Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería

Adaptive analysis of multistage down-hole throttling and optimization design of process parameters in Sulige gas field

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Abstract

The Sulige Gas Field mainly adopts down-hole throttling production technology. For gas Wells with high bottom-hole pressure and productivity and low pressure drop in the testing process, it is difficult to reduce the wellhead pressure to the ideal value by installing a single-stage down-hole throttle, which cannot meet the needs of existing middle and low-pressure gas gathering technology in Sulige Gas field. Therefore, it is proposed to adopt down-hole multi-stage throttling technology, which not only makes full use of the residual pressure and heat of the well bore, but also ensures the safety of the surface gathering and transportation process system and the normal production of gas wells. In this paper, the optimization design method and theory for the technological parameters of the down-hole multi-stage throttling system of gas wells are established. According to the constraint of low-pressure gas collection mode in a temperature and pressure of wellhead safety to determine the number of down-hole choke and the process parameters. Discuss the applied conditions of down-hole multi-stage throttling, and provide theoretical support for the selection of the down-hole choke technology of the Sulige gas well and the safe and stable production of the gas well. It has important guiding significance for gas field quality and efficiency improvement and fine management.

OPEN ACCESS

Published: 09/06/2022

Accepted: 07/06/2022

DOI:
10.23967/j.rimni.2022.06.001

1. Introduction

Sulige gas field mainly adopts the gas production technology of "Down-hole throttling, wellhead emergency cut-off, liquid metering, wellhead data remote transmission, no heating, inter-well serial connection, middle and low-pressure gas collection, normal temperature separation, and two-stage pressurization". The application of down-hole throttling can not only reduce the wellhead pressure, make it conform to the pressure level of wellhead device and surface gas gathering and transportation system, inhibit the formation of hydrates, but also greatly reduce the investment and construction cost of surface water jacket furnaces and related equipment, and save the cost of single well production and operation [1-2].

Due to the high unblocked flow rate and high well bore pressure in some new wells, if a single-stage down-hole choke is used, the residual heat and pressure of the well bore cannot be fully utilized, which will affect the productivity of the gas well and the safety of the surface medium and low-pressure gas gathering system [3-5]. However, there are few studies on the down-hole multistage throttling technology for reducing wellhead pressure in new high-pressure gas Wells. Therefore, for the newly put into production of high-pressure gas Wells, adopting down-hole multistage throttling can solve the problems of overpressure of surface gathering and transportation system and energy utilization of well bore, which has higher technical and economic benefits.

2. Mechanism and characteristics of down-hole flow throttling

Downhole throttling technology is to install the throttling device to a certain depth of the well bore to achieve throttling and depressurization in the well, Meanwhile, the formation heat transfer is used to heat the gas after throttling, so that the gas will not form hydrate in the well bore and gas production pipeline and block the pipeline due to the temperature reduction. Therefore, downhole throttling technology can not only reduce the pressure level of the surface natural gas gathering and transportation system, but also simplify the surface flow, save investment and realize the rapid production of gas wells. A variety of downhole throttles have been developed at home and abroad, but their throttling mechanism is the same. When natural gas passes through the throttle, there are two possible flow states:

1. When $p_c/p_1 \le p_2/p_1 \le 1$, is the non-critical state. Among them, p_1 is the pressure in front of the throttle, p_2 is the

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pressure at the end of the throttle, p_c is the critical pressure after the throttle. Downstream of the throttle, the gas velocity decreases with the increase of p_B/p_1, and the downstream pressure p_2 is equal to the back pressure.

2. When $0 \le p_B/p_1 \le p_C/p_1$, Is the critical state, Downstream of the throttle, the gas velocity reaches its maximum and the downstream pressure p_2 is equal to the critical pressure p_C. Under critical flow conditions, if there is a choke nozzle downhole, the pressure wave cannot pass through the choke nozzle and affect the upstream (well bottom) pressure when any pressure fluctuation occurs downstream, that is, between the pipe string above the choke nozzle and the gas gathering system, which can ensure the stable production of the gas well. Therefore, experts and scholars of oil and gas fields are inclined to study and design choke models for critical flow conditions. At the same time, downhole choke nozzles have auxiliary functions such as slowing downhole excitement and reducing sand production in gas wells.

