Wellbore Flow Model and Process Optimization for Gas-Lift Leakage Drilling for Shallow Shale Formations

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ABSTRACT: The shallow surface karst landform in the Nanchuan-China shale gas area, with developed caves and underground rivers, frequently lost circulation during the drilling operation. To solve the issue, first, according to the actual drilling engineering, this paper analyzes the geological factors and drilling and completion characteristics, optimizes the construction plan, and suggests a new technology for gas-lift leakage drilling based on double-wall drill pipes. Second, a distributed coupling improved Beggs–Brill gas–liquid–solid multiphase flow model is established. This model is used to complete the optimization design of the gas-lift leakage penetration construction scheme of the well sy20-2. Finally, the accuracy, process feasibility, and effect of the model are verified after the field application. The test results show that this method can establish a full drilling fluid circulation without plugging the leakage, control the leakage rate to within 0.5 m³/h, more than 90% reduction in the loss of circulation, and significantly shorten the nonproduction time limit with good application prospects.

1. INTRODUCTION

Nanchuan shale gas block is in the transition zone of the southeast basin margin of Chongqing, structurally located in the east Sichuan high-steep structural belt and the northwestern margin of the Wuling fold belt in the Sichuan Basin. The frequent occurrence of lost circulation not only causes a significant increase in the construction period but also frequent downhole accidents such as stuck drills, broken drilling tools, and casings. Meanwhile, it is one of the major engineering and technical problems due to the occurrence of scrapping boreholes on one platform and huge economic loss.

Zhao et al. proposed the use of inflatable drilling technology to deal with the situation that drilling construction could not be carried out normally due to malignant lost circulation and formation of saltwater. Ma et al. studied the formation leakage analysis and parameter optimization of “upper leakage and lower injection” by establishing the intersection graphical method of ECD line and equilibrium pressure coefficient line, put forward reasonable parameter optimization suggestions, formed a set of new ideas for the formation leakage analysis and parameter optimization design of upper leakage and lower injection, and successfully solved the low pressure-bearing capacity of Yanchang Formation and Liujiagou formation of Jingnan natural gas well in Changqing.

Conventional mud drilling is prone to malignant lost circulation and even mud loss, which makes drilling construction difficult. Deng et al. used the technology of aerated continuous circulation drilling to control the deep formation lost circulation, combined conventional aerated drilling with the continuous circulation drilling technology, realized the continuous circulation of aerated fluid medium, effectively solved the problems of large pressure and liquid-level fluctuations and long reconstruction cycle time in conventional aerated drilling in the deep well section, maintained the stable ECD value of annulus, and significantly improved the safety and timeliness of the gas-filled drilling of deep adjacent well BQ1.

The application of conventional techniques such as leak plugging was poorly performed in the field. To overcome the problems, a set of new methods for gas-lift leakage drilling was put forward based on an in-depth analysis of the characteristics and major causes of leakage. The new scheme for speed-up and efficiency-increasing drilling in shallow karst cave-return formations can greatly reduce downhole complexity and shorten the drilling cycle, meeting the demand of the efficient development of shale gas in this area.

2. ANALYSIS OF DIFFICULTIES IN DRILLING SHALLOW LAYERS IN NANCHUAN WORK AREA

2.1. Lost Circulation Statistics of Drilled Platforms

The Dongsheng structural belt in the Nanchuan work area is parallel to the Pingqiao structural belt, which is sandwiched by the Longqiqiao fault and the Hepingqiao west fault and the...
Yuanjiagou fault and roughly divided into three parts (south, middle, and north) from east to west. The leakage statistics of drilled platforms are shown in Table 1.

Based on the data in Table 1, the frequency of lost circulation is very high (more than 85%), most of which are malignant losses of return type due to the special geological structure. The losses in the north-central part are more serious than those in the south, which poses great challenges to drilling construction.

2.2. Effects of Shallow Surface Complex on the Drilling Cycle. The frequent occurrence of lost circulation has caused an increase in the drilling cycle. The typical shallow surface drilling cycle statistics in this work area are shown in Figure 1.

Figure 1 shows the complexity of the lost circulation of the southern platform. The shallow drilling cycle is about 10 days, accounting for 15.48% of the entire drilling cycle. However, due to the occurrence of more malignant lost circulation, the shallow surface drilling cycle is around 50–70 days, which accounts for an average of 55.53% of the entire drilling cycle. Therefore, it seriously affects the exploration and development process of the entire work area.

