Transient dynamics study on casing deformation resulted from lost circulation in low-pressure formation in the Yuanba Gasfield, Sichuan Basin

Shen Chen

Engineering Technology Division of Sinopec Natural Gas Project Management Department, Chengdu, Sichuan 610081, China

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Abstract

In the course of completion of an ultra-deep well newly drilled in the Yuanba Gasfield, Sichuan Basin, long-section and large-scale deformation occurred in the heavy casing section and nickel base alloy casing section of the sealing Triassic limestone interval, so a new hole had to be sidetracked, which impels us to rediscover the applicability of conventional drilling and completion technology in ultra-deep wells. In this paper, based on the borehole condition and field operation data of this well, the borehole pressure field variation initiated by lost circulation in the low-pressure formation was analyzed from the perspective of dynamics, then, the variation pattern of differential pressure inside and outside the well bore at different time intervals was depicted, and the primary cause of such complication was theoretically revealed, i.e., the pressure wave generated by instant lost circulation in low-pressure formation would result in redistribution of pressure inside the downhole confined space, and then the crush of casing in the vicinity of local low-pressure areas. Pertinent proposals for avoiding these kinds of engineering complexities were put forward: ① when downhole sealing casing operation is conducted in open hole completion, liner completion or perforated hole, the potential damage of lost circulation to casing should be considered; ② the downhole sealing point and sealing mode should be selected cautiously: the sealing point had better be selected in the section with good cementing quality or as close to the casing shoe as possible, and the sealing mode can be either cement plug or mechanical bridge plug. This paper finally points out that good cementing quality plays an important role in preventing this type of casing deformation.

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Casing deformation has very serious effect on drilling, completion and production of oil and gas wells and generally results in local or full abandonment of the wells, so attention has always been paid to the related mechanisms [1–6]. Based on currently used static or quasi-static pipe string mechanics verification methods, Wang Tao [7] and Ai Chi et al. [8,9] investigated casing damage status and rules in the Tarim Oilfield and analyzed several main reasons for casing damage, including plastic or high-permeability formations outside the casings and defective cementing quality. Zeng Yijin [10], Zhang Jincheng [11] and Song Shengli [12] evaluated the crushing stress exerted on the casings by studying the creeping rules of gypsum salt beds. Zhang Guangqing et al. [13] established creeping load and swelling stress model for mud shale formations and found out that swelling stress of mud shale formations could reach several to tens of times the far-field loads with the changing of formation swelling factors. As for the casing strength under the force of non-uniform external load induced by the creep of gypsum salt beds, Han Jianzeng et al. [14] pointed out that increasing wall thickness is more suitable for improving the casing collapsing strength under the force of non-uniform load than increasing steel grades. Deng Jingen et al. [15] described quantitatively the non-uniform external load on casings by using “equivalent breaking loads” and short-long axis ratio of elliptic loads and established casing strength design chart with non-uniform external loads, so as to detect the safety of running casing in...
rheological formations (e.g., salt beds) or conduct casing strength design with given casing external loads.

The Yuanba Gasfield in the Sichuan Basin is a typical ultra-deep “three-high” (high temperature, high pressure and high sulfur content) gas field, and its development well is characterized by TVD of 6900 m, formation temperature of 165 °C, formation pressure of over 70 MPa, average H₂S content of 5.14% and average CO₂ content of 7.5%. The development well is mainly in the configuration of five sections with liner completion in the reservoirs.

Multiple large-scale long deformations occurred in the fourth casing section below 5800 m in a newly drilled horizontal well when it was put into production in the Yuanba Gasfield, even though various adverse factors were taken into consideration and the casing strength index was designed by ensuring the values stipulated by the regulations. In this paper, analysis is performed on the change of borehole pressure fields induced by lost circulation in the low-pressure formation by considering the borehole condition and field operation data of this well. The variation patterns of differential pressure inside and outside the borehole at different time intervals are illustrated, and the primary cause of such complication is theoretically revealed. Then, some specific suggestions are provided on avoiding complication of similar engineering.