3. Dynamic analysis of well bore

When the downhole throttle is not installed, the well bore fluid pressure and temperature are affected by the temperature of the borehole wall and show a nonlinear trend along the depth of the well, shown as in Figure 1. When there is a downhole throttle, the fluid pressure and temperature at the downstream outlet of the throttles will decrease dramatically, and then the temperature will gradually rise due to the influence of geothermal heat. The change of well bore pressure and temperature during downhole throttling is shown by the dotted line in Figure 1.

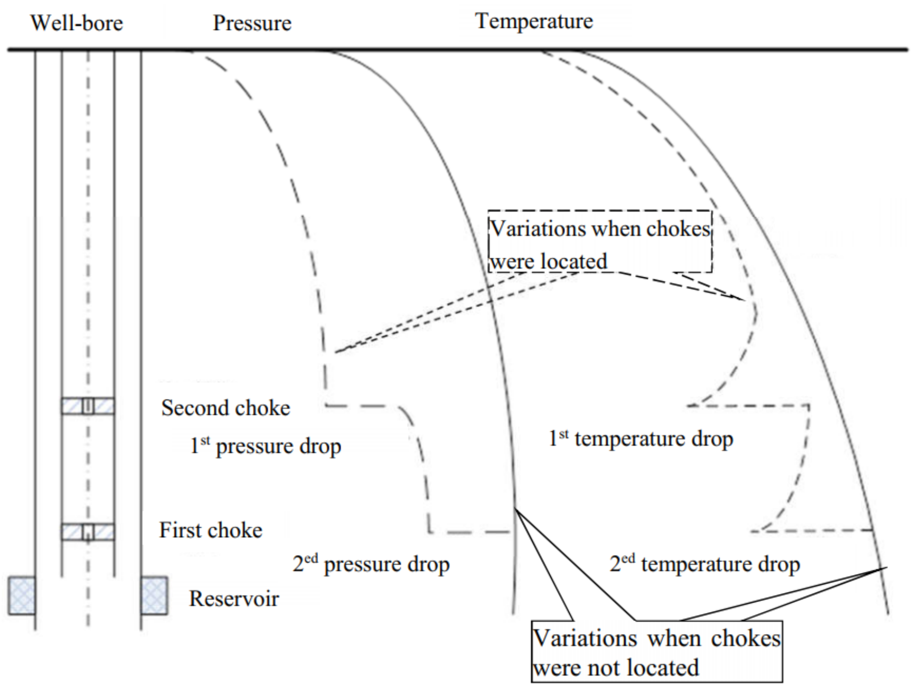

Figure 1. Schematic diagram of well bore pressure and temperature variation

For downhole throttling single phase or multiphase pipe flow in gas well, the core is to explore the laws of pressure and temperature changes, combining with the hydrate formation temperature prediction of nozzle flow analysis, optimized design of throttle mouth down to the position, the throttle nozzle diameter, the multistage downhole throttling process, also include the reasonable distance between various choke, to ensure the full use of geothermal, Prevent hydrate formation, avoid well bore fluid accumulation and gas well safety production, etc. This paper refers to the pressure and temperature analysis model in reference. Using the node system analysis method, the gas reservoirs in central as the ordinary nodes, choke as function node, considering well bore heat transfer process is the steady state heat transfer, and the heat transfer process in the formation of unsteady heat transfer, the accurate mathematical solution of stable heat source structure related to time heat relational expression into the equation of conservation of energy, coupling analysis the distribution law of pressure and temperature in the entire well bore.