2.3. Geological Factors. The complexity of the leakage in this work area is mainly caused by its special geological factors. The openings in the Dongsheng structural zone are Ziliujing Formation, Xujiahe Formation, Leikoupo Formation, Jialingjiang Formation, within the shallow surface (400–1400 m) range. There are many kinds of weak geological structures with certain pressure, whose lithological feature is that the upper part of the Leikoupo Formation is interbedded with gray limestone and gray argillaceous limestone of unequal thickness; the middle and lower parts are interbedded with gray limestone and gray argillaceous limestone of slightly equal thickness, occasionally interbedded with gray dolomite limestone. The upper part of Jialingjiang Formation is gray-white gypsum rock. The gray limestone and gray dolomite limestone are interbedded with different thickness. The middle and lower part are gray and light gray limestone. During the process of drilling, the leakage was mainly concentrated on the second section of Leikoupo-Jia and the leakage types are mainly karst-cavity leakage, fracture-cavity leakage, and fracture-type leakage.

Its geological stratification and karst model characteristics are shown in Table 2 and Figure 2.

2.4. Actual Drilling Conditions of Typical Wells. Three sample wells in the central and northern parts of the typical case are selected for the analysis based on the geological characteristics, including the main complex conditions, leakage pressure, and drilled strata. The specific analysis is shown in Table 3, in which ECD means equivalent circulating density.

2.5. Engineering Difficulties. Taking the geological factors and typical drilling data into account, it can be found that the shallow surface layers feature the following construction difficulties, as shown in Table 4.

Three major difficulties are analyzed in Table 4. The first major problem is high leakage and block risks. In the shallow limestone karst formation, caves and cracks are widely distributed and on a large scale, which leads to many leaks, large leakage losses, and high leak plugging challenges. Second, there is the limited drilling method. It is difficult to operate conventional drilling due to the low leakage and loss of pressure-bearing capacity and abundant water. The last major problem is that water leakage does not leak sand. After the loss of repatriation, the rock-carrying capacity is poor, and the construction period is long. There is a certain pressure or

| platform number | number of wells drilled | number of lost wells | geographical Location | average loss of single well (m³) | type of leakage | probability of loss (%) |
|-----------------|------------------------|---------------------|-----------------------|-------------------------------|-----------------|------------------------|
| 1               | 2                      | 2                   | central               | 67.167                        | cave-return type | 100                    |
| L3              | 1                      | 1                   | north                 | 156.314                       | cave-return type | 100                    |
| 2               | 7                      | 6                   | south                 | 5327                          | crack-return type | 85.71                  |
| 3               | 1                      | 1                   | north                 | 47.156                        | cave-return type | 100                    |
| 12              | 4                      | 4                   | south                 | 6971                          | cave-return type | 100                    |
| 14              | 2                      | 2                   | central               | 16.763                        | crack-return type | 100                    |
| 20              | 1                      | 1                   | central               | 132.353                       | cave-return type | 100                    |

Figure 1. Comparative analysis of the construction period of shallow surface drilling.

Figure 2. Characteristics of the near-surface karst model.
inclination angle in the cave, and there are too many deposits, resulting in a high risk of stuck drilling. The three difficulties are all related to the effective loss pressure difference between wellbore and formation, so the difficulty of construction can be