1. Brief introduction and preliminary cause analysis of casing deformation

When a well in the Yuanba Gasfield was drilled to the depth of 6580 m, the liner of 2482 m long (Ø 206.4 mm BG 110TSS × 19.05 mm + Ø 193.7 mm BG110TS × 12.7 mm + Ø 193.7 mm BG 2532-125 × 12.7 mm) was run in for well cementing so as to isolate high-pressure gas reservoir of the Upper Triassic Xujiahe Formation from high-pressure water layers of the Lower Triassic Xujing Formation. After the fifth drilling was completed, Ø 127 mm liner was run in the pay zones. Sealing cement plugs were temporarily set at the depth of 5746—6005 m to isolate the low-pressure pay zones below, so as to tie the Ø 193.7 mm casing back to the wellhead. After tieback of the casing, the whole borehole pressure test proved qualified and completion was finished in the whole well. The main lithologies of the lower formations are shown in Table 1.

Abnormal pressure occurred twice when liner cementing was conducted at the fourth casing section and when temporary sealing cement plugs were set. One time is during slurry displacement in liner cementing, the pump pressure rose abnormally and resulted in overflow, which was controlled by means of throttling circulation well-killing. Based on logging interpretation, the cementing was unqualified at the middle-upper interval of this casing section. The other time is when the standpipe pressure dropped slowly to 2.2 MPa from 3 MPa and then rose to 9.9 MPa after temporary sealed cement plugs were set for building pressure and waiting on cement. Based on interpretation, high-pressure formation fluids channeled and leaked into the borehole.

In the subsequent production operations, cement plugs were drilled to 5843 m by using three-cone bits. After the gas was blown off, the pump pressure dropped and no drilling fluids flowed back to the wellhead. After plugging operation was completed, the cement plugs were further drilled to 5946.85 m where touch sticking happened. When it was treated to the depth of 6200 m by using caliper log, milling, washing over and fishing, five deformed casing sections of 0.5—1.37 m long were totally washed over from carbon steel and nickel base alloy casing sections. The whole section below 6200 m was sealed due to casing damage, so it is decided that the treatment of the casing be abandoned and sidetracking be conducted to connect the pay zones.

It is concluded on the basis of drilling and completion operations that large-scale casing deformation took place after the setting of temporary sealing cement plugs. Moreover, it is indicated by the serious casing damage discovered at the nickel base alloy casing section (BG 2532-125) in limestone interval that high-pressure creep and high-acidity gas corrosion in gypsum salt beds are not the direct reasons for casing damage.

In this study, the reason for casing damage is preliminarily analyzed. High-pressure formation fluids break through the borehole before temporary sealing cement plugs are set. After the setting of cement plugs, the high-pressure fluids are sealed below cement plugs, so the pressure inside the casing below the cement plug rises gradually. The pressure coefficient is lower in Changxing Formation (Table 1), so lost circulation takes place and results in transient low pressure in the borehole below the temporary sealing cement plugs when borehole

<table>
<thead>
<tr>
<th>Formation</th>
<th>Well depth of top boundary/m</th>
<th>Well depth of bottom boundary/m</th>
<th>Bottom boundary TVD/m</th>
<th>Pressure coefficient</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Triassic Jialingjiang Formation</td>
<td>5362</td>
<td>6182</td>
<td>6146</td>
<td>1.50—2.03</td>
<td>Anhydrite rocks occur in Jia 2 and Jia 5 — Jia 4 Members, and limestones and dolomites are dominant in other intervals. High-pressure water layers appear in Jia 2 Member.</td>
</tr>
<tr>
<td>Lower Triassic Feixianguan Formation</td>
<td>6182</td>
<td>6624</td>
<td>6467</td>
<td>1.20—1.95</td>
<td>In Fei 4 Member, anhydrites are interbedded with gypsum dolomites, argillaceous dolomites and limy dolomites in the same thickness. Limestones are dominant in other intervals.</td>
</tr>
<tr>
<td>Upper Permian Changxing Formation</td>
<td>6624</td>
<td>7788</td>
<td>6551</td>
<td>1.01—1.12</td>
<td>As the principal pay zone, it is dominantly composed of limestones and dolomites. H₂S and CO₂ occur in natural gas.</td>
</tr>
</tbody>
</table>
pressure is higher than its loading capacity. In this way, the casing at the poorly cemented whole section collapses instantly due to the high pressure outside the casing.