4. Dynamic analysis of nozzle flow

4.1 Single-phase gas throttling pressure drop

According to the downhole throttling mechanism, after the high temperature and high-pressure gas well adopts downhole throttling technology, when the natural gas flows through the downhole throttling device, the natural gas velocity will increase rapidly due to the sudden reduction of the cross-section, and part of the pressure energy in the well bore will be converted into natural gas kinetic energy. Therefore, the flow pressure at the downstream outlet of the throttle will decrease significantly. According to the principle of isentropic expansion during natural gas throttling [6], in the subcritical state, the relationship between the flow rate of natural gas and the upstream and downstream pressure ratio of throttling is,

$$q_{sc} = \frac{0.408 p_1 d^2}{\sqrt{\gamma_g T_1 Z_1}} \sqrt{\frac{k}{k-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right]} \tag{1}$$

where, q_{sc} is natural gas production (under standard conditions), $10^4 \mathrm{Nm}^3/\mathrm{d}$; p_1 and p_2 are the the upstream and downstream pressures of the throttle, respectively, MPa; d is the diameter of the orifice, mm; T_1 is the upstream inlet temperature of the throttle, K; Z_1 is the gas compressibility coefficient at the inlet of the throttle; γ_g is the relative density of natural gas; k is the natural gas adiabatic index.

In the critical flow state, when the critical pressure ratio is calculated according to Eq.(1), the maximum output is

$$q_{max} = \frac{0.408 p_1 d^2}{\sqrt{\gamma_g T_1 Z_1}} \sqrt{\frac{k}{k-1}\left[\left(\frac{2}{k+1}\right)^{\frac{2}{k-1}} - \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \right]} \tag{2}$$

When the output of natural gas, the temperature and pressure at the upstream inlet of the throttle are known, substituting them into Eq.(1) and calculating after deformation, the pressure p_2 after throttling can be determined, the pressure drop can be obtained as $\Delta p = p_1 - p_2$.

4.2 Gas-liquid two-phase throttle pressure drop

Most of the gas Wells in Sulige gas field produce liquid such as condensate oil and water. In the process of exploitation, the ratio of liquid to gas will gradually increase, which will obviously affect the productivity of the gas well, and even make the gas well water flooded and stop production. Therefore, the correct prediction of gas-water two-phase throttling of gas nozzle is of great significance to the optimization design of downhole gas nozzle parameters of water-producing gas wells, gas well dynamic analysis and drainage gas production process design [7]. For gas wells with high gas-liquid ratio mist flow, the condensate oil and gas are taken as compound gas, and then the gas-liquid two-phase throttling of compound gas-water mixture is considered, and the throttling calculation model for high gas-liquid ratio gas well is obtained:

$$q = \frac{0.408 p_1 d^2}{\sqrt{F_w \gamma_w T_1 Z_1}} \sqrt{\frac{k}{k-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right]} \tag{3}$$

In the critical flow state, the maximum output of gas-liquid two-phase flow when the critical pressure ratio is calculated according to Eq.(3):

$$q_{max} = \frac{0.408 p_1 d^2}{\sqrt{F_w \gamma_w T_1 Z_1}} \sqrt{\frac{k}{k-1}\left[\left(\frac{2}{k+1}\right)^{\frac{2}{k-1}} - \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \right]} \tag{4}$$

where, F_w is water cut correction coefficient, and γ_w is the relative density of the composite gas and the other parameters are the same as before.

4.3 Downhole throttling temperature drop

The natural gas temperature at the downstream outlet of the throttling device can be obtained based on the classical thermodynamic as,

$$T_2 = T_1\frac{Z_1}{Z_2}\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \quad (5)$$

where, Z_1 and Z_2 are the gas compressibility coefficients at the inlet and outlet conditions of the throttle respectively, and T_2 is the downstream outlet temperature of the throttle. The phase balance equation before and after gas throttling and the throttling temperature drop model established in literature are used for calculation.

5. Analysis of applicable conditions for multistage downhole throttling

The application purpose of downhole multistage throttling process is basically the same as that of conventional downhole single-stage throttling process, which is to simplify surface process flow, prevent hydrate, improve liquid carrying capacity of well bore, etc., and ensure the normal production of gas well and the safety of middle and low-pressure gas gathering process system. In general, the downhole single-stage choke well selection conditions are gas wells with perfect well bore, wellhead oil pressure higher than the starting pressure of emergency cut-off valve (generally 5.0MPa), and infrequent opening and closing. The downhole multi-stage throttling process is mainly considered for gas wells with high bottom hole pressure to ensure stable production for a long time and the wellhead pressure before throttling is higher than the safe gas gathering pressure, avoiding the use of single-stage downhole throttling process to cause surface gathering system overpressure abnormal shut-in, and the well bore conditions are consistent with the single stage throttling. The conditions for the implementation of the multi-stage downhole process are obtained as follows,

