Research on Technology of Drilling in High Temperature and High Pressure Gas Field in South China Sea

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Abstract. The HTHP (high temperature and high pressure) areas of the Ying-qiong Basin in south China Sea has the characteristics of high temperature, high pressure, many pressure steps and narrow safety density window. The severe geological conditions pose a serious challenge to safe drilling in HTHP environment. Through more than 20 years of technical research and field practice. A set of key drilling technologies suitable for HTHP areas in south China Sea have been formed, including: multi-genesis formation pressure prediction, HTHP drilling fluid system, safe cementing technology, ECD accurate prediction technology, and drilling speed increasing technology. The engineering practice of safe drilling in the HTHP area of the South China Sea improves the efficiency of operation and ensures safe drilling. At the same time, the key technology also provides guidance for offshore drilling in HTHP areas.

1. Introduction
The Yinggehai Basin and the Qiongdongnan Basin are typical HTHP basins in south China Sea. They are one of the three HTNH areas in the world. The Ying-qiong Basin is rich in oil and gas resources, of which the HTHP natural gas resources are expected to exceed 4 trillion m³, and the resource potential is huge [1,2]. HTHP drilling is one of the world’s drilling technology problems. The limitation of offshore working environment makes the high risk of HTHP drilling [3]. The stratum in the Ying-qiong Basin of the South China Sea has complex geological features such as narrow pressure window, large pressure gradient change, and many pressure steps. In addition to the harsh environment such as typhoon weather in South China Sea, it becomes a problem to carry out drilling operations safely and efficiently. By reviewing the operation history of HTHP drilling in south China Sea and analysing the complex situation of HTHP drilling operations, we summarize the technical measures formed through tackling and on-site practice, and aim at the development of HTHP exploration in south China Sea in recent years.

2. The HTHP drilling process in South China Sea
The HTHP exploration in south China Sea is mainly concentrated in the Yinggehai Basin and the Qiongdongnan Basin. The operation time began in the early 1980s[4]. In 1984, Arco conducted the first HTHP well drilling operation in south China Sea. As of 2016, four domestic and foreign operators of Arco, Chevron, Shell and CNOOC carried out HTHP drilling operations in south China Sea. The exploration mode experienced three stages. In 2010, self-operated exploratory well DF1-1-14 tested high-yield natural gas, and we discovered the DF13-1 HTHP gas field. Since then, HTHP exploration
in the western part of the South China Sea has entered a stage of rapid development, and several gas fields such as DF13-1, DF13-2, YC13-2 and LS25-1 have been discovered. The HTHP wells drilled by domestic and foreign companies in south China Sea are shown in Table 1.

| Time          | Well numbers | Operators         |
|---------------|--------------|-------------------|
| 1984.03-1996.01 | 6            | Arco              |
| 1998.11-1996.06 | 1            | Chevron           |
| 1991.05-2004.10 | 8            | self-operated    |
| 2009          | 1            | Foreign operators |
| 2010-2015     | 34           | self-operated    |

There are 4 wells with a depth of more than 5000 m in the drilled well, 15 wells with a depth of more than 4000 m and less than 5000 m, and 33 wells with a depth of less than 4000 m. Due to the obvious difference in the maximum temperature encountered during drilling processes, the well depth is relatively shallow and its temperature is relatively low. Among them, there are 4 wells with a measured temperature greater than 200°C (2 wells over 240°C), 13 wells at 180-200°C, and 36 wells at 150-180°C. In the HTHP wells drilled in south China Sea, there are 10 wells whose drilling fluid density exceeding 2.20 g/cm³. The well number distribution of different drilling fluid densities is shown in Table 2.

| Drilling density | Well numbers | Drilling density | Well numbers |
|------------------|--------------|------------------|--------------|
| 1.8 ≤ γ < 2.0    | 27           | 2.2 ≤ γ < 2.3    | 7            |
| 2.0 ≤ γ < 2.2    | 13           | γ ≥ 2.3          | 3            |

During the “Twelfth Five-Year Plan” period, the HTHP exploration process in the western part of the South China Sea has been accelerating. So far, more than 50 HTHP wells have been drilled in the western part of the South China Sea.

