Research and practice on drilling and completion technology for highly deviated wells in an extremely deep and thick salt–gypsum layer in Keshen area

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Abstract. There are multiple sets of vertical salt faults in some blocks of the Keshen area of the Tarim Basin. The formation of the pressure system is complicated and vertical wells cannot meet safe drilling requirements. Using highly deviated wells to avoid faults is an effective means to ensure safe drilling. Simultaneously, it can also increase the drainage area to increase well production. There is a series of engineering problems faced in the implementation of highly deviated wells in the salt and gypsum layer, such as trajectory optimization and directional drilling, well structure design, stress checks of bending casings, and running casings in the deviated section. The engineering geology multidisciplinary integration concept is used to carry out the design of a drilling and completion plan for thick salt–gypsum and highly deviated wells. Through the successful initial drilling of Keshen 1002 in the Tarim Oilfield 600,000 m³/day of natural gas production was obtained. The drilling and completion technology has completely freed up the development of the Keshen 10 reservoir and provided reliable engineering technical support for the development of similar gas reservoirs.

Key words: Ultra-deep, Highly deviated well, Salt and gypsum formation

1. Introduction

The Keshen area of the Tarim Oilfield has a complex geological and tectonic background, forming a thrust imbricate stratigraphy. In some blocks such as Keshen 10, Keshen 6, and Keshen 11, there are multiple sets of salt discontinuities in the vertical direction, superimposing the upper and lower, high- and low-pressure systems. Among them, the Keshen 10 structure has three faults and four sets of salt–gypsum layers longitudinally and there are seven necessary sealing points from top to bottom. The existing well structure cannot meet the requirements of safe drilling. Four wells have been drilled in the Keshen 10 structure, and only one well successfully avoided the faults and successfully completed drilling. The drilling experience of many wells has shown that whether the Kela 1 and Kela 8 faults in the middle and deep parts can be successfully avoided is the key to safe drilling in this block. Combining the structural characteristics of underground faults and the conditions of surface wells, a new idea of using highly deviated wells for directional drilling from south to north is proposed to effectively avoid the faults. However, the upper well section of the target layer is a thick composite salt layer, it is impossible to avoid directional deflection in the salt and gypsum layer. To evaluate the oil and gas content of the Keshen 10 block as a whole, considering the effective avoidance of faults in the underground wells and the layout conditions of the surface well site, the locations of Keshen 1002...
well were optimized, and the first salt reservoir in the Keshen area was innovatively designed and explored. Drilling highly deviated well in gypsum layer\textsuperscript{[1-3]} are very difficult. The complex geological conditions and the special technology of a highly deviated well in a gypsum layer bring a series of four main technical problems to drilling engineering.

(1) Trajectory design and directional technology of highly deviated wells, such as stability analysis of a highly deviated well under high in-situ stress in Keshen area. The key parameters of trajectory design such as build-up point, build-up rate, well deviation angle, and azimuth are optimized. The optimization of inclining tools and instruments are difficult.

(2) Highly deviated well structure design, such as analysis of the necessary sealing points and determination of intermediate completion principle, well structure design to meet the needs of well completion and production, etc.

(3) Casing checking and anti-wear measures in the bending section, such as strength reduction under casing bending conditions, casing wear and residual strength in the bending section, and formulation of active casing anti-wear measures\textsuperscript{[4]}, etc.

(4) Running the casing in highly deviated wells, such as safe running of a highly deviated well section with high rigidity and thick wall casing\textsuperscript{[5]}.

2. Well-path design and orientation optimization

Since 2016, the Tarim Oilfield has carried out research on geomechanics-related technologies for the entire process of exploration and development to support the optimization of well trajectory, design of drilling parameters, and optimization of well completion in oil and gas field development.