$$\begin{cases} p_{wf} - \sum_{i=1}^{N}\Delta p_{ci} - \Delta p_w \le \Delta p_{wsmax} \\ T_{ws} \le T_{hp} + 3^{\circ}\mathrm{C} \end{cases} \quad (6)$$

where, p_{wf} is the bottom hole pressure under reasonable production allocation of gas wells, MPa; p_{wsmax} is the highest safety gas gathering pressure at the wellhead of gas well, MPa; T_{hp} is the hydrate formation temperature corresponding to the highest safe gas gathering pressure, °C; Δp_w is well bore pressure loss, MPa; Δp_{ci} is the throttling pressure drop of the downhole throttling device, MPa; N is the number of downhole throttles. T_{ws} is the wellhead flow temperature after multistage throttling of the well bore, °C.

6. Optimization design of downhole multistage throttling parameters

Using gas well node system analysis method and taking downhole throttle as function node, the calculation model of well bore pressure and temperature distribution is combined with the downhole throttle temperature step-down and pressure-drop model, and the established well bore nozzle flow dynamic analysis model is used to predict the distribution law of pressure and temperature in multi-stage downhole throttle process. Optimize the design of the number of throttles, throttle down depth at all levels, throttling nozzle diameter and other parameters.

6.1 the number of downhole throttles entering

Assuming the highest gas gathering pressure at the wellhead as the critical condition and take the reasonable production distribution of gas well and the corresponding bottom hole flow pressure into consideration, the downhole throttling series can be preliminarily obtained as,

$$N = \frac{\ln p_{wsmax} - \ln p_{wf}}{\ln p_{rc}} \quad (7)$$

where p_{rc} is the critical pressure ratio of the throttle nozzle. The calculated number of downhole throttles is rounded according to the analysis results to ensure that all levels of throttles are in critical state and avoid the change of surface production parameters affecting the gas well productivity.

Assuming that the adiabatic index of Sulige gas field is 1.3, the critical pressure ratio is 0.546. According to the take-off pressure of the wellhead emergency shutoff valve as 5.0 MPa, the one-stage throttling should be adopted when the bottom hole flow pressure is 9.2-16.78 MPa, and when bottom hole pressure is 16.78-30.72 MPa, two-stage throttling should be adopted; when bottom hole pressure is 30.72-56.26 MPa, three-stage throttling should be adopted.

6.2 Minimum lowering depth of the first downhole throttle

From the perspective of facilitating well bore fluid carrying, hydrate prevention and making full use of ground temperature and considering the hydrate formation temperature, the formula for calculating the minimum lowering depth of the first downhole throttle is theoretically determined as

$$L_{min} \geq GT_{wf}\left[(T_{h1}+273)p_{rc}^{-Z_1(k-1)/k}+(T_0+273)\right] \quad (8)$$

where T_0 is the average surface temperature, $^\circ$C.

6.3 Distance between multiple downhole throttles

The distance between the throttles uses the well bore temperature field analysis theory, and the temperature after each level of the throttle is used as the starting point, and the node system analysis method is used to analyze the distance Δx when the temperature after the throttles returns to the geothermal gradient as the lowering position of the next-level throttle, namely

$$\frac{\partial T(Q_g,p,GLR,K)}{\partial x}\Big|_{x=\Delta x}=GT_{wf} \quad (9)$$

where GT_{wf} is the average temperature gradient, m/$^\circ$C; Q_g is the reasonable distribution of production for gas wells, $10^4\mathrm{m}^3/d$; GLR is the gas and liquid ratio, m^3/m^3; K is the total heat transfer coefficient of well bore which can be obtained according to the well structure, W/(m^2.K).

The average cryogenic gradient of Sulige gas field is 2.5-2.9°C/100m, considering the current production parameters and well structure of the gas well, the initial calculation of the spacing between each throttle is 300-500m.