3. Difficulties of HTHP drilling process in south China Sea

The HTHP operation area of the South China Sea is far away from the logistics base, and the water depth is 65-130 m. The working condition is harsh and the risk is very high. The main performances are: well leakage and kicks caused by narrow formation pressure window, fatigue fracture, cementing and abandoning cement plugs and casing wear problems [5,6]. The statistics of the complexities of HTHP wells drilled in south China Sea are shown in Fig. 1.

![Figure 1](image-url)
3.1. The formation pressure is complex and the prediction accuracy is low
The Ying-qiong Basin is located at the intersection of regional active faults, with strong anisotropy of geostress, development of mud diapirs, wide distribution of waterways, complicated mechanism of high pressure and rapid formation pressure rise (Fig. 2). The pressure prediction is difficult, and the error is as high as 30% [7]. The deviation of the pressure prediction causes the casing program, the drilling fluid density, and the technical scheme to be unreasonable, resulting in frequent overflow, well leakage, wellbore collapse, and stuck. In complex situations, the wellbore is scrapped, which seriously threatens the safety of the platform and personnel [8].

3.2. Difficult control on drilling fluid performance
High-density drilling fluid has high solid content and low free water. It is a thick colloidal suspension system. High temperature increases the difficulty of high-density drilling fluid performance control. Under high temperature environments, solid phase clay dispersion is intensified, and the efficiency of drilling fluid treatment agent is reduced, and viscosity and shear force increase sharply, and it is very difficult to flow [9]. In addition, the large set of mudstones in the upper high-pressure caprock of the Ying-qiong Basin is easy to hydrate, and the ROP is low, which is likely to cause repeated cutting and aggravate the hydration of mudstone.

3.3. High-risk well control
With the increase of drilling depth in the HTHP exploration wells of the South China Sea, the formation pressure window has gradually narrowed, and the drilling problems have become more and more prominent [10]. The narrow formation pressure window of drilled HTHP exploration wells in South China Sea is only 0.3. During the drilling process, there is a complex downhole situation in which the high-density drilling fluid is prone to leakage, and the narrow pressure window also makes the conventional casing procedure unable to meet the operation requirements, which is a technical bottleneck that seriously restricts the drilling operation of HTHP exploration wells.
3.4. Poor cementing quality

The multi-pressure system with narrow formation pressure window and small annulus clearance, high pressure gas layer and low pressure easy-leakage layer is usually in a pre-sealed section, where the leakage and kick are easy to occur during operation [11]. It is easy to cause early coagulation of cement under high temperature environments, affecting the performance of cement stone. The high temperature has higher requirements on the temperature resistance of cementing materials and the comprehensive performance of high-density cement slurry. In addition, gas channeling in high pressure gas wells is serious, which is an important factor affecting cementing quality [12].

3.5. Poor formation drillability

After entering the high-pressure stratum, the liquid column pressure and cyclic pressure consumption of the high-density drilling fluid are more and more obvious. The plasticity of mudstone formation is increased under the influence of the high-density drilling fluid, and the drill bit is difficult to destroy the formation [13]. The combined effect of the factors results in a lower drilling rate when drilling high pressure formation.

4. Key technologies for HTHP drilling in south China Sea

In order to overcome the challenges of drilling technology in HTHP well exploration, after a long period of research, the key technologies and management measures for drilling HTHP exploration wells in south China Sea have been formed, including formation pressure prediction, well structure design, drilling fluid, cementing, narrow pressure window drilling, and drilling speed-up tools.

4.1. Muti-mechanism formation pressure prediction

The traditional formation pressure prediction method is based on under-compaction theory. The main methods are acoustic time difference, Eaton method [14], etc. However, the South China Sea is located at the intersection of Eurasian, Pacific and Indo-Australian plates, making this area is coupled by under-compacting and external geological movements. The error of the traditional pressure prediction model can reach 30%.

