Development and Application of Downhole Chokes with Pressure and Temperature Monitoring Function

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Abstract. For wells employing downhole choking technology, the traditional well testing methods no longer accommodate the requirements for dynamic monitoring of production performance due to the existence of downhole chokes. On one hand, the wellhead pressure data of gas wells with downhole chokes can neither truly reflect the actual situation of gas wells nor directly provide effective data for the dynamic gas well performance analysis. On the other hand, because of the calculation error with the nozzle flow pressure drop in the calculation method, the calculation error of wellbore pressure is significant, resulting in failure of the annulus liquid level method to carry out monitoring as most wells are installed with packers. In this regard, the downhole choke with pressure and temperature monitoring function has been independently developed by combining the production features of the wells with downhole choking technology. Under the condition of no change of tubing string, no use of cable running and no impact on gas well production, the steel wire operation was implemented, achieving the downhole choking production of gas wells and the monitoring of pressure and temperature prior to the choking operation, thus to establish a wellbore pipe flow prediction model and a nozzle flow model. Through the field application and evaluation, the error between the calculation results of the flow model and the field measured data is controlled within 5%, which provides a theoretical calculation basis for the accurate pressure prediction of wells using choking technology as well as technical support for the dynamic analysis of downhole choking gas wells.

Keywords: Downhole choking; pressure monitoring; temperature monitoring; shock absorption; tool development; nozzle flow model; field application; error analysis

1. Introduction

For wells employing downhole choking technology, the traditional well testing methods no longer accommodate the requirements for dynamic monitoring of production performance due to the existence of downhole chokes. There are limitations with the traditional methods. As for the calculation method, because of the large calculation error of nozzle flow pressure drop, the calculation error of wellbore pressure is significant, resulting in failure of this method to meet the requirement for dynamic data analysis. The application of the electronic detacher requires repeated operations; while the application of the annulus liquid level method, which requires no installation of packers, is completely limited because most wells employing downhole choking technology have packers. In addition, the application of permanent downhole pressure and temperature monitoring technology requires running cable with high installation cost. According to the characteristics of high gas-liquid ratio of downhole choking gas wells, and in combination of downhole choking pressure and
temperature monitoring technology [1,2], the homegrown integrated tool is intended to be used to continuously monitor the pressure and temperature prior to the choking operation. Starting from the basic mathematical model, by establishing pipe flow prediction model and nozzle flow model with higher prediction accuracy, and by verifying the accuracy of the model through experimental data and field application, this study provides a theoretical calculation basis for accurate pressure prediction for wells employing choking technology and technical support for the dynamic analysis of downhole choking gas wells.

2. Tool Development

2.1. Technical Solution
The technical solution mainly weights in the availability that the tool can place the tool seat in the working barrel at the target depth by steel wire operation without moving the pipe string and using cables, thus to realize choking production, real-time collection of downhole pressure data [3] (it is capable of working continuously for more than 1 year), data back-reading, analysis and evaluation through well testing steel wire operation. The tool design consists of two parts, as shown in figure 1, namely the choke itself and the temperature and pressure measuring assembly. The whole temperature and pressure measuring assembly is connected with the lower end of the choke through screw threads. The choke enables the choking production, while the temperature and pressure measuring assembly can achieve real-time acquisition of downhole pressure data.

![Figure 1. Schematic Diagram of Downhole Choke with Pressure and Temperature Monitoring Function](image1)

2.2. Shock Absorption Mode
At present, there are mainly two types of methods for the protection of electronic pressure gauge, namely the integral type and split type. Combining the actual conditions for field application, and considering the fact that the tool is subject to substantial impact force in the process of construction and production, it is recommended to adopt the split-type protection solution, that is, the solution of conventional pressure gauge+shock absorption barrel, to protect the pressure gauge. The solution is designed with a shock absorption barrel externally, where the longitudinal and transverse shock absorption mechanisms are employed between the pressure gauge and the shock absorption barrel. The shock absorption springs are set up at the top and bottom of the pressure gauge, and the shrapnel shock pad is used for transverse shock absorption to address the difficulties with the disassembly and assembly of the pressure gauge. The dimensions of the pressure taking channel is large enough to prevent the potential blockage by dirt, and the tool can be reused. The schematic diagram of the shock absorption solution is shown in figure 2 [4,5].

