safely by conventional drilling techniques. In view of the poor stability and inhibition of water-based drilling fluids, oil-based drilling fluids with good lubricity, anti-pollution ability and strong inhibition are commonly used in the high temperature and high pressure salt and gypsum formation in the K field.

MPD technology can control bottom hole pressure and be used in narrow density window formation drilling. After analyzing the pressure in the well, especially the drilling of narrow-density window formation, a simple control method for balanced pressure drilling was proposed and applied. The method achieves a real-time balance between bottom hole pressure and formation pressure by controlling the constant circulation fluid volume. Compared with the method of back pressure pump boosting,

Fig. 1 K field of Tarim Basin general location (Google Earth)

auxiliary throttle control and bottomhole pressure measurement, the field operation is simple and convenient for popularization and application [2–7].

2 Managed Pressure Method for Constant Liquid Volume

2.1 Relationship Between Pressures in the Well

Wellbore pressure mostly comes from the hydrostatic column pressure of the drilling fluid, the other also has the circulation flow resistance, the formation fluid pressure which invades the well, the surge pressure, the swabbing pressure, the ground back pressure and so on. The wellbore pressure is analyzed based on the U-tube principle. The pressure during managed pressure drilling is shown in Fig. 2. The casing pressure is closely related to the standpipe pressure. Changing the casing pressure can control the bottomhole pressure and affect the standpipe pressure [8].

Real-time balance between bottomhole pressure and formation pressure under different drilling conditions can be achieved by controlling the constant liquid volume. In the field application, it is not necessary to carry out complex calculations on the pressure of the wellbore system and the formation pressure can be roughly predicted by the usual methods, which greatly simplifies the calculation and control

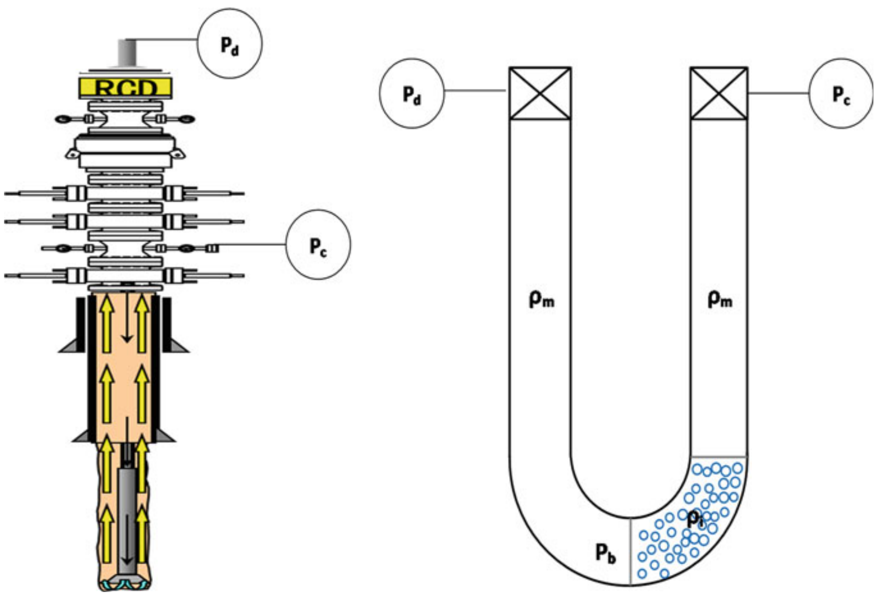

Fig. 2 Interpretation of wellbore pressures during MPD

of the balanced pressure drilling [9]. Under this control mode, the basic relationship of pressure balance under different working conditions is as follows.

While drilling: $P_p = P_b = P_{ma} + P_{la} + P_{ax}$
While connecting drillpipe: $P_p = P_b = P_{ma} + P_{ax}$
While tripping: $P_p = P_b = P_{ma} + P_{ax} + P_{sw}$ or $P_p = P_b = P_{ma} + P_{ax} - P_{sb}$.

The principle of MPD of the constant liquid volume is the balance between the bottomhole pressure and the formation pressure. During drilling, the control of choke valve keeps the circulating fluid volume stable and the real-time balance between formation pressure and bottomhole pressure can be achieved. In fact, the constant liquid volume is a state that neither wellkicks nor mud losses, but is the ground performance of the balance between bottomhole pressure and formation pressure.