Based on structural modeling, a three-dimensional in-situ stress model of the Keshen 10 block is established by combining understandings of the geological structure, drilled well logging data, research on the distribution behavior of the current stress field in the whole wellbore, natural fracture prediction, reservoir fracturing ability, and wellbore stability\textsuperscript{[1]}. According to the geo-mechanical modeling, the main stress direction of the target layer in well Keshen 1002 is 172\degree, When approaching the target layer from south, the whole well is located in an area with small horizontal stress, which is conducive to the formation of natural fractures and high production. According to the prediction of fracturing pressure, when drilling from south to north, the whole well is located in the area easily to inducing fractures (Figure 1). In addition, under the mechanism of strike-slip in-situ stress in the Keshen 10 block, the minimum drilling fluid density in the salt–gypsum formation of the deviated section is lower than that of the vertical well, and the wellbore stability is better than that of the vertical well as a whole, especially when the deviation is greater than 30\degree (Figure 2). The fractures in the Keshen 10 block have nearly east–west strike(Figure 3). Considering that the borehole can pass through the natural fractures to increase production, the drilling orientation of the Keshen 1002 well is 15\degree NE.

Figure 1. Prediction of fracturing ability of the target formation.
Figure 2. Analysis of wellbore stability of the inclined section.

Combined with the lithologic characteristics of adjacent wells, it is showed that the mudstone stratum drillability is good, and well diameter is regular. So begins to kick-off in the middle mudstone in 5370 m. The natural fractures mainly dip to the south, at 70° to 90°. To make the borehole parallel to the natural fracture surface as much as possible, increase well production, and take into account the vertical thickness requirements of geological drilling and accessing the reservoir, the well inclination angle is designed to be 60°. Concurrently, to ensure smooth running of the casing and reduce the strength degradation and wear caused by excessive casing bending, the designed build-up slope is 2.8°/30 m. The designed total well depth is 7049 m (Figure 4).

Figure 3. High dip angle fracture in core of well Keshen 10.
3. Optimization of wellbore structure based on creep mechanism of the gypsum layer

After sampling the composite gypsum layer in the Keshen block, a laboratory evaluation experiment was carried out. The main component is NaCl and it is relatively dry. The salt layer creep is mainly controlled by a dislocation slip mechanism, and the creep rate is mainly affected by horizontal stress difference, temperature, and other factors. When the well depth is less than 1000 m, the formation temperature is less than 57°C and the horizontal stress difference is less than 15 MPa. The main body of the salt layer is brittle, and the creep rate is low. The wellbore stability can be considered according to the sand and shale formation. The shallow thin salt in the Keshen 1002 well is consistent with the Lower Neogene formation. However, with the increase of depth, the formation temperature and horizontal stress difference increase, and the salt layer shows strong plastic characteristics and a fast creep rate. Therefore, high density drilling fluid should be used to restrain salt layer creep. To sort out and analyze the four necessary sealing points in the vertical direction of the whole well, it is necessary to design a well structure with five sections.

To meet the requirements of 127-mm liner completion and ensure the cementing quality of the target formation in highly deviated wells, the wellbore structure commonly used in the Keshen 10 block is optimized. In the first spud, a 558.8-mm hole was drilled to about 520 m in the shallow salt top, and a 457.8-mm surface casing was run to seal the surface loose layer. In the second spud, a 431.8-mm hole was drilled to about 2500 m in the Paleogene salt top in the footwall, and a 365.125-mm + 374.65-mm composite casing was run to seal the relatively low-pressure layer above the salt. In the third spud, a 333.375-mm well was drilled to about 4950 m in the stable mudstone formation of the middle mudstone section, and a 273.05-mm + 293.37-mm composite casing was run to sealing of the strong creep salt and the high pressure salt water section, and to create good borehole conditions for directional deviation in the fourth spud. In the fourth spud, a 241.3-mm well was drilled to about 6871 m in the top of the target formation, and a 206.375-mm salt sealed thick wall casing was run to ensure that all remaining salt-bearing formations were sealed. In the fifth spud, a 168.275-mm hole was used to reach the drilling depth, and a 127-mm liner was run to achieve the sealing of the target formation. Simultaneously, considering the safety of the salt sealing casing across the whole life cycle under the
conditions of well completion and gas production, the liner suspension point was designed to avoid the salt-bearing formation. The wellbore structure takes into account the needs of safe drilling and later development of highly deviated wells.