Through the analysis of the stress model, sonic logging data and density logging data, the relationship between the source and other source is found, revealing the formation pressure mechanism of the South China Sea (Fig. 3). One part of the high pressure is self-source: due to the under-compaction causes high pressure formed by geological loading. This part of the pressure can be calculated by traditional methods. The other part is the other source of high pressure: due to geological loading and unloading movements, including geological structure movement extrusion, crack filling, water channel sand, and other factors. Based on above, a new method for multi-mechanism formation pressure prediction is established, as shown in equation(1).

\[
P_p = P_1 + P_2 = P_1 + \sigma_f - \sigma_o
\]

In formula (1): \(P_p\) is the formation pressure, MPa; \(P_1\) is the self-source pressure, MPa; \(P_2\) is the other source pressure, MPa; \(\sigma_f\) is the effective stress of the unloading starting point, MPa ; \(\sigma_o\) is the effective stress at the end of the unloading, MPa.

The multi-mechanism formation pressure prediction method has increased the accuracy of the formation pressure prediction in south China Sea from 70% to 95%, which solves the accidents in HTHP drilling process[15].
4.2. HTHP drilling fluid technology

Aiming at the problems of high-density drilling fluid rheology control in high temperature environment, combined with regional stratigraphic characteristics, the introduction of organic salt inhibitors, preferably sulfonated materials and temperature stabilizers, to enhance the system inhibition, and forming a water-based improved drilling fluid system with a temperature resistance of 200°C and a density of 2.20 g/cm$^3$.

The application of ultrafine barite significantly reduces the contradiction between high-density drilling fluid rheology and sedimentation stability. The ultrafine barite has a small particle size compared to ordinary barite and the average particle size is about 5 μm[16].

Since the ultrafine barite is modified and the particles exhibit elastic collision, making the ultra-fine barite high-density drilling fluid have a lower viscosity. In another aspect, the electrostatic repulsion between the ultrafine barite particles is significantly larger than that of ordinary barite, making the ultrafine barite high density drilling fluid more uniformly dispersed. For example, in the target layer of a HTHP well in the western part of the South China Sea, the bottom hole temperature is 195°C, and when drilling to 4057 m, the abnormal high pressure is drilled. During the fluid density increasing process, the barite is used to increase from 2.17 g/cm$^3$ to 2.19 g/cm$^3$, and found that the addition of barite is double the amount of calculation. It can be seen from Fig. 4 that as the density increases, the viscosity of the drilling fluid continues to rise. After switching to ultra-fine barite, the viscosity did not change as the density of the drilling fluid increased, and the viscosity was controlled well. The ultrafine barite weight-enhanced water-based drilling fluid system has good high temperature rheology and sedimentation stability, and has been successfully applied in many HTHP wells in the Ying-qiong Basin.
4.3. **Safe cementing technology**

In the HTHP well cementing operation in the western South China Sea, it is very difficult to achieve pressure balance. On the one hand, due to the high formation pressure and complicated pressure system, it is difficult to accurately predict the pressure in each layer [17]. In another aspect, the cement will lose weight in the initial solidification stage, and if the resistance of the cement slurry against gas channeling is not enough, once the high pressure gas in the formation is more active, it will cause gas channeling. In order to solve the problem of channeling, leakage and low cementing quality in offshore HTHP cementing operations, according to the irregular particle grading concept and neuron theory, combined with experimental data, high quality cement external admixture is selected. By optimizing high temperature leak-proof material and channeling-proof material, a new type of cement slurry system with channeling-proof, leak-proof and temperature-proof was developed. The system is composed of filling material and cement, which has a compact structure with high fluidity, small free liquid, small filtration capacity, good rheological property and enhanced anti-channeling effect. In order to solve the crack problem caused by cement paste, a substance which can spontaneously respond to oil and gas stimulation is embedded in the repairing agent. The oil-gas response self-repairing cement slurry was developed, and a dynamic fracture width plugging evaluation instrument was developed to evaluate the plugging of cement slurry under simulated working conditions. In order to improve the cementing quality of the liner section, the rotary tail pipe hanging technology is used together, and the cementing quality is further improved by proper rotation during the tail pipe cementing. This technology has been promoted and applied in HTHP exploration wells on field. The accidental rate of casing in HTHP well is 0. The cementing quality logging result shows that the qualification rate of cement ring is close to 100%.