2.2 MPD Equipment

MPD of the constant liquid volume does not require auxiliary pump, automatic chokes, downhole pressure measurement tools, coriolis flow meter and ground automatic control system. It mainly uses rotating control head, liquid level monitor, conventional choke manifolds and killing manifolds (Fig. 3). The liquid level monitor can accurately monitor the total amount of drilling fluid in the wellbore [4]. The choke valve is operated by observing the change of the liquid level to ensure the correct implementation of MPD.

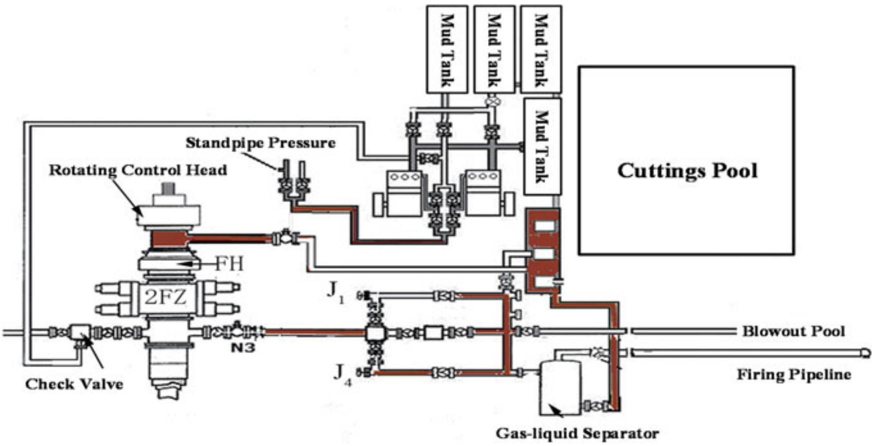

Fig. 3 MPD equipments and process

2.3 MPD Program Implementation and Operation Points

- While drilling

During drilling the salt and gypsum formation, the changes in the standpipe pressure and rate of penetration (ROP), drilling mud performance, lithology and bit bouncing should be paied attention. It is found that the well is shut in immediately after well-kicks, and the circulation with choke of MPD is used instead. After shut-in, we can determine the safety control pressure value based on the standpipe pressure and casing pressure and monitor the total amount of drilling fluid to determine fluid quantity benchmark of MPD. In order to facilitate and safe operation, the casing pressure should not be above 5 MPa and the drilling fluid volume should meet the circulation requirements.

Open the flat valve behind the choke valve before opening the pump. Gradually open choke valve to find the balance point of circulating liquid level while opening the pump. The pump should be synchronized with the open of choke valve to reduce the effects of the surge pressure.

Observe the mud tank level and operate the choke valve to control casing pressure according to the principle of no wellkick and lost circulation during MPD. If the mud tank level has an increasing tendency, the choke valve should be properly turned down. If the mud tank level has a decreasing tendency, the choke valve should be opened wider to ensure a constant liquid volume. Since the saltwater is substantially incompressible, the control method ensures that the formation fluid does not invade the well and drilling fluid does not lost circulation.

- While picking up standpipe

In the process of connecting, it is necessary to stop the pump and then open the pump. It is an important part of the wellhead pressure control. Before the drillpipe is connected, the drilling fluid in the wellbore is in a circulatation state and the pressure is in equilibrium. But the circulating pressure goes to zero when the pump is stopped, the bottomhole pressure will be less than the formation pressure. If the liquid volume is kept constant, the pressure in the well will still be in equilibrium. After drilling, quickly close the throttle valve and shut off the well while stopping the pump. For the saltwater layer, the formation fluid after well shut-in is basically unable to enter the wellbore and will not be lost because the liquid is basically incompressible. At this time, drillpipe can be connected. The floating valve is connected to the drilling string, so the drilling fluid does not have the problem of reversal. After connecting, the choke valve is opened when the pump is opened and the pressure in the well can be kept stable. The drilling is proceeding normally.