| System | Part      | Group         | Thickness | Lithology                          | Lithology description                                                                 | source                                |
|--------|-----------|---------------|-----------|------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------|
| Jurassic | Central   | Shaximiao Formation | 300       | Purple-red, gray-green sandstone mixed with purple-red, gray mudstone | Sandy mudstone with medium-thick limestone                                              | Regional Research Information-Nanchuan Sheet |
|        |           | Xintiangou Formation | 180       | Purple-red, gray-yellow quartz sandstone | Grey-white, yellow-gray detrital quartz sandstone                                       |                                       |
|        | Lower part | Ziluijing Formation | 160       | Green mud shale and gray breccia limestone |                                                                                       |                                       |
|        | Upper part | Xujiahe Formation | 105       | Gray dolomite, limestone, breccia limestone |                                                                                       |                                       |
|        | Central   | Leikoupo Formation | 585       | Purple-brown, gray shale; gray thick massive limestone |                                                                                       |                                       |
|        | Lower     | Jalingjiang Formation | 518       | The upper gray micrite limestone intercalated with light purple-red limestone mudstone, the middle gray-dark gray limestone and micrite limestone interbedded, and the lower gray-black argillaceous limestone |                                                                                       |                                       |
|        |           | Feixianguan Formation | 584       | Thick lumpy limestone, occasionally sandwiched shale |                                                                                       |                                       |
|        | Upper part | Changing Formation | 120       | Layered limestone intercalated with shale and siltstone |                                                                                       | Shengye l Well                        |
|        |           | Longtan Formation | 99        | The middle and upper part is dark gray-light gray thick layer, green flaky argillaceous limestone |                                                                                       |                                       |
|        | Lower part | Maokou Formation | 261       | Massive limestone interbedded with flaky limestone |                                                                                       |                                       |
|        |           | Qixia Formation | 92        | Gray-green, gray-yellow shale, silty shale intercalated with siltstone |                                                                                       |                                       |
|        | Central   | Hanjiadian Formation | 665       | Medium-thick layered siltstone |                                                                                       |                                       |
|        | Lower part | Xiaoheba Formation | 489       | The upper part is gray shale and silty shale, the lower part is gray-black shale |                                                                                       |                                       |
|        |           | Longmaxi Formation | 348       |                                                                                       |                                       |
Table 3. Analysis on Actual Drilling of Three Typical Wells

| Hashtag | Drill time | Geographical level | Superficial cycle | Location | Complex situation | Lost ECD $\left(\frac{\text{m}^3}{\text{m}}\right)$ |
|---------|------------|--------------------|------------------|----------|-------------------|-----------------------------------------------|
| SY1     | 2016       | Leikoupo (bottom depth of 224 m), Jialingjiang Formation | 65 d             | central  | loss, return and loss, water leakage and no water leakage, hard drilling is difficult | ≤0.9 |
| SY20-2  | 2019       | Leikoupo (bottom depth of 216 m), Jialingjiang Formation | 85 d             | central  | lost return, water leakage, no water leakage, sand, clean water rush to drill to 603 m, the bottom of the well is about 41 m sand, repeated cleaning of the sand surface is not reduced, no strong drilling is possible | ≤0.6 |
| SYL3-1  | 2019       | Leikoupo (bottom depth of 418 m), Jialingjiang Formation | 185 d            | north    | lost return, leakage, water leakage and no leakage of sand, unable to forcibly drill, and eventually abandon the well; loss overview: drilling to 490 m and returning 558–589 m venting, 589–592.74 m broken zone, 600–666.4 m venting; the maximum vent section is 31 m | ≤0.75 |
circulating condition increases the circulating pressure loss $\Delta p$ compared with the static condition. By contrast, the calculation of the circulating pressure loss $\Delta p$ is more complicated because the drilling fluid is a non-Newtonian fluid. Fan$^{29-32}$ and others established models for the accurate calculation of rheological parameters under different rheological modes and proposed an innovative four-parameter rheological model. Based on the characteristics of gas-lift through-through drilling, the following rheological model was used as the drilling fluid. The calculation of cyclic pressure loss provides a theoretical basis.

$$\tau = K\gamma^n$$  \hspace{1cm} (1)

where $\tau$ is the shear stress at a radial distance of $r$ to the axis of the annular runner, Pa, $\gamma$ is the fluid shear rate, $s^{-1}$, $K$ is the consistency coefficient in the power-law mode and the Herbarium mode, Pa·sn, and $n$ is the index of flow characteristics in the power-law mode and the Hertz–Barr mode.

The first rheological model is the power-law model, and the rheological equation is
The second rheological model is the BA model, and the rheological equation is
\[ \tau = \tau_0 + K\gamma^n \]  
(3)

where \( \tau_0 \) is the fluid yield value, Pa.

Also, the pressure loss formula is
\[ \Delta p = \frac{4KL}{D} \left( \frac{2n + 1}{4n} \right) \left( \frac{4\nu}{D} \right)^n \]  
(2)

where \( \Delta p \) is the cycle pressure loss, Pa, \( L \) is the annulus length, and \( \nu \) is the average velocity in the annulus, m/s, and \( D \) is the diameter difference between the inner and outer pipes of the annulus, m.

The third rheological model is the Luo Si model, and the rheological equation is
\[ \tau = A(\gamma + C)^B \]  
(5)

where \( A \) is the consistency coefficient in the Roth–Sis mode, Pa–s\( B \), \( B \) is the flow characteristic index, and \( C \) is the shear rate correction value in the Roth–Sis mode, s\(^{-1}\).