6.4 Calculation method and precedence

According to the above proposed theory, the specific calculation method and precedence of multi-stage downhole throttle parameter optimization design are as list follows:

1. The production and bottom hole pressure of gas well are determined according to the reasonable production distribution method of gas well.
2. The number of downhole throttles is determined preliminarily according to the pressure of surface gathering system.
3. Predict the hydrate formation temperature based on the bottom hole flowing pressure, and preliminarily determine the minimum lowering depth of the downhole first-stage throttle.
4. Calculate the temperature and pressure upstream of the first downhole throttle according to the well bore dynamic analysis method.
5. Call the downhole throttle pressure and temperature drop model to calculate the pressure and temperature downstream of the first-stage throttle.
6. Calculate hydrate formation temperature, T_{h1}, under downstream pressure of the throttle, if the temperature behind the nozzle ($T_2 > T_{h1}+3^\circ$C), reduce the lowering depth of the first throttle, otherwise increase the lowering depth of the throttle, repeat steps (4)-(6) to optimize and determine the lowering depth of the first throttle.
7. Using the well bore fluid analysis theory to calculate the pressure and temperature at the depth under the optimization of the first-stage throttle, and calculate the diameter of the first-stage throttling nozzle.
8. Using the well bore fluid analysis theory and node analysis method to calculate the pressure and temperature distribution behind the throttle nozzle. According to the distance between the downhole throttles, the depth of the remaining throttles and the temperature and pressure of the multi-stage throttles were determined successively, optimizing and determining the lowering depth and the diameter of the remaining throttles.
9. If the wellhead pressure does not meet the presented safe gas gathering pressure value, readjust the number of throttles and repeat step (2)-(9) until it meets the requirements of the surface gathering and transportation system.

7. Application

Based on the dynamic analysis in this paper and the theory and method of parameter optimization design of downhole multi-stage throttles, carrying out the parameter optimization design of three newly put into production gas wells of *Su X1*, *Su X2* and *Su X3*. The design results and application conditions are shown in Table 1. After the downhole first-level throttling is adopted, the pressure behind the throttling nozzle is greater than the safety gathering and transportation pressure at the wellhead. If the production is direct, there is the risk of overpressure, so it is necessary to use the gas production tree needle valve to throttle again, because the pressure before the wellhead throttling is high, and it is easy to form hydrate and block the pipeline. After the downhole two-stage throttle is adopted, the pressure behind the throttle nozzle is reduced to below the design pressure of the gas pipeline. At the same time, the temperature behind the throttle nozzle is higher than the hydrate formation temperature, which improves the safety of the wellhead and meets the needs of stable gas well production.

Table 1. Application of multi-stage downhole choke

No.	Production ($10^4 m^3/d$)	Mean annual temperature (℃)	Choke series	Choke depth (m)	Pressure before choke (MPa)	Temperature before choke (℃)	Pressure after choke (MPa)	Temperature after choke (℃)	Hydrate formation temperature (℃)
SuX1	7.00	8	1st level	2501	20.88	89.45	11.40	42.21	22.23
			2nd level	1999	10.93	74.89	5.97	29.55	18.34
SuX2	6.00	8	1st level	2500	17.99	87.72	9.82	40.70	21.34
			2nd level	2005	9.43	73.36	5.15	28.22	17.45
SuX3	10.00	8	1st level	2408	20.77	90.24	11.34	42.90	22.20
			2nd level	2008	10.97	78.64	5.99	32.81	18.37

8. Conclusion

This paper optimizes the design of downhole multi-stage choke process parameters for Sulige gas wells that have been put into production, aiming at adapt to the Sulige medium and low-pressure gas gathering mode and improve the production efficiency of gas wells, from the aspects of gas well bore dynamic analysis, mouth flow dynamic analysis, applicable conditions of multi-stage throttling and optimization design of process parameters, etc., a systematic method and theory for the optimization design of process parameters of gas well downhole multi-stage throttling system have been established. Through the practical application of typical wells, it is verified that the research theory in this paper can be used to guide the selection of throttling technology and the optimization design of production parameters for new wells and high-pressure and high-yield gas wells in the Sulige Gas Field, ensuring the safety of the gathering and transportation system and the efficient and stable production of gas wells.

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