![Figure 2. Schematic Diagram of Overall Shock Absorption Solution of the Tool.](image2)

2.3. Shock Absorption Structure Design
The steel wire operation mode is adopted for the field implementation of the tool, which is subject to substantial impact force during fishing, therefore the shock absorption structure design is extremely crucial. In the design, for the spring, the wire diameter is 12mm, the pitch diameter is 18mm, the total number of coils is 6, the number of effective coils is 4, and the pitch is 16mm. After calculation,
the maximum compressible load of the spring is as follows:

\[ k = \frac{Gd^4}{8D_m^3N_c} \]  
\[ F_n = k(t - d) \]

The spring compression can be calculated from Equation (3):

\[ \Delta x = \sqrt{\frac{8m_v^2D_m^2N_c}{Gd^4}} \]  

According to Hooke's law, the elasticity received by the spring is:

\[ F = k\Delta x \]

Based on the steel wire operation, assuming that the jar collides with the tool at the maximum speed of 1.5m/s, and the rigid body collision conforms to the principle of completing elastic collision, it can be calculated that the maximum force \( F \) of the spring is 139N and the maximum compressible load \( F_n \) of the spring is 159N. Therefore, the spring design is appropriate with adequate shock absorption effect.

In the formula, \( m_3 \) is mass of pressure gauge, kg; \( v_3 \) is post-shock velocity of pressure gauge, m/s; \( k \) is spring elasticity coefficient, N/m; \( G \) is shear modulus, Pa, 79×10^9 for steel; \( d \) is spring wire diameter, m; \( D_m \) is pitch diameter of spring, m; \( N_c \) is the number of effective coils of spring; \( F_n \) is maximum compressible load, N; \( t \) is pitch, m.

2.4. Tool Stress Analysis

2.4.1. Finite Element Analysis of Segment and Working Barrel. The main stress parts of the tool are the segment and working barrel, so the stress analysis, restraint and loading tests mainly focus on the segment and working barrel is shown in figure 3:

![Figure 3. Working Barrel Constraints and Stress Diagram.](image)

The red arrow is the load while the green arrow is the constraint face. Assuming that the bottom hole pressure is 70MPa, the pressure indicated by the red arrow \( P=737 \) MPa can be obtained from the formula, with grid breakdown as follows is shown in figure 4:

![Figure 4. Grid Breakdown Diagram of Working Barrel.](image)
Element size: 7.98833 mm, tolerance: 0.319533 mm, total number of nodes: 43122, total number of elements: 24513, finite element calculation result is shown in figure 5 and figure 6:

![Finite Element Calculation Diagram of Working Barrel](image1)

![Stress Concentration Diagram of Working Barrel](image2)

**Figure 5.** Finite Element Calculation Diagram of Working Barrel.  
**Figure 6.** Stress Concentration Diagram of Working Barrel.

From the above figure: \( \delta_{\text{max}} = 8.859 \times 10^8 \text{Pa} < \delta_b = 1.19 \times 10^9 \text{PA} \), so it is safe.

### 2.4.2. Internal Pressure Strength of Working Barrel

According to the design where the allowable stress of the working barrel material \([\sigma_b] = 1310 \text{MPa}\), and internal pressure strength \(P_{\text{internal}} = 100 \text{MPa}\), calculate the internal pressure strength of the weakest part of the working barrel, i.e., the segment sealing section.

\[
\sigma_b = \frac{P_{\text{internal}} \times D_{\text{internal diameter}}}{2t_{\text{wall thickness}}} \times n_{\text{safety factor}} = \frac{100 \times 71}{2 \times 12} \times 2 = 591.6 \text{MPa} \leq [\sigma_b] = 1310 \text{MPa}
\]

### 2.4.3. Tensile Strength Analysis of Working Barrel

According to the design where 3YC51 is selected for the working barrel materials and the allowable stress \(\sigma_b = 1310 \text{MPa}\), calculate the tensile strength of the weakest part of the working barrel. Considering the safety factor \(n=2\), the tensile strength of the working barrel is \(P_{\text{tensile}} = 143.5 \text{t}\).