4.4. **ECD accurate prediction technology**

In order to solve the problem of well leakage and well control risk in HTHP narrow pressure window formation during drilling, based on the three-dimensional description of reservoir pressure and real-time calculation of wellbore pressure distribution, the wellbore temperature, pressure and drilling fluid parameters are coupled and combined[18]. According to data analysis of drilling fluid in HTHP wells in the western South China Sea, a new set of empirical prediction model for HTHP drilling fluid density is proposed. The new model overcomes the influence of traditional experience prediction model on temperature. At the same time, the effects of displacement, rotation speed, drilling speed, casing speed and weighting speed on the equivalent cyclic density were studied, and the accurate prediction model of ECD was established. The result is shown in Fig. 5.

![Figure 5](image_url)

*Figure 5. Full-hole ECD accurate prediction model under the effect of different factors.*
According to the prediction model, a set of drilling technology based on accurate hydraulics calculation and "constant micro-over-balance" bottom hole pressure safety control is formed by fully considering the influence of different BHA. The downhole ECD is monitored in real time according to the pressure measurement while drilling technology. By adjusting the displacement, pump pressure and rotational speed, the ECD is controlled between pore pressure and leakage pressure, so that the bottom hole pressure is always within the safe density window. During the drilling operation in HTHP narrow pressure window in the Ying-qiong Basin, the bottom hole pressure is always higher than the formation pressure of 0.01 g/cm$^3$, and the complex conditions such as well leakage and kicks are greatly reduced.

5. Technology outlook

5.1. Formation pressure fine prediction technology
At present, in the prediction of abnormal high pressure, the urgent problems to be solved include the identification of the genetic mechanism of overpressure in permeable formations and the fine interpretation of fracture pressure in different lithologic formations. Therefore, it is necessary to systematically analyze the existing geological results, study the influence of geological processes such as sedimentary compaction, tectonic compression, hydrocarbon migration and accumulation on abnormal high pressure, and systematically understand the genesis mechanism of abnormal high pressure in target strata in new exploration area. In view of the complex geological characteristics of HTHP formation, the method of formation pressure prediction and monitoring in HTHP wells is studied, and the pre-drilling prediction technology of formation pore pressure based on multi-information such as geology, logging, seismic and so on is established. According to the real-time information while drilling, the pre-drilling pressure prediction model is updated in real time, and the real underground pressure is judged correctly to ensure the safety of operation.

5.2. Unconventional casing design
The complex geology conditions in HTHP areas determine the complexity of well casing design. In addition, geological data acquisition equipment with high temperature resistance is difficult to adapt to small borehole operations, which limits the bottom extension of traditional wellbore casing design to a certain extent. The current design theory and practice of unconventional well structure are still lacking. The supporting technology need to be further studied. According to the geological characteristics of the Ying-qiong Basin, the influence of HTHP environment on casing load is studied. The effects of temperature, wear and casing manufacturing deviation on the casing strength are considered, and the set suitable for safe drilling in this area is found.

6. Conclusion
The drilling of HTHP exploration wells in south China Sea has experienced many years of development. In recent years, a number of HTHP exploration wells have been completed in the Yinggehai Basin with high quality and efficiency, and accumulated rich technical experience. The drilling operation management of HTHP exploration wells has been initially established. However, with the expansion of the HTHP exploration field in south China Sea, during the “13th Five-Year Plan” period, HTHP exploration drilling faces new situations and challenges. The existing level is difficult to adapt to the future ultra-high temperature and high pressure exploration and deep water high temperature and high pressure. Therefore, it is necessary to continue increasing the investment in offshore HTHP exploration wells, accelerate the research and development of HTHP exploration drilling technology, and form a new system of offshore HTHP drilling technology.

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