- While tripping

Before trip-out operation, the pressure is in a balance in the circulation state. After the pump is stopped, the standpipe pressure and the casing pressure are P_{ax} (greater than P_{ax} during drilling). At this time, the bottomhole pressure is reduced by P_{sb} and the formation fluid has a tendency to enter the wellbore. Due to the incompressibility of the saltwater, the formation fluid can hardly enter the wellbore, which can be neglected from the engineering point of view. If the drilling fluid is properly squeezed into the well to improve the wellhead back pressure in shut-in, the formation fluid can not be more into the wellbore. When trip-out operation, the method of first squeeze can basically achieve the pressure balance in the well and meet the requirements of drilling. Drilling fluid which volume is equivalent to drillpipe column should be squeezed into the annulus in shut-in before each drillpipe column is tripped out. According to this method, the formation and the wellbore pressure are basically under equilibrium, and wellkicks and mud losses will not occur. After tripping out to the casing shoes, the wells are shut down to obtain the casing pressure. According to the casing pressure, the height and volume of the weighted mud cap are calculated according to the field weighted mud density and then the weighted mud is injected. The calculation method is as in formula 4. After the completion of the weighted mud, the outlet can be cut off normally. During tripping out, the drilling fluid is continuously grouted according to the drillpipe volume. If the wellkick is found, the well is immediately shut in and the mud is squeezed by kill manifold. Tripping out is continued after the casing pressure is 0 and the outlet is interrupted.

$$H_{wm} = 1000 \times P_{ax}/((\rho_{wm} - \rho_m) \times g)$$

When trip-in operation, mud losses may occur due to surge pressure acting on the bottom of the well. The method of releasing the drilling fluid after running in hole can meet the requirements of safe drilling. The drill string can be tripped in under openning well when no wellkicks occurs. But the drill string must be tripped in under shut-in when wellkicks occurs. When running in hole to the weighted mud cap, the pump is opened to circulate the weighted mud out of the wellbore. The specific operation method is that the choke valve is opened to release the drilling fluid corresponding to the volume of the drill string after tripping in a column of drill string in the case of shut-in until the trip-in is completed. According to this method, the formation and the wellbore are basically in a balance state of pressure.

3 Geology of the Filed and Well Design

The surface of K field is a soft Quaternary stratum with an unstable gray sandstone and conglomerate above 700 m. The well depth of 700–6776 m is sandstone, mudstone and conglomerate with good stability. The well depth 6776–7400 m is a concentrated section of the salt-gypsum bed of about 700 m. The well depth 7400–7626 m is the sandstone which is the target zone of gas exploration, as in Fig. 4.

The un-API well structure design of the area which considers:

