Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 11, No. 2, 2024

Current Status of Research on Gas Well Fluid Accumulation and Throttling Technology and Field Measures

Chenyu Zhang

School of Xi'an Shiyou University, Xi'an 710065, China

Abstract: An overview of current theories and measures of gas well fluid accumulation and throttling is presented. The principles of gas well fluid accumulation and hydrate generation are described in detail. The solution measures are explained for gas fields where fluid accumulation and hydrates occur. Provide reference for similar situations in the future.

Keywords: Gas Well Fluids; Hydrates; Throttling.

1. Introduction

In China, due to the huge difference in geological conditions, the production conditions of individual gas reservoirs vary during the natural gas development process. However, the gas reservoir strata in China belong to hydrophilic strata, and the water phase is very easy to intrude into the reservoir. With the continuous exploitation of natural gas, gradually the gas wells will be blocked by fluid accumulation or natural gas hydrate, resulting in water flooding of the gas wells or complete blockage of the tubing columns, which will make the natural gas production reduced or stopped, resulting in huge economic losses. At present, domestic scholars have done a lot of research on the throttling of gas wells in different blocks and have made great progress. However, there is no systematic summary of the flow control measures and effects corresponding to different reservoir characteristics. Therefore, it is of guiding significance to investigate the current throttling methods in different domestic gas reservoirs and formulate throttling measures for gas wells in different blocks.

2. Current Status of Research on Gas Well Fluids and Gas Hydrates

Accurately obtaining the fluid accumulation situation of gas wells enables safe and stable production of gas wells. Therefore, scholars at home and abroad have carried out meticulous research on gas well fluid accumulation, while using various methods to predict gas well fluid accumulation. Combining the views of various researches, the fluid accumulation situation of gas wells is judged according to the inversion of liquid droplets and liquid film.

2.1. Current Status of Research on Droplet Inversion Modelling

The droplet inversion model first proposed by Turner (1969) determines the minimum air velocity required to carry a droplet by analysing the force equilibrium of a single droplet. The model focussed on the drag coefficient and the shape and size of the droplet, assuming a spherical shape with a drag coefficient and maximum Weber number of 0.44 and 30, respectively, with an additional factor. However, Coleman et al. (1991), in their analysis of gas wells with less than 500 psi oil pressure, concluded that the Turner model is more conducive to predicting the fluid accumulation phenomenon in low-pressure gas wells without increasing the safety factor. Also, Guo et al. (2006) suggested that the use of droplet force equilibrium alone does not bring out the distribution of flow velocity from suspended gas wells, thus requiring a larger range of gas flow velocities to avoid fluid build-up in the wellbore, and therefore the inclusion of a flow coefficient of 1.2 needs to be considered on top of the Turner model.

Nosseir (2000) and others believe that the drag coefficients of the air core on the droplets are different under different flow regimes (laminar, transitional and turbulent), while the hypothesis of Turner's model is still used for the size and shape of the droplets. Li Min (2001) and others proposed that: due to the difference in pressure before and after the droplet in the air core, the pressure difference on the surface of the droplet will be generated, which will change the shape of the droplet to ellipsoidal, resulting in the increase of its force area. They simplified the droplet as a cylinder for differential solution in the actual calculation, and found that the coefficient is only 38% of the coefficient of Turner model. On the basis of Li Min's model, Wang Zhibin(2012) and others obtained the new coefficients considering the maximum size of the droplet and the droplet deformation by integrating the new coefficients considering the change of the internal energy of the droplet in the deformation process and the equal work done by the outside, and combining with the definition of Weber's number, they rigorously deduced the relationship between the characteristic parameters of the droplet deformation and the critical Weber's number. Wang Zhongyi(2007) et al. established a minimum critical gas volume model for spherical cap-like droplets. Tan(2013) et al. proposed a new model, which is based on the total surface energy of droplets in the gas flow and the turbulent kinetic energy of the gas, and considers the effect of the size of the liquid volume and the diameter of the largest droplet on the critical flow rate carried by the liquid.