Also, the pressure loss formula is
\[ \Delta p = \frac{4KL}{D} \left( \frac{1 + 2n + 12\nu}{3n} \right)^n + \frac{4L\tau_0}{D} \left( \frac{2n + 1}{n + 1} \right) \]  
(4)

Also, the pressure loss formula is
\[ \Delta p = \frac{2\tau_wL}{R} \]  
(8)

where \( \tau_w \) is the shear stress at the pipe wall, Pa.

### 3.3.2 Gas–Solid–Liquid Multiphase Flow Model

Taking the results of the nonbovine solid–liquid two-phase flow as the initial conditions, Yan and Teng, Zeng, and others used a gas–solid–liquid multiphase flow model using an improved Beggs–Brill model considering the effects of cuttings and gas–liquid slippage. The flow pattern of the drilling fluid was divided into separate flow, transition flow, intermittent flow, and dispersed flow. The calculation method for liquid holdup corresponding to each flow pattern was given, and the influence of acceleration pressure drop on the total pressure drop was also considered.

First, the bottom-hole pressure calculation method of annulus cuttings was considered. When aerated drilling went deep into the bottom hole, the gas–liquid two-phase mixed drilling fluid continued to be mixed with drilling cuttings, and the continuous accumulation of drilling cuttings led to the continuous increase of the bottom-hole pressure. At this time, the annular pressure drop gradient caused by rock cuttings is

**Table 6. Comparison of the Advantages of the Two Processes**

| Project                          | Gas-Lift Through-Hole Drilling | Pneumatic Drilling |
|---------------------------------|-------------------------------|-------------------|
| Injection Method Efficiency     | High efficiency, easy to control the pressure reduction ability | Gas–liquid mixed injection |
| and Ability                     | by adjusting various parameters (drilling fluid density, displacement, double-wall drilling depth, gas injection volume, etc.) various control effects such as microgushing, balance, and microleakage can be obtained | Although theoretically higher, the actual effect is not high, especially the pressure reduction ability is not easy to control, and the means are single, which can generally only be achieved through air volume adjustment, especially for formation water volume, which is difficult to control |
| Economy                         | Low pressure, less equipment, good economy | High pressure, more equipment |
| MWD Effect                      | Does not affect the use of MWD, the effect is stable | Seriously affect the use of MWD |
| Recovery Cycle                  | Short time (5–10 min)         | Long time (more than 40 min) |
| Plugging While Drilling         | Can be implemented simultaneously to enhance the effect of leakage and leakage prevention | Do not plug leakage while drilling |

**Figure 4.** Flow channel model of gas-lift drilling.
\[ \frac{dp}{dz} = \rho_m g \frac{\xi}{g_s} + \frac{2f_s \rho_m v_s^2}{g_s (D_b - d)} \]  

(9)

where \( \rho_m \) is the mixing density of the gas–liquid flow in the wellbore, \( \frac{kg}{m^3} \), \( g_r \) is the acceleration of cuttings in the drilling fluid, \( \frac{m}{s^2} \), \( g \) is the acceleration of gravity, \( \frac{m}{s^2} \), \( f_s \) is the friction coefficient of rock cuttings rising in drilling fluid, \( \frac{m}{s} \), \( v_s \) is the rising speed of rock cuttings in drilling fluid, \( \frac{m}{s} \), \( D_b \) is the outside diameter of the drill string, \( m \), and \( d \) is the wellbore diameter (consider the expansion rate), \( m \).

After ignoring the acceleration pressure drop during drilling, the newly drilled rock cuttings enter the well and mix with the drilling fluid. After being accelerated to a stable speed, they return together with the mud and drilling fluid, resulting in an increase in the effective liquid column pressure at the bottom of the well. The influence of cuttings on the bottom-hole pressure increases with the increase of ROP. After derivation, the density of rock cuttings mixed with mud and gas after entering the well is

\[ \rho_l = \rho_m \xi + (\rho_l - \rho_m) \delta - (\rho_l - \rho_g) \lambda \]  

(10)

where \( \rho_l \) is the total density of annulus drilling fluid, \( \frac{kg}{m^3} \), \( \rho_g \) is the annular gas density, \( \frac{kg}{m^3} \), \( \xi \) is the volume factor of drilling fluid, \( \frac{m}{v} \), \( \delta \) is the volume coefficient of rock cuttings, and \( \lambda \) is the gas volume factor.