4. Safe design of the casing in the gypsum layer

The 206.375-mm salt sealing casing in the deviation section of well Keshen 1002 has complex bending stress conditions. Scientific casing strength design is conducive to ensure the long-term safety of the wellbore. Starting from the stress situation of the casing under bending conditions, the bending stress under different bending degrees is quantified, and then the triaxial equivalent stress of the casing under the bending conditions is calculated using the classical von-Mises theory. According to the triaxial equivalent strength coefficient under different build-up rate conditions, such as 2.8°/30 m, the triaxial safety coefficient of the casing at 5400-m depth decreased by 2.71%. In view of the extreme working conditions during drilling, and considering the possible dangerous conditions of the casing during production, a strength check of the casing in full life cycle service was carried out, and the 206.375 mm casing is found to meet the requirements of casing design.

5. Safe running evaluation in a highly deviated well section

The deviation of well Keshen 1002 is 60°. The length of the build-up section is about 900 m, so it is necessary to run 206.375-mm casing (wall thickness 22 mm, steel grade 140) in the 241.3-mm hole, resulting in a narrow annular space gap between the casing and the hole, and high creep shrinkage friction of the salt–gypsum layer, so the likelihood of safely running the casing is high. First of all, the casing running condition is finely simulated, and the casing running friction is calculated. The simulation results show that the casing can run smoothly (Figure 5). Second, to design a reasonable simulated through-hole drill string and verify the running ability of the casing, relevant mechanical analysis software independently developed by Tarim was used to calculate the bending deformation energy of the casing string and through-hole drill string, compare the stiffness ratio of the casing and different through-hole bottom hole assembly (BHA)\textsuperscript{[5]}, and optimize the through-hole simulation before running the casing with a double stabilizer BHA.

![Figure 5. Simulation of bottom hole assembly (BHA) buckling under casing running conditions.](image)

6. Implementation effect
Aiming at the complex oil and gas reservoirs in ultra-deep, multifault, and extremely thick gypsum layers in the Keshen area, a highly deviated well was innovated to avoid the faults between salt layers. A highly deviated well in the Tarim ultra-deep salt–gypsum layer was successfully drilled for the first time. Compared with the Keshen 10 vertical well, the daily production of a single natural gas well increased from 200,000 m$^3$ d$^{-1}$ to 600,000 m$^3$ d$^{-1}$, and the drilling time decreased from 392 days to 344 days. Through research and practical exploration, a breakthrough from failure to success despite the multiple faults in the Keshen area has been achieved, valuable experience in drilling and completion technology of highly deviated wells has been obtained, and the design and supporting technology of highly deviated wells in an ultra-deep and thick salt–gypsum layer have been innovated, which has laid a solid technical foundation for the promotion and application of subsequent highly deviated wells and horizontal wells in the Kuqa Piedmont of the Tarim Basin.

7. Conclusion
(1) With the help of geomechanics, considering factors such as safe drilling and stimulation, the optimization of borehole trajectory such as the kick-off point, slope length, well deviation angle, and borehole orientation is completed, which provides an important technical guarantee for the successful drilling and high production of highly deviated wells.
(2) Based on research on the creep mechanism of the salt and gypsum layer, the safty drilling mud window is carried out, the number and locations of the necessary sealing points of the whole well are reasonably determined, and a wellbore structure is designed for meeting the safe drilling conditions of highly deviated wells.
(3) The strength of the casing under service conditions in the whole life cycle was scientifically checked. Combined with the actual wellbore trajectory, casing wear prediction, and residual strength analysis, casing wear prevention measures are formulated to ensure the long-term integrity of the wellbore.
(4) From the point of view of casing mechanics, the running ability of thick wall casing in a highly deviated well section is evaluated, and the tripping BHA is scientifically designed to ensure the smooth running of the casing at one time.

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