The above studies mainly focus on vertical wells, and there are fewer studies on horizontal gas wells. Belfroid(2008)et al. added the angle correction term on the basis of Turner's model, but they thought that the liquid film reversed and became the root cause of the liquid accumulation. Shi(2016)et al. proposed a model of critical gas volume of liquid-carrying in vertical section based on ‘half-hamburger’ shape droplets by experimentally observing the change of droplets' shape with their size in different inclination angles. 'Fadili(2016) et al. considered the elastic collision motion of the droplets in the inclined section, and concluded that the direction of motion of the droplets would change after collision with the wall of the tubing, and calculated the pre-collision velocity based on the collision energy loss, which is the critical gas flow rate for the liquid-carrying capacity. velocity. Liu Yonghui (2018) and others developed a set of horizontal well visual simulation experimental device, through the high-speed camera to capture the liquid film reversal point as the starting point of the accumulation of liquid experimental experimental data and WALLIS liquid flooding empirical formulas and angular correction relationship, established a simple model of the critical gas flow rate of the liquid carrier.

The droplet inversion model is widely used in various atmospheric fields at home and abroad due to its simple analytical formulation and high accuracy. However, the model lacks experimental and mechanistic validation. van'tWestende et al. (2007) found that the maximum droplet size observed in the experiment was only 350 μm, which is much smaller than the 8.5 mm assumed by Turner's model. in addition, only a very small amount of droplets (0.4%) undergoes flow reversal even in the annular/churning flow transition. The experimental results of Alamu (2012) confirmed that the droplet entrainment rate is less than 5% during the annular flow/churning flow pattern transition, which indicates that most of the liquid is transported upwards in the form of a liquid film. In summary, the plausibility of the droplet reversal model is still debatable.

2.2. Current Status of Research on Liquid Membrane Inversion Modelling.

In recent years, a large number of experimental and theoretical studies have found that there are a large number of liquid film overturning phenomena in the wellbore, and Belfroid (2008) et al. suggested that the interaction between gas-liquid two-phase flow and instability and flow pattern transition is an important cause of leakage in gas wells, and Veeken (2010) et al. used a non-constant numerical method in OLGA, combined with the steady-state multiphase flow model, to investigate the flow characteristics of seepage in gas wells. Veeken (2010) and others used a non-stationary numerical calculation method of OLGA, combined with a steady state multiphase flow model, to investigate the flow characteristics of seepage in gas wells. On this basis, a new gas-liquid two-phase flow model is proposed in this project, and the onset of gas-well fluid phase transition calculated by this model corresponds to the gas-liquid phase transition, which confirms that it is caused by the reversal of gas-well fluid phase.

Several scholars have conducted experimental studies on liquid film reversal to improve the understanding of gas well fluid accumulation. They have systematically studied the effects of inclination angle, tubing diameter and liquid volume on the critical gas flow rate of liquid-carrying wells. Although these experiments only analysed the change rule of liquid-carrying critical gas flow rate from the phenomenon and test data, and lacked in-depth theoretical analysis, they provided an experimental basis for the understanding of gas well fluid accumulation and the modelling of liquid film reversal. There is still a lack of research on the theoretical modelling of liquid film reversal. In vertical wells, Wallis (1969) proposed the causeless gas flow as the judgement criterion of liquid film reversal, but the method is an empirical rule, which does not take into account the influence of other parameters on the liquid-carrying critical gas volume.The liquid film thickness model proposed by Barnea (1986), which is currently the most widely used model, also has some defects in horizontal wells. For this reason, Luo (2014) and others from the University of Tulsa in the United States proposed an empirical relationship equation for calculating the maximum liquid film thickness at the bottom of the tubular section, so as to determine the liquid-carrying critical gas volume in horizontal wells at different inclinations. Since then, some scholars have revised or re-fitted the empirical relational equation by considering other influencing factors on this basis.