At this time, the annular bottom-hole pressure increment caused by rock cuttings is

\[ \Delta p_f = H \Delta \rho_l \left( g + \frac{2f_s v_s^2}{D_b - d} \right) \]  

(11)

where \( \rho_g \) is the cuttings density, \( \frac{kg}{m^3} \), and \( H \) is the well depth, \( m \).

Finally, the total pressure gradient is obtained by an iterative method

\[ \frac{dp}{dz} = \rho_l g \sin \theta + \lambda \frac{v_s^2}{2 \mu} \rho_l \]  

(12)

where \( v_s \) is the velocity of the gas–liquid–solid mixed phase, \( \frac{m}{s} \), and \( \theta \) is the well deviation angle.

### 4. OPTIMIZATION AND APPLICATION OF GAS-LIFT LEAKAGE IN SHALLOW SHALE GAS FORMATION

#### 4.1. Condition of the Test Well

A pilot test of gas-lift penetrating drilling was carried out on the shallow karst cave reversion formation on well SY20-2. The basic situation is shown in Table 7.

Table 7 describes the basics of the SY20-2 well used in the test, where the well depth is 5187 m, the borehole size is 406.9 mm, the well structure is surface layer 473 mm, casing depth 188.5 m, the early well depth is 602 m, the lithology of the mine-head slope (216 m) is argillaceous limestone intercalated with argillaceous dolomite, Jialing River (1216 m) limestone and dolomite, complex situation loss of loss of multilayer karst cave + falling of broken zone, sedimentation 41 m, strong drilling with clean water, leak plugging, etc., all invalid, no footage in more than 1 month, sedimentation of 41 m, clear-water drilling, plugging leaks, etc., that make it ineffective and there is no footage for more than 1 month.

#### 4.2. Optimal Design of Construction Parameters

The flow model of gas-lift penetrating drilling is established with some key parameters optimized in combination with the construction plan.

#### 4.3. Optimized Design of Gas-Lift Depressurization Capability

As shown in Figure 5, the impact of the drill pipe depth and the injected gas volume on the bottom-hole ECD under different schemes is linear, and the injected gas volume has a greater impact on the bottom-hole ECD relative to the drill pipe depth. As the injected gas volume increases from 20 to 60 m³/min, the bottom-hole ECD decreases linearly from 0.85 to 0.55 g/cm³. When the depth of the drill pipe is increased from 300 to 550 m, the bottom-hole ECD change also reaches 0.2 g/cm³.

SY20-2 well features a low leakage pressure and a large borehole size, which aim to meet the gas-lift pressure reduction requirements of the well. When the drilling fluid displacement is 50 L/s, the drill pipe depth can be 400 m, the gas injection rate is 60 m³/min, the drill pipe depth length is 450 m, the gas injection rate is 60 m³/min, the drill pipe depth length is 500 m, the gas injection rate is 60 m³/min, the drill pipe depth is 550 m, and the gas injection rate is 40 m³/min. These four options are used for drilling work.

**Table 7. Basic Information of Test Well**

| SY20-2 well |                     |
|-------------|---------------------|
| design well depth | 5187 m (vertical 3960 m/horizontal 1400 m) |
| bore size      | 406.9 mm            |
| well structure | surface layer 473 mm, casing depth 188.5 m |
| early well depth| 602 m               |
| formation      | Leikoupo (216 m) argillaceous limestone intercalated with argillaceous dolomite, Jialing River (1216 m) limestone and dolomite |
| lithology      |                     |
| complex situation | loss of loss of multilayer karst cave + falling of broken zone, sedimentation 41 m, strong drilling with clean water, leak plugging, etc., all invalid, no footage in more than 1 month |
| well-head liquid level drops | 204–228 m |
| missing ECD    | 0.62–0.66 g/cm³     |

**Figure 5.** Design of key parameters for depressurization of gas lift.
4.4. Design of Drilling Pump Displacement. Pump displacement is one of the main fluid mechanics indexes when drilling fluid circulates. It not only meets the requirement of carrying drill cuttings but also can control and adjust bottom-hole pressure with its circulating pressure loss. Conventional drilling has a wide formation pressure window, so the cyclic pressure loss can be ignored under normal circumstances. When it comes to normal low pressure and leaky formations, the impact of displacement should be considered.