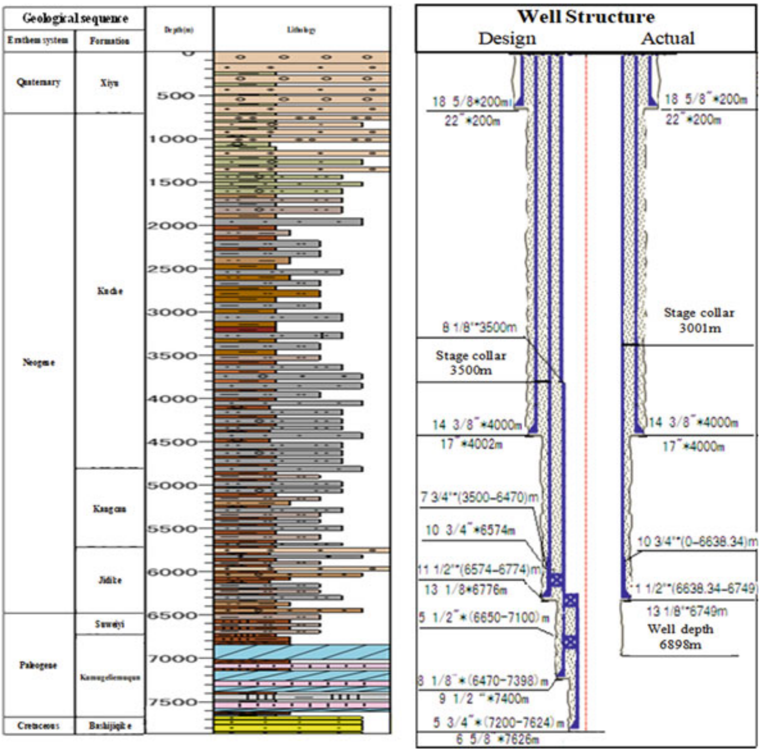

Fig. 4 Geology of the K filed and un-API well structure design

- 18 5/8″ surface casing at 200 m to seal unstable gray sandstone and conglomerate layers.
- 14 3/8″ casing string set at the beginning of the abnormal pressure zone at Kangcun formation (approximately 4000 m).
- 11 1/2″ + 10 3/4″ casing set at the top of the Kumugeliemuqun formation.
- 8 1/8″ liner + tieback set through mudstone (hard to pick) at base of the Kumugeliemuqun formation.
- 5 3/4″ + 5 1/2″ liner at lower Bashijiqike formation.

4 Field Challenges and Motivations to Implement the MPD Technique

Through a delicate analysis of offset wells, which included investigation of operational data, electrical logs, mud logging reports, production data, seismic information among others, a calibrated geomechanical model was developed and the four pressure profiles of K field (taking well K1 as an example) was predicted seen below.

As shown in Figs. 4 and 5, results of such summaries indicated that most of the operational issues in the offset wells related to salt and gypsum formation which was drilled in 9 1/2″ diameter and cased 8 1/8″ casing. Events presented were mainly related to:

- Stuck pipe associated with the plastic behavior of the salt. According to the offset wells, the mud weight required to control the plastic behavior of the salt varies between 2.32 and 2.40 g/cm^3.
- Ultra-high pressure saltwater kicks while drilling the salt and gypsum formation, which occurs as a result of pressurized sands, trapped between the salt (Fig. 6). The drilling operation of well K1 showed that the pressure coefficient of saltwater formation reaches 2.66, which is the highest in the working area. The saltwater may invade the wellbore to contaminate OBM. The high-concentration saltwater under high temperature and high pressure conditions will return to the wellhead to precipitate the crystalline salt to block the annulus and the ground manifold.
- Fluid losses while drilling the salt and gypsum formation, which occur due to lower pressure sand and mudstone formations trapped between the salt.