Liquid film overturning model is a more reasonable explanation of the flow mechanism of gas reservoir fluids, especially applicable to the fluid flow of horizontal wells, but it has been rarely applied in the field of major gas fields in China. The reasons for this are: the mathematical expression of the liquid film overturning process is very complicated, and it is difficult for field technicians to make a quick and accurate determination of it; the model has no guiding significance for the application of low-permeability and unconventional gas reservoirs, and the calculation results of the liquid film overturning model are much higher than those of the Turner model, whereas the wells of the Chuanxi, Sulige, Dainuidi, and Guang'an fields in China have a gas volume much lower than that calculated by the Turner model. Turner model calculations, can still be extracted with liquid. Pipeline flow tests have found that the liquid is most likely to invert at an inclination of 55°, a phenomenon that explains why horizontal wells are more prone to liquid accumulation; however, in actual horizontal wells, where the angle of inclination is continuously changed from 90° to 0°, the small-angle liquid film at the bottom of the well does not invert even at an inclination of 55°. Therefore, some scholars have tried to apply the nodal system analysis method to the seepage and suction phenomena in gas wells. However, the current nodal system analysis methods are all based on the coupling relationship between the formation and borehole states under steady state seepage conditions, while seepage in gas wells is a transient process. In addition, the nodal system analysis method does not reflect the long-term stability of gas wells after pumping. As for the concept of 'minimum pressure point', although the two-phase flow tests of tubular flow by Zabaras (1986) and Sarica et al. (2013) show that the minimum pressure point on the TPC curve is consistent with the liquid film overturning point. However, the degree of stabilisation of natural gas wells does not necessarily coincide with liquid film overturning.

2.3. Conditions for the Formation of Natural Gas Hydrates

For natural gas hydrates, temperature and pressure determine whether hydrates form or not. The conditions for hydrate formation can be obtained from the hydrate phase equilibrium curve as shown in Figure 1. From the figure, it can be seen that the left side of the curve is the high-pressure and low-temperature region, where hydrates can form and exist stably; the right side is the high-temperature and low-pressure region, where no hydrates are generated.

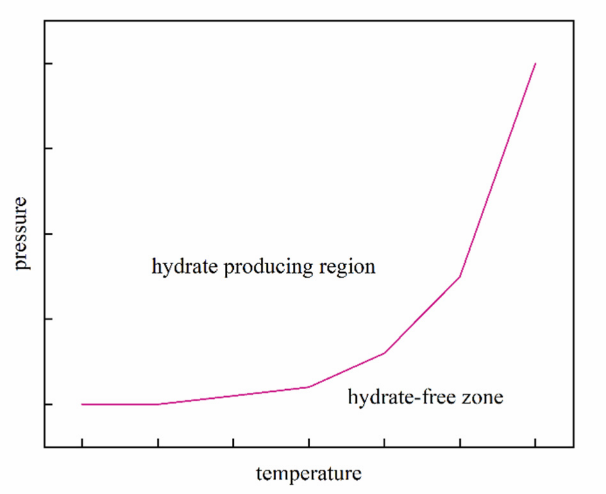

Fig 1. Hydrate phase equilibrium curve

3. Current Status of Research on Throttling Processes

The throttling process includes both downhole throttling and surface throttling. Downhole throttling process refers to placing the downhole nozzle with its supporting tools at the designed location of the tubing. When the gas well is in production, the natural gas passes through the downhole nozzle with lower temperature and pressure and faster fluid flow rate. And after passing through the nozzle, the natural gas fully absorbs heat in the wellbore, and the gas temperature rises again, at which time the gas is at a high temperature and low pressure, destroying the conditions for hydrate generation. Downhole throttling method can reduce the pressure of the surface pipeline, reduce the amount of alcohol injection, and improve the fluid-carrying capacity of gas wells.