As shown in Figure 6, under the same drill pipe depth, increasing the displacement of the drilling pump from 25 to 60 L/s causes a slight increase in the bottom-hole ECD, ranging from 0.08 to 0.2 g/cm³. As the gas injection rate increases, the impact of drilling pump displacement changes on the bottom-hole ECD is greater. When the gas injection rate is 30 m³/min, the bottom-hole ECD increase is less than 0.1 g/cm³. Therefore, it is possible to further optimize the depressurization effect of the well by changing the displacement of the drilling pump and other combined drilling parameters such as the amount of gas injected and the depth of the drill pipe.

4.5. Comparative Analysis of Standing Pressure. As shown in Figure 7, the impact of pneumatic drilling and gas-lift penetration on riser pressure is very different. Because gas-lift penetration drilling uses a gas–liquid split injection, the riser pressure does not appear immediately. In aerated drilling, the riser pressure first increases and then decreases with the passage of time, which reduces the gas–liquid mixed-phase fluid pressure loss. Compared with aerated drilling, gas-lift penetration has a lower bottom-hole pressure and controlling the depressurization effect of the well is easier so that circulation can be established in low-pressure formations with reversion.

Therefore, gas-lift penetration drilling has more advantages, and this method can be used for drilling work.

5. RESULTS AND DISCUSSION

Based on the above analysis, the simulation results are combined with the construction plan, gas-lift penetration technology is adopted, the drilling pump displacement is controlled to 50–60 L/s, the double-wall drill pipe depth is 400–550 m, and the gas injection rate is 30–40 m³/min; the field test of SY20-2 well achieved very good construction results.

The construction effect is shown in Figure 8. The specific construction site results are shown as follows. Under the premise of no plugging, a full drilling fluid circulation is established, 41 m of sedimentation at the bottom of the well can be cleaned within 3 h, new footage of 12.5 m can be achieved, and the leakage rate can be controlled. Within 0.5 m³/h, the complicated aging caused by lost circulation can be reduced by more than 90% year-on-year; meanwhile, it can meet the needs of geological mud logging. Test results show that the optimized construction plan can effectively solve the drilling problem of shallow karst caves in well SY20-2, which greatly shortens the construction period and achieves speed and efficiency improvement.

Figure 6. Displacement design of the drilling pump.

Figure 7. Comparison of vertical pressure between aerated drilling and gas-lift drilling.
At the same time, well SY20-2 was tested using the pneumatic drilling technology and compared with the gas-lift penetration test. Test results show that due to the gas–liquid mixed injection method of aerated drilling, the gas leaks into the formation with the drilling fluid after passing through the drill bit, failing to establish circulation and failing to meet the construction requirements.

6. CONCLUSIONS

(1) In this paper, a Beggs–Brill gas–liquid–solid multiphase flow model for the gas-lift seepage drilling process is established, and the whole model is divided into a non-Newtonian solid–liquid two-phase flow model and a gas–solid–liquid multiphase flow model. Compared with other rheological models, this model has improved correlation coefficients and is more accurate, allowing one to use it to describe the rheological properties of drilling fluids at different shear rates.

(2) The gas-lift penetration drilling technology realizes high efficiency and precise control of wellbore ECD pressure reduction under the condition of gas–liquid split injection. The maximum ECD reduction capacity is 0.5 g/cm³. Under the condition of no plugging leaks, it can solve the loss of shallow karst caves. The problems of drilling fluid circulation and rock carrying have been reduced by more than 90% year-on-year in the complex aging caused by lost circulation, which proves to have good market potential and application prospects. Meanwhile, an optimized construction plan for shallow drilling in the Sichuan shale gas field is proposed, i.e., gas-lift penetration technology is used for drilling, the drilling pump displacement is controlled to 50–60 L/S, the double-wall drill pipe is deep 400–550 m, and the gas injection rate is 30–40 m³/min.

(3) The accuracy of the calculation model, technical feasibility, and application effect are verified through field application. The parameters are designed reasonably during the construction process, and a set of key technologies for gas-lift penetration and leakage in shallow karst caves of shale gas wells is initially formed. This method can reduce nonproduction timeliness and meet the requirements for low-cost and high-efficiency development of deep and shale oil and gas reservoirs.

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Figure 8. Test results display (a) drilling fluid discharge, (b) drilling cutting settlement, (c) drilling cutting drying, (d) drilling cutting collection, and (e) drilling cutting samples.
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