\[
P_{\text{tensile}} = \sigma_b \times S = 1310 \times 3.14 \times \left(39.3^2 - 29.1^2\right) = 2869836 \text{N} \approx 287 \text{t}
\]

### 2.5. Tool Intermediate Test

To ensure the reliability and stability of the tool application, the intermediate test was carried out. Two times of tool fishing tests were successfully completed on the simulated well. The setting out and fishing were successful at one time. The setting out working barrel depth was 245m, the lifting force was 100kg, the jam was released smoothly, the fishing was successful, the pressure gauge downhole worked stably in the simulated well, and no data was missing, as shown in figure 7 and figure 8. The intermediate test of the simulated well showed that the homegrown tool has reliable and stable pressure gauge performance, which lays a foundation for the subsequent field application.

![Experimental Data of Simulation Well with Quartz Pressure Gauge](image3)

![Experimental Data of Simulation Well with Sapphire Pressure Gauge](image4)

**Figure 7.** Experimental Data of Simulation Well with Quartz Pressure Gauge.  
**Figure 8.** Experimental Data of Simulation Well with Sapphire Pressure Gauge.

During the fishing process, as the pressure gauge of the tool is subject to substantial impact force, it was tested to confirm whether the shock absorption effect of the structure is sufficient and whether
there is deviation in the accuracy of the pressure gauge. After the intermediate test, the pressure gauge was verified, as shown in figure 9. High temperature and high pressure verification experiments were carried out for two sets of pressure gauges indoor. The pressure was pressurized and depressurized for three times. The pressure range is 0 ~ 70MPa, the test temperature is 150℃, and the maximum indication error of quartz pressure gauge is 0.01997mpa (the allowable error is 0.035MPa); The maximum indication error of sapphire pressure gauge is 0.02878mpa (allowable error is 0.035MPa), therefore, the performance index is stable, as shown in figure 10.

3. Field Application
The field test was carried out for 4 wells, and the results showed that both the tool performance and the production of the test well was stable, the launching and fishing were successful at one time, the maximum depth of the working barrel was 2398.45m, the maximum tension during fishing was 3170N, and the monitoring data were complete. The longest field test cycle of downhole choke with pressure and temperature monitoring was 365 days. The field test achieved good results. The downhole choke tool with pressure and temperature monitoring was stable and reliable, achieving the objectives of choking production, and real-time collection of downhole pressure data, as shown in figure 11. The study met the technology requirements of downhole choking pressure and temperature monitoring in Sichuan and Chongqing gas fields. The successful field test of the tool provides reliable field data for model correction and evaluation, and the basis for downhole choking production performance analysis and production system adjustment, as shown in table 1 and table 2.

| Well No.       | Implementation time | Starting time | Nozzle diameter, mm | Gas production, 10^4 m³/d | Water produced, m³/d |
|---------------|---------------------|---------------|---------------------|---------------------------|----------------------|
| B004-X2 Well  | 2015.7.2            | 2015.9.25     | 2.4                 | 3                         | 1                    |
| B004-X2 Well  | 2015.9.25           | 2016.4.6      | 3.0                 | 4.2                       | 3                    |
| J002-X2 Well  | 2016.7.29           | 2016.11.9     | 4.6                 | 5.3                       | 0                    |
| LH005-X1 Well | 2016.4.1            | 2017.3.30     | 4.4                 | 7.5                       | 0.5                  |

| Well No.       | Working barrel depth, m | Sampling interval, min | Maximum tension, N | Test overview                                      |
|---------------|-------------------------|------------------------|--------------------|---------------------------------------------------|
| B004-X2 Well  | 2398.45                 | 15                     | 3080               | The tool was placed in the well for 85 days, the tool performance was reliable, and no monitoring data missed. |
The tool was placed in the well for 190 days, the tool performance was reliable, and no monitoring data missed.

The tool was placed in the well for 103 days, the tool performance was reliable, and no monitoring data missed.

The tool was placed in the well for 365 days, the tool performance was reliable, and no monitoring data missed.

Figure 11. Measured Data of Field Test Pressure Gauge for LH005-X1 Well.