Ground throttling method is to further reduce the temperature and pressure of the gas extracted from the gas wells through the angular valve, gas nozzle, tandem regulating valve and other equipment, but the throttling process will still be extremely easy to generate hydrates due to the sudden drop in temperature, resulting in the clogging of ground throttling valves or pipelines, which seriously affects the safety of gas wells and production. The throttled gas can meet the requirement of pressure-bearing material of gathering pipeline pipe.

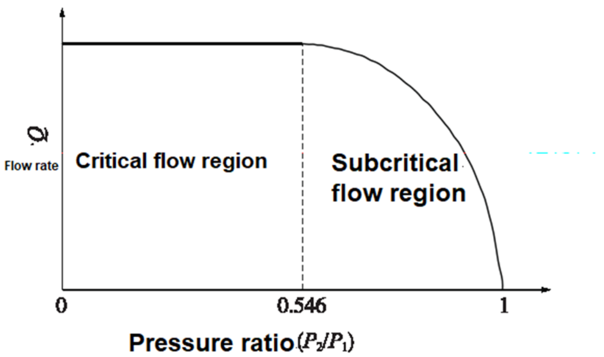

Fig 2. Fluid flow versus throttle pressure ratio

When the fluid passes through the throttling nozzle, it can be divided into two states: critical flow and subcritical flow. As shown in Fig. 2, in petroleum engineering operations, it is considered that when the ratio of inlet and outlet pressures is less than 0.546, the pressure downstream of the throttling section has no effect on the upstream pressure, which is critical flow; when the ratio of inlet and outlet pressures is less than 0.546, the pressure downstream of the throttling section has an effect on the upstream pressure, which is subcritical flow.

From the thermodynamic principle, the pressure ratio between the throttled inlet and outlet can be expressed as:

$$\beta_k = \frac{p_2}{p_1} = \left(\frac{2}{k+1}\right)^{k/k-1} \tag{1}$$

Where: β_k for the critical pressure ratio; p_1, p_2 for the pressure before and after the throttle, MPa; k for the adiabatic coefficient, usually take 1.3.

In the throttling section, there is a correlation between the flow rate and the inlet/outlet pressure ratio for the critical state, $p_2 / p_1 \le \left(\frac{2}{k+1}\right)^{k/k-1}$, The maximum flow rate through the throttling section is:

$$q_{\max} = 0.408 \frac{p_1 d_c^2}{\sqrt{F_\omega r_g T_1 Z_1}} \times \sqrt{\frac{k}{k-1}\left[\left(\frac{2}{k+1}\right)^{2/k-1} - \left(\frac{2}{k+1}\right)^{k+1/k-1}\right]} \tag{2}$$

For subcritical states $p_2 / p_1 > \left(\frac{2}{k+1}\right)^{k/k-1}$ The flow rate through the throttling section is

$$q = 0.408 \frac{p_1 d_c^2}{\sqrt{F_\omega r_g T_1 Z_1}} \times \sqrt{\frac{k}{k-1}\left[\left(\frac{p_2}{p_1}\right)^{2/k} - \left(\frac{p_2}{p_1}\right)^{k+1/k}\right]} \tag{3}$$

Where: $q_{\max}$ is the flow rate through the throttling section under critical condition, 10^4 m^3/d; d_c is the diameter of the throttling section, mm; T_1 is the inlet temperature of the throttling section, K; γ_g is the relative density of natural gas; and F_ω is the water content correction factor.

4. Examples of Solving Fluid and Hydrate Accumulations in Various Oil Fields

Dongsheng gas field is characterized by poor gas-water ratio, unclear gas-water interface, etc., and the phenomenon of 'gas and water coming out at the same time' often occurs in the process of exploitation, which is very easy to cause waterlogging, production decline, and even lead to flooding of shut-in wells. In the past, Dongsheng gas field used downhole throttling technology, and the traditional methods of oil jacket differential pressure and flow pressure test could not work well. For this reason, Dongsheng Gas Field proposed in 2022 a method based on the difference between the theoretical production and the actual production of downhole fractured gas wells to determine whether there is a waterlogging condition in the gas wells.