Based on the practical parameters of this well’s drilling and completion, a mechanical model was built up for the drilling fluids inside the borehole below the cement plug, so as to reveal the reasons for casing damage by analyzing the pressure change of drilling fluids after lost circulation.

2. Theoretical model

A model was built with the whole interval of 5843–7788 m as the research object and its trajectory was simplified to be the broken line in drill hole inclination plan (Fig. 1).

Fig. 2 shows the change of vertical depth of each section in the model well with the measured depth. The upstream boundary I–I is the temporary sealing cement plug. It is assumed that casing damage occurs at the upstream boundary I–I, and the drilling fluid pressure at this boundary inside the borehole was taken as formation pressure and simplified as the fixed end. The bottom hole was taken as the lower boundary. If the inflow velocity of formation fluids running through local casing damage points is neglected, the drilling fluids inside the whole borehole are at quiescent state before lost circulation happens.

In view of formation pressure, the most dangerous case of casing damage induced by lost circulation is that the formation pressure is excessively high in the upper high-pressure formation and excessively low in the lower formation. Therefore, the pressure coefficient is set at high value for Jialingjiang and Feixianguan Formations, but low value for the Changxing formation and excessively low in the lower formation. Therefore, pressure is excessively high in the upper high-pressure formation and excessively low in the lower formation. Consequently, a large amount of drilling fluid is lost and the pressure drops abruptly to the formation pressure. In this way, great pressure drop is induced by the differential pressure between bottom-hole drilling fluid pressure and formation pressure which occurs before lost circulation. Decompression surge waves are instantly generated and propagated to the upstream of the borehole. Low-pressure reflective waves are formed when the decompression surge wave are propagated to the interval isolation of temporary sealing cement plugs at the upstream, and result in ultra low pressure between the interval isolation and the borehole of the pay zone. As for poorly cemented whole sections, casing will collapse when outer pressure resistance of this casing interval is conquered by the combination of high-pressure water layer outside the casing and instantaneous ultra low pressure inside the casing. The basic reasons for casing collapse are revealed by simulating the formation, propagation, reflection and superposition of surge waves by means of transient flow models.

3. Transient flow model

As shown in Fig. 1, curvilinear coordinate $s$ was established with the section I–I of the upstream boundary as the original point. If the energy loss during the propagation of pressure waves is neglected, the propagation of pressure disturbance in drilling fluids can be characterized with kinematic and continuity equations [16].

$$\frac{\partial H}{\partial s} + \frac{\partial H}{\partial t} + v = 0$$

$$g \left[ \frac{\partial H}{\partial t} + \frac{\partial H}{\partial s} \right] - v \sin \alpha = -\frac{\partial u}{\partial s}$$

where, $C$ is the wave velocity, $C = \sqrt{E/\rho}, \text{m/s}; E$ is the elastic modulus of drilling fluid, taken at 2.03 GPa; $\rho$ is the density of drilling fluid, kg/m$^3$; $H$ is the hydraulic slope, $H = \frac{\partial z}{\partial x}$, m; $p$ is the pressure of drilling fluid, Pa; $z$ is the elevation, m; $s$ is the curvilinear coordinate, m; $v$ is the flow velocity, m/s; and $\alpha$ is the included angle between borehole axial line and horizontal plane, ($^\circ$).

It is assumed that lost circulation occurs at $t = 0$. The drilling fluid in the whole borehole is at high-pressure
quiescent state at the moment of lost circulation, and its initial conditions are as follow.

\[
\begin{align*}
\frac{\partial v}{\partial t} &= 0 \\
H|_{t=0} &= z_1 + \frac{\rho_1}{\rho g}
\end{align*}
\]

(3)

where, \(p_1\) and \(z_1\) are the pressure and elevation of section I–I before lost circulation happens. The upstream temporary sealing cement plugs are simplified to be fixed ends and fluid material points are permanently quiescent, so the upstream boundary condition is \(v|_{x=0} = 0\). The downstream boundary is connected with the formation after lost circulation happens and the formation pressure at the bottom hole is assumed to be constant permanently, so the downstream boundary condition is \(H|_{x=L} = z_H + \frac{\rho_2}{\rho g}\), where \(L\) is the total length of model borehole, \(p_1\) and \(z_H\) are the pressure and elevation of bottom-hole drilling fluid respectively.