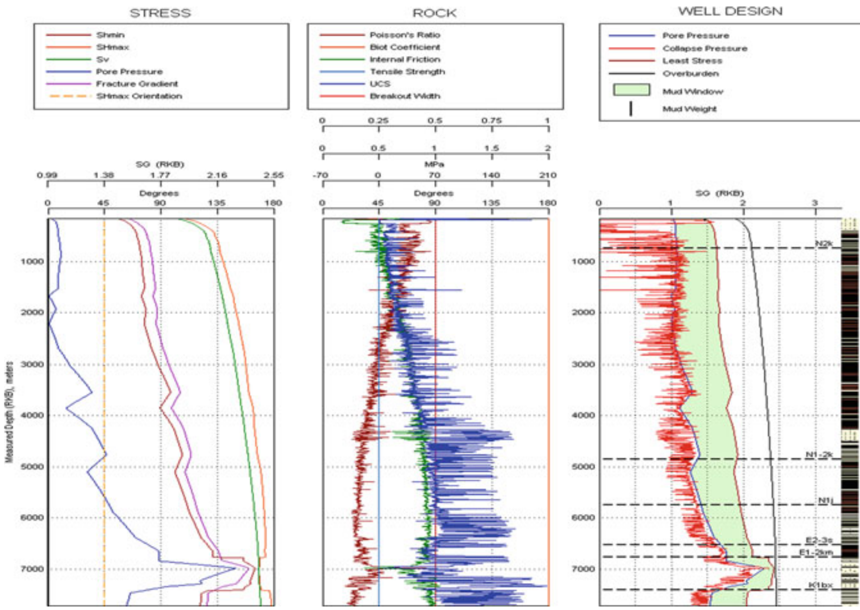

Fig. 5 Results of the geomechanical model and mud window

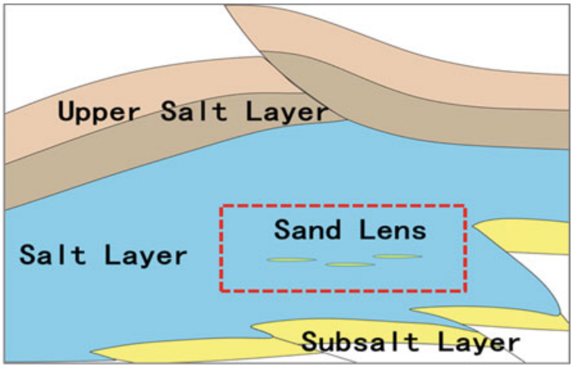

Fig. 6 Geological environment of salt water development

5 Case Analysis of MPD in Well K1

5.1 Brief Description of the Previous Situation

The oil-based drilling fluid with a density of 2.50 g/cm^3 was used to drill to the depth of 6898 m, then the top drive suddenly stopped and mud tank level rose 0.8 m^3 (the torque fluctuation was large). The standpipe pressure was 7.5 ↘ 4.8 ↗ 5.9 MPa and casing pressure was 12.5 ↘ 12.3 ↗ 12.5 MPa after the well was closed immediately. After the circulation killing, the drilling fluid density was forced to increase to 2.60 g/cm^3 and the casing pressure of the shut-in is 3.8 MPa.

Due to the high density of drilling fluid, normal drilling operations cannot be performed. Production management department carries out the exploration and practice of managed pressure drainage technology to reduce the pressure coefficient of saltwater formation and solve safe drilling problems of ultra-deep and ultra-high pressure saltwater. However, the saltwater layer pressure did not decrease after the cumulative 1717 m^3 saltwater was drainaged (Fig. 7) and the average amount of drilling fluid lost per day was about 6 m^3 (the drilling fluid density window was less than 1 MPa).

5.2 Simulation of Hydraulic Parameters of MPD

A summary of modeling and well parameters is contained in Table 1.

Figure 8 shows the wellhead backpressure simulated in the static state and the circulation state for the well depth of 6898 m. The principle of determining drilling fluid density and the pressure control value of the wellhead is to achieve the balance between the bottomhole pressure and formation pore pressure as much as possible. Besides, the maximum dynamic pressure of RCD rubber core is 10.5 MPa, so the maximum wellhead back pressure does not exceed 7 MPa if taking 30% safety

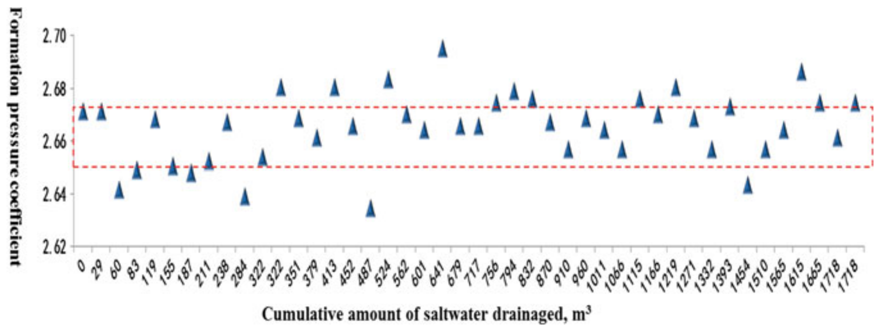

Fig. 7 Calculate the formation pressure based on the casing pressure in shut-in

Table 1 Summary of input parameters of the MPD simulation

Drillbit size (mm)	Well depth (m)	Mud performance		Drilling parameters			
		Density (g/cm^3)	Viscosity (MPa s)	Weight on bit (KN)	Rotating speed (r/min)	Standpipe pressure (MPa)	Flow rate (L/s)
241.9	6898	2.54–2.6	6–18	40–80	40–100	18–22	10

margin. When designing the mud density of 2.58 g/cm^3 for MPD, the backpressure value of the circulation is 0.5–3 MPa and the pressure value is 3–6 MPa while stopping the pump.