Taking the daily production rate at the bottom of the well without fluid accumulation as the constraint, and the actual production rate of the downhole throttling gas well as the constraint, the following formulas are derived: 1) Assuming that there is no fluid accumulation in the downhole throttling gas well, and keeping the casing pressure, the liquid-to-gas ratio, and the gas component unchanged; 2) Starting from the wellhead pressure, the seepage pressure at the bottom of the well in the case of no water content is derived by using the hydrostatic pressure formula; 3) Based on the gas-liquid two-phase flow model, the downhole throttling valve inlet pressure from the bottom of the well is derived (iii) Based on the gas-liquid two-phase flow model, the inlet pressure of the downhole throttle is calculated from the downhole flow pressure; (iv) Based on the gas-liquid two-phase flow model, the outlet pressure of the downhole throttle is calculated from the oil pressure at the wellhead; (v) Setting up the average gas flow rate of one day, and based on the gas-liquid two-phase flow model of the nozzles, and combining it with the calculated inlet and outlet pressures of the throttles, the diameter of throttle nozzles is calculated; (vi) By the deviation of calculated throttle nozzles diameters and the true value, the production rate is continuously adjusted for each day. The daily gas production is continuously adjusted through the deviation between the calculated throttle nozzle diameter and the real value, and if the deviation meets the specified accuracy, then the corresponding production is the theoretical gas production. The ratio of the actual production rate to the theoretical production rate of the Dongsheng gas field production is below 0.75, which indicates that there is a large leakage from the well.

The Dongsheng gas field is subject to frequent gas well fluid accumulation and water flooding in 2023 due to the difficulty of carrying fluids using the small casing extraction process. Restricted by the surface low-pressure gathering technology and hydrate blockage, it is necessary to test gas at the surface, prevent hydrate blockage through water jacket furnace heating, and throttle and reduce pressure at the surface nozzle to meet the gathering requirements, which leads to management difficulties and high production costs. In order to increase the liquid-carrying capacity of gas wells, reduce gas reservoir decreasing, and solve the problem of well operation volume, a new development idea was proposed. In order to solve this problem, the experiment of velocity tubing column tandem discharge production process under downhole throttling condition was carried out and achieved good results.

Continuous pipe speed column is a proven technical method to discharge gas by installing a smaller diameter continuous pipe downhole as an oil extraction column. The basic idea is: without changing the original downhole extraction tubing column, use natural energy to introduce formation fluid into the small diameter tubing column, and use the principle of fluid dynamics of the variable diameter tubing to increase the fluid flow rate in the small diameter tubing, which in turn improves the gas well drainage capacity and prevents the accumulation of fluids and flooding of the gas wells. The downhole throttling technology, by setting a throttle at a suitable location on the tubing, will have a temperature drop during the throttling process, that is, the natural gas near the throttling port, but because the throttling hole is located at the bottom of the deeper wells, the temperature of the throttled gas is heated so that the temperature of the throttled gas is higher than the initial temperature of the hydrate generation at the post-throttling pressure state, and therefore, the wellbore, the wellhead, and the surface Therefore, no hydrate blockage will occur in the wellbore, wellhead and surface pipeline, which achieves the purpose of effectively reducing the pressure of surface pipeline, controlling the production of gas wells, and exempting the surface from heating and heat insulation. Velocity tubing-column composite drainage and extraction technology under downhole throttling conditions refers to a reliable and practical technical means to install fixed gas nozzles at the bottom of the continuous oil tubing to realise gas drainage and extraction. Through throttling, the pressure energy is converted into kinetic energy, the gas pressure is reduced after throttling, the flow rate increases, and the liquid-carrying capacity increases accordingly; at the same time, by using the ground temperature to heat the fluid, the temperature after throttling is guaranteed to be higher than the hydrate-generating temperature under the current conditions, so as to solve the problem of hydrate clogging of the wellbore under the conditions of low-pressure gathering and transmission.