Eqs. (1) and (2) are partial differential equation sets. The minor terms of the equations are neglected, and they are converted into compatibility equations along characteristic lines \(C^+\) and \(C^-\) by means of characteristic methods.

\[
\begin{align*}
\frac{dv}{dt} + \frac{g}{C} \frac{dH}{dt} &= 0, \quad \text{along } \frac{ds}{dt} = C \\
\frac{dv}{dt} - \frac{g}{C} \frac{dH}{dt} &= 0, \quad \text{along } \frac{ds}{dt} = -C
\end{align*}
\]

(4) and (5)

Eqs. (4) and (5) are solved by using the finite difference approach. The drilling fluid in borehole is diverged as \(M\) spatial nodes with spacing as spatial step length \(\Delta x\), and the time step length is \(\Delta t = \Delta x/C\) (Fig. 4). It is assumed that \(j = 1, 2, \ldots, M\) for spatial nodes and \(n = 1, 2, \ldots\) for time nodes, and based on the hydraulic slope \(H^n_j\) and velocity \(v^n_j\) at the known time \(t = n \cdot \Delta t\), the unknown variable \(H^{n+1}_j\) and the velocity \(v^{n+1}_j\) at the unknown new time \(t = (n+1) \cdot \Delta t\) by integrating Eqs. (4) and (5) along two characteristic lines \([17]\).

\[
\begin{align*}
H^{n+1}_j &= H^n_j - \frac{C}{g} \left( v^{n+1}_j - v^n_{j-1} \right) \\
v^{n+1}_j &= \frac{g}{2C} \left( H^n_{j-1} - H^n_{j+1} \right) + \frac{v^n_j + v^n_{j+1}}{2}
\end{align*}
\]

(6)

Based on initial and boundary conditions, \(H\) and \(v\) of each grid point in time horizons \(n = 2, 3, \ldots\) were calculated in turn from the initial time horizon \(n = 1\). In this way, the variation of stress wave with time and space was obtained.

4. Propagation of pressure waves

The drilling fluid at the bottom hole is completely connected with the formations at the moment of lost circulation, so such fluid flows to the formations due to the differential pressure between high borehole pressure and low formation pressure, and then low-pressure waves are formed at the bottom holes and propagated upwards along the borehole. The pressure and velocity distributions of drilling fluid at each section plane inside the casing at different moments are presented below.
When \( t = 0.8878 \) s, decompression waves generated at the bottom hole run upwards 1000 m at the wave velocity \( C \) (Fig. 5, the solid arrow in the figure presenting the propagation direction of decompression waves). When the decompression waves reach the well depth of 6789 m, abrupt pressure drops occur at the interval swept by decompression waves (6789–7788 m), with the pressure at the section plane of 6789 m dropping abruptly to 64.17 MPa from 102.07 MPa, and downward flowing velocity is 20.404 m/s. The drilling fluids in the whole interval unswept by decompression waves (6789–7788 m) are still at high-pressure quiescent state.

When \( t = 2.6634 \) s, pressure waves have propagated cumulatively by 3000 m and are reflected into decompression waves at the upstream temporary sealing cement plugs. When the decompression waves run downwards to the depth of 6898 m, abrupt pressure drops occur again at the interval swept by decompression waves (5843–6898 m), with the pressure at the section plane of 6898 m dropping abruptly to 26.346 MPa from 64.252 MPa, and the drilling fluid is quiescent. The drilling fluid in the whole interval unswept by decompression waves (6898–7788 m) is still at high-pressure downward flowing state.

When \( t = 3.4535 \) s, the cumulative propagation of pressure waves is 3890 m and a cycle has just been completed, reaching a downstream section plane, and at this moment, the drilling fluid in the whole borehole is quiescent with the lowest pressure. Fig. 7-a shows the pressure distributions inside and outside the whole borehole when \( t = 3.4535 \) s. Fig. 7-b shows the spatial distribution of differential pressure between inside and outside the borehole at that moment. It indicates that the differential pressure is large at the hole interval (5846–6453 m) of Jialingjiang and Feixianguan Formations. As for all drilling fluid densities except 1.20 g/cm³, the outer pressure resistance of casings is lower than the differential pressure in the high-pressure formations. The higher the drilling fluid density is, the stronger the decompression surge wave is, and the higher the instantaneous differential pressure inside and outside the casings is, so the casings tend to collapse.