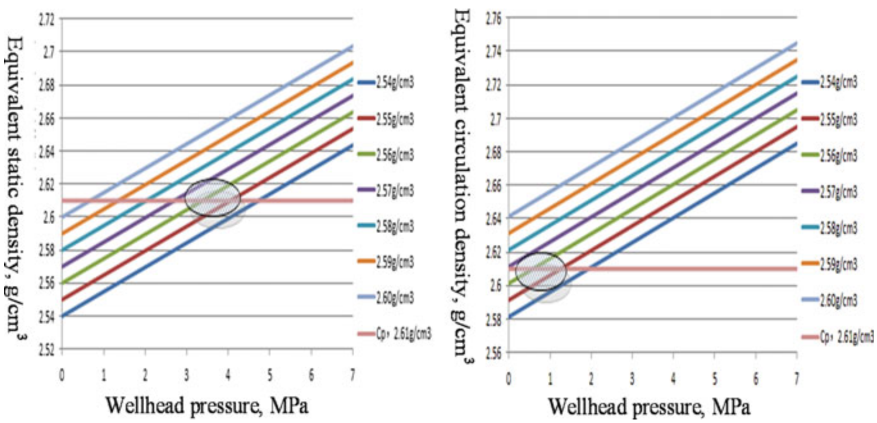

Fig. 8 ECD and ESD versus drilling fluid density

Fig. 9 Wellhead backpressure and flow rate monitor while reaming

5.3 Summary of MPD Field Operations

The reaming well section is 6749–6898.21 m. The well section of 6883–6895 m is difficult to ream and the top drive is frequently stopped. Lost circulation is found in 6894.10 m, but the reaming of open hole is smoothly operated by controlling the wellhead backpressure accurately. The drilling fluid density is 2.58 g/cm^3, the viscosity is 120–144 s, the flow rate is 10.1–13.4 l/s, the standpipe pressure is 18.5–21.3 MPa, the wellhead backpressure is 2.3–4.5 MPa and the bottomhole ECD is 2.65–2.67 g/cm^3 (Fig. 9).

The well section of MPD is 6898.21–7068 m. Lost circulation is found in 6924 m. The micro-overbalanced method is used to control the wellhead backpressure to ensure that the saltwater does not invade the wellbore during drilling. The drilling fluid density is 2.56–2.58 g/cm^3, the viscosity is 90–160 s, the standpipe pressure is 18.5–21.3 MPa, the flow rate is 10.1–13.4 l/s, the wellhead backpressure is 0.5–5.1 MPa, and the bottomhole ECD is 2.63–2.64 g/cm^3. Backpressure of tripping and connecting is 3.5–7 MPa (Fig. 10).

6 Conclusions

- The high-pressure saltwater formation was drilled successfully during the MPD operation. MPD of constant liquid volume effectively reduced the non-production time, shortened the drilling duration, and opened up a new method for safe and rapid drilling of the high-pressure saltwater formation.
- As a result of the use of MPD, 325 m of salt and gypsum formation were drilled in only 29 days while field average is around 97 days.

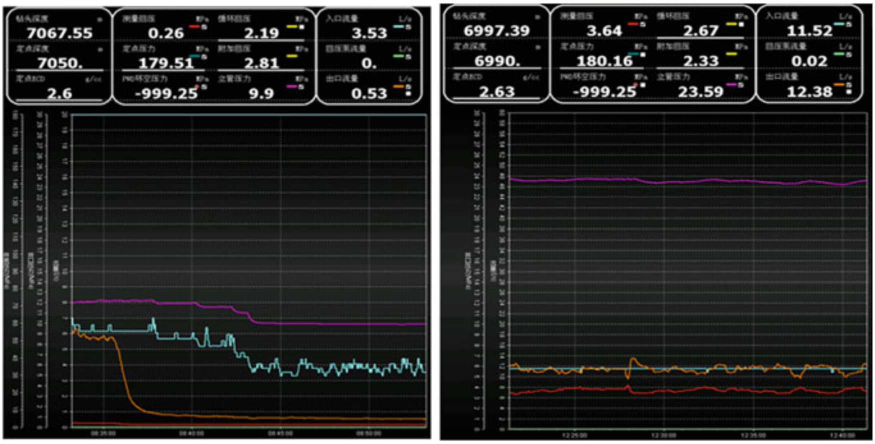

Fig. 10 Wellhead backpressure and flow rate monitor while drilling

- During the MPD operation, the saltwater from salt and gypsum formation is effectively controlled to contaminate the drilling fluid, which greatly saves the cost of drilling fluid.

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