The advantages of this technology are: the gas flow rate increases, the critical carrying capacity of gas wells decreases significantly, and the liquid-carrying capacity of gas wells is enhanced, so as to achieve the purpose of controlling the casing pressure and natural decreasing, and to prolong the stable production cycle of gas wells; this technology can effectively solve the difficult problem of gas wells with hydrate stuck in natural gas wells, and it can avoid the manpower and cost increase caused by the warming of the process of the ground surface; in order to ensure the long-lasting stability of the gas wells and to increase the well bore's In order to ensure the long-term stability of the gas well and improve the integrity of the borehole, it is necessary to fill the annulus with bubbling and discharging agents and corrosion and scale inhibitors; the method can be achieved without pressurisation of the well, which can effectively prevent the contamination of the formation due to the leakage of pressurised wells during the production process and shorten the construction period; it has solved the problems of safety, environmental risks and the treatment of alcohol-containing wastewater brought about by the use of methanol in preventing and controlling hydrates.

The large fluctuation of daily gas production and daily gas volume in the Makuhu Oilfield, the limited capacity of surface gathering and transmission, and the high gas content in some blocks have led to hydrate freezing in the downhole pipe-surface pipeline under high pressure. To address this problem, this project takes the Makuhu Oilfield as the research object, and based on the downhole throttling technology, proposes the ‘secondary throttling’ technology, which achieves the dual goals of ‘hydrate prevention and control and production adjustment’ by installing throttling nozzles at the wellhead and downhole. In June 2021, Makuhu Oilfield carried out five experimental wells with ‘dual throttling’ technology for the first time in this area. Table 1 shows the comparative results of the experimental wells before and after adopting the dual throttling technology to control hydrate plugging.

Table 1. Comparison of hydrate clean-up before and after implementation of double throttling process in test wells (single/twin throttling)

pound sign	Nozzle Diameter /mm	Hydrate clean-up		
		production time /d	Number of clean-ups	Average interval /d
M1	4.5/(7.0~4.0)	30/46	2/0	15.5/—
M2	4.5/(7.0~4.5)	9/175	1/10	9/17.5
M3	4.5/(7.0~4.5)	37/172	4/3	9.3/57.3
M4	4.0/(6.0~5.0)	156/190	9/10	17.3/19
M5	5.0/(7.5~5.0)	187/99	19/0	9.8/—

For the experimental wells M1, M2, M3, M4, the average discharge time is very short before double throttling, which leads to more serious hydrate freezing phenomenon, for this reason, this project proposes a double throttling scheme based on the large-diameter wellhead nozzle with the prevention and control of hydrate freezing as the main purpose. The experimental wells M5, due to the long time of discharging the hydrate layer before the double throttling, are The well was designed with double throttling by adjusting the production capacity and assisting the release of the spray. After adopting the double throttling technique, all five experimental wells obtained better production increase.

Aiming at the characteristics of 'medium and high pressure gas gathering + liquid dosing + gas-liquid mixing + central pressure boosting + centralised treatment' of tight gas reservoirs in Southwest oil and gas fields, heating and throttling are carried out on the platform, and the gas-liquid mixing in the internal gas gathering and transmission is transferred to the gathering station through the 'string connection + branch' pipeline network for centralised treatment, and electric induction heating is gradually implemented at a later stage to prevent the formation of hydrates on the surface pipelines. In order to prevent the formation of hydrates on the ground pipeline, water jacket furnace heating was adopted on the platform with reference to the conventional gas field at the initial stage, and electric induction heating was gradually implemented at the later stage. In order to further optimise and simplify the surface process and reduce the extraction cost, this project proposes to use QL20H as the first experimental well for downhole throttling in March 2022, and field tests were conducted in QL212-8-H1 and QL212-8-H1 in June 2022, respectively. The production conditions of the gas wells before and after downhole throttling were compared by three experimental application wells. 2) The use of downhole throttling device can reduce the casing pressure of throttling wells slower, effectively control the production differential pressure, and ensure the normal production of gas wells; 3) The use of downhole throttling process can effectively simplify the formation flow and reduce the operation cost.