4. Model Modification

4.1. Model Fitting

According to the characteristics of high gas-liquid ratio of downhole choking gas wells, and with reference to the calculation formula of single-phase flow choking pressure drop, the correlation coefficient was corrected, the quasi single-phase flow calculation method was used to predict the choking pressure drop, and the quasi single-phase flow correction coefficient was obtained through experimental data processing to ensure the calculation accuracy.

Based on the isentropic principle of gas nozzle flow, the relationship between flow and pressure ratio is as follows, for subcritical flow state [6]:

\[
q_{sc} = \frac{0.408 \rho_d d^2}{\sqrt{\gamma_g T Z_1}} \left( \frac{k}{k-1} \left[ \left( \frac{p_2}{p_1} \right)^{\frac{k+1}{k}} - \frac{p_2}{p_1} \right] \right)
\]  

(5)

where \(q_{sc}\) is volumetric flow through nozzle (under standard condition), \(10^4 \text{m}^3/\text{d}\); \(p\) is pressure, MPa; \(d\) is nozzle diameter, mm; \(T\) is temperature, K; \(K\); \(k\) is the gas adiabatic index; Suffixes 1 and 2 indicate the position before and after the nozzle, respectively; \(p_2/p_1\) is pressure ratio.

For critical flow, the maximum gas production of nozzle flow is:

\[
q_{\text{max}} = \frac{0.408 \rho_d d^2}{\sqrt{\gamma_g T Z_1}} \left( \frac{k}{k-1} \left[ \left( \frac{2}{k+1} \right)^{\frac{k+1}{k}} - \frac{2}{k+1} \right] \right)
\]  

(6)

Considering that the thickness of the downhole choking nozzle is much larger than the nozzle diameter and the potential impact, the modified nozzle flow coefficient \(C_d\) is introduced. For quasi single-phase flow, the above formula is changed to:

\[
q_{\text{max}} = \frac{C_d \rho_d d^2}{\sqrt{\gamma_g T Z_1}} \left[ \frac{k}{k-1} \left( \frac{2}{k+1} \right)^{\frac{k+1}{k}} - \frac{2}{k+1} \right]
\]  

(7)
where $\gamma_m$ is relative density of mixture and $C_d$ is corrected nozzle flow coefficient.

Introduce variable $X$:

$$X = \frac{p_d d^2}{\sqrt{\gamma_m T_i Z_i}} \left[ \frac{k}{k-1} \left( \frac{2}{k+1} \right)^{\frac{2}{k-1}} - \left( \frac{2}{k+1} \right)^{\frac{k+2}{k+1}} \right]$$  \hspace{1cm} (8)

a simplified relationship can be obtained:

$$q_{max} = C_d X$$  \hspace{1cm} (9)

365 groups of field measured data sources were used to fit and correct the flow coefficient $C_d$ in the quasi single-phase nozzle flow calculation model, which further improves the accuracy of the model. The results are shown in figure 12 and figure 13.

![Figure 12. Fitting Curve of Nozzle Flow Coefficient.](image)

![Figure 13. Comparison Curve between Model Predicted Value and Measured Value.](image)

4.2. Model Prediction
Using this technology, 79 groups of data were predicted on the site. The comparison curve between the predicted value and the measured value is shown in figure 14. From the comparison curve, the predicted value by the modified model is very consistent with the measured value, and the average error of the predicted value of the model is increased from 8.41% of the principle to 1.7%, greatly improving the prediction accuracy of the model.
5. Conclusion

(1) The downhole chokes with pressure and temperature monitoring function were applied for 4 wells, the results indicated that the choking production was normal, and the downhole monitoring data were easily accessible, breaking through the bottleneck of pressure monitoring of this type of gas wells.

(2) The homegrown downhole choke with pressure and temperature monitoring function can solve the problem that the downhole monitoring data cannot be directly obtained by the traditional well test methods for downhole choking wells, achieve the real-time and long-term monitoring of downhole data of downhole choking well, and establish a new set of downhole choking well pressure monitoring technology.

(3) The nozzle flow coefficient is corrected through the experimental data. The predicted value of the corrected model is in good agreement with the field measured value. The average error of the fitting model is 1.7%, which greatly improves the prediction accuracy of the model.

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