5. The effect of drilling fluid density on the internal pressure of casings

If only the drilling fluid density is changed and other borehole conditions are kept unchanged, the pressure state in the whole borehole will change before lost circulation happens, subsequently resulting in the variation of the differential pressure inside and outside the bottom hole, as well as the variation of pressure wave propagation velocities. In this study, the densities of drilling fluid were set at 1.20 g/cm³, 1.40 g/cm³, 1.80 g/cm³ and 2.00 g/cm³, respectively. Fig. 8-a shows the pressure state in the whole model borehole when the low-pressure waves are generated at the bottom after lost circulation reaches the bottom hole after a cycle (2 \( L \)), when the pressure in the borehole is minimum. It also shows the on-way variation of formation pressure outside the borehole. It can be seen that the internal pressure of the whole borehole is lower than the formation pressure. Fig. 8-b shows the on-way variation of differential pressure inside and outside the borehole at that moment. It indicates that the differential pressure is very large at the hole interval (5846–6453 m) of Jialingjiang and Feixianguan Formations. As for all drilling fluid densities except 1.20 g/cm³, the outer pressure resistance of casings is lower than the differential pressure in the high-pressure formations. The higher the drilling fluid density is, the stronger the decompression surge wave is, and the higher the instantaneous differential pressure inside and outside the casings is, so the casings tend to collapse.

6. Conclusions

6.1. Basic conditions

The above mentioned casing damage occurs in specific borehole, pressure and engineering conditions.

1) The casing is sealed underground and a confined space is formed.
2) Outside this confined space, there is a pressure system (formation) in which the differential pressure is large with high pressure at the upper part and low pressure at the lower part. The high-pressure formations are isolated by casings and the low-pressure formations are connected with casings.
3) For some reason, the pressure of high-pressure formations outside the casings are connected with that of the confined space inside the casings in a limited way, so the pressure of the confined space rises gradually.

![Fig. 5. Distribution of pressure and velocity in the borehole at the whole interval of 5843–6898 m when \( t = 0.8878 \) s.](image-url)
4) The bearing capacity of low-pressure formations is lower than the pressure of high-pressure formations at the upper part. When the pressure of the confined space is equal to the bearing capacity of low-pressure formations, lost circulation will occur instantaneously on a larger scale in low-pressure formations.

6.2. Cognition from the case study

In the case of lost circulation, the low-pressure waves generated at the bottom hole run upwards to the cement plugs and ultra low-pressure waves are reflected back, so abrupt pressure drop occurs at the confined space inside the casing. When the low-pressure waves reach the bottom hole after one cycle, the pressure in the whole borehole is minimum. Based on calculation, the equivalent density of drilling fluid is 1.60 g/cm³, the lowest pressure at the cement plugs is only 5.843 MPa and the pressure of the whole confined space is no more than 27 MPa when lost circulation happens.

The two intervals with damaged casings are located in the high-pressure water layers of Jialingjiang Formation and Feixianguan Formation with higher pressure coefficient. The casings to seal them are 315 m and 295 m long. The pressure
on the outside of long casings is high due to poor cementation, so a long section of casing will collapse when the differential pressure inside and outside the casing is higher than the collapsing strength of the casing.

The higher the bearing capacity of the pay zone at the bottom hole is, the stronger the decompression waves are when lost circulation happens, and the higher the casing collapsing probability is.

### 6.3. Countermeasures

1) It is necessary to take into consideration the potential damage of lost circulation on casings when downhole casing sealing operation is conducted in holes completed as open-hole, completed with liner or perforated.

2) It is necessary to select downhole sealing points and modes cautiously. Sealing points shall be set at the well cemented hole intervals or the location close to casing shoes to the best. The sealing mode can be either cement plug or mechanical bridge plug.

3) Good quality of cementation plays an important role in preventing this kind of casing damage.

### References