With the continuous development of oil and gas exploration and development in China, the number of ultra-high-pressure gas reservoirs is also increasing. Some UHP gas wells in the western edge of Sichuan Basin ('West Sichuan area') have reached initial formation pressures of 130 MPa and 110 MPa, and conventional prevention and control methods can no longer meet the demand for safe exploitation. Downhole throttling is an effective method to effectively control natural gas hydrates, which can reduce surface construction costs under the premise of ensuring the safety of extraction and gathering and transmission, and has been popularised and used in China's Southwest Oil and Gas Field, Changqing Oil Field and Tarim Oil Field, among other fields. There is an urgent need for field promotion of downhole throttling technology for ultra-high-pressure gas wells in western Sichuan. Therefore, this project takes the ultra-high pressure gas wells as the research object, takes the determination of its key parameters as the entry point, and takes the actual engineering as the background to carry out the research on the design and commissioning process of the downhole throttling technology of the ultra-high pressure gas wells, so as to provide the theoretical basis for its application in the actual production. The results of the study show that: 1) Compare the relationship between the deviation coefficients obtained by DAK method, LXF method and modified LXF method and the measured values, and propose the improved LXF method for the calculation of natural gas deviation coefficients in the ultra-high-pressure gas reservoirs. 2) In the design of downhole throttling technology, the study focuses on the downhole depth of the throttling device and the diameter of the nozzle; the depth of the throttling valve required for a higher hydrate formation temperature than the corresponding depth after throttling is obtained by replacing the relevant parameters with the reverse calculation using the corresponding calculation method; and the diameter of the nozzle is optimised by taking into account the factors of pressure, temperature and predicted production. 3) During the process of opening the ultra-pressure gas well to the smooth operation of the downhole throttling device, the wellhead faces high throttling pressure, and how to prevent the wellhead needle tube from freezing at the early stage of opening is an important prerequisite to ensure the safe production of ultra-pressure gas wells. 4) Transient simulation software is used to dynamically simulate parameters such as pressure, temperature, production and hydrate supercooling degree of extra-pressure natural gas wells in different blocks under different opening methods, in order to optimise the development plan and ensure the safe production of extra-high-pressure natural gas wells.

The volcanic gas reservoir in Daqing Xushen gas field is water-producing, with high formation pressure, high well construction cost, hydrate freeze plugging and low well opening rate, so we carried out experiments on downhole throttling technology in Daqing oil field. Taking Xushen gas field as the research object, we used OLGA software to optimize its design, which overcame the difficulty that the single-phase gas formation throttling parameter model used in the previous experiments was not suitable for water-producing reservoirs, and provided an effective guidance for the downhole throttling technology in Xushen gas field, and as of the end of 2020, a total of 17 wells experiments were carried out, with a success rate of 100%, which effectively lowered the oil pressure at the wellheads of the gas wells and prevented and controlled the hydrate freeze plugging, and achieved energy saving and consumption reduction.

5. Summary

(1) A detailed summary of the theory of gas well fluid accumulation and hydrate generation has been provided, and it has been found that there are large differences in the liquid velocity prediction methods of several natural gas wells that have been studied so far, which illustrates the fact that gas well fluid phase change is not just a liquid-liquid inversion phenomenon, but rather a formation-wellbore coupling result.

(2) Approaches for coping with gas well fluid accumulation and hydrates in gas fields with different characteristics are summarised to provide experience for subsequent similar situations.

References

[1] Turner RG, Hubbard MG & Dukler AE. Analysis and prediction of minimum flow rate for the continuous removal of liquid from gas wells[J]. Journal of Petroleum Technology, 1969, 21(11): 1475-1482.

[2] Coleman SB, Clay HB, Mccurdy DG & Norris LH. A new look at predicting gas-well load-up[J]. Journal of Petroleum Technology, 1991, 43(3): 329-333.

[3] Guo BY, Ghalambor A & Xu CC. A systematic approach to predicting liquid loading in gas wells[J]. SPE Production & Operations, 2006, 21(1): 81-88.

[4] Nosseir MA, Darwich TA, Sayyouh MH & Sallaly ME. A new approach for accurate prediction of loading in gas wells under different flowing conditions[J]. SPE Production & Facilities, 2000, 15(4): 241-246.

[5] Li Min, Guo Ping & Tan Guangtian. New look on removing liquid from gas wells[J]. Petroleum Exploration and Development, 2001, 28(5): 105-106.

[6] Wang Zhibin & Li Yingchuan. The mechanism of continuously removing liquids from gas wells[J]. Acta Petrolei Sinica, 2012, 33(4): 681-686.

[7] Wang Yizhong & Liu Qingwen. The mechanism of continuously removing liquids from gas wells[J]. Petroleum Geology & Oilfield Development in Daqing, 2007, 26(6): 82-85.

[8] Tan Xiaohua & Li Xiaoping. Gas wells model of continuous removal of liquids through a new estimation of droplet diameter[J]. Journal of Hydrodynamics, 2013, 28(1): 41-47.

[9] Belfroid S, Schiferli W, Alberts G, Veeken CAM & Biezen E. Predicting onset and dynamic behaviour of liquid loading gas wells[C]// SPE Annual Technical Conference and Exhibition, 2124 September 2008, Denver, Colorado, USA.

[10] Shi JT, Sun Z & Li XF. Analytical models for liquid loading in multifractured horizontal gas wells[J]. SPE Journal, 2016, 21(2): 471-487.

[11] Fadili YE & Shah S. A new model for predicting critical gas rate in horizontal and deviated wells[J]. Journal of Petroleum Science & Engineering, 2016, 150: 154-161.

[12] LIU Yonghui,AI Xianting,LUO Chengcheng,et al. A new model for predicting critical gas velocity of liquid loading in horizontal well[J]. Journal of Shenzhen University Science and Engineering,2018,35(6) 551-557.

[13] van't Westende JMC, Kemp HK, Belt RJ, Portela LM, Mudde RF & Oliemans RVA. On the role of droplets in cocurrent annular and churn-annular pipe flow[J]. International Journal of Multiphase Flow, 2007, 33(6): 595-615.

[14] Alamu MB. Gas-well liquid loading probed with advanced instrumentation[J]. SPE Journal, 2012, 17(1): 251-270.

[15] Veeken K, Hu B & Schiferli W. Gas-well liquid-loading-field-data analysis and multiphase-flow modeling[J]. SPE Production & Operations, 2010, 25(3): 275-284.

[16] Wallis, GB. One-dimensional two-phase flow[M]. New York: McGraw-Hill, 1969.

[17] Barnea D. Transition from annular flow and from dispersed bubble flow—unified models for the whole range of pipe inclinations[J]. International Journal of Multiphase Flow, 1986, 12(5): 733-744.

[18] Luo S, Kelkar M, Pereyra E & Sarica C. A new comprehensive model for predicting liquid loading in gas wells[J]. SPE Production & Operations, 2014, 29(4): 337-349.

[19] Zabaras G, Dukler AE & Moalem MD. Vertical upward cocurrent gas-liquid annular flow[J]. AIChe Journal, 1986, 32(5): 829-843.

[20] Sarica C, Yuan G, Sutton RP & Pereyra EJ. An experimental study of liquid loading of vertical and deviated gas wells[C]//SPE Production and Operations Symposium, 23-26 March 2013, Oklahoma City, Oklahoma, USA.