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气顶油藏水平井最优垂向位置研究*

吕爱民 姚 军

(中国石油大学石油工程学院, 山东东营 257061)

摘要: 水平井开发油藏是避免气顶油藏过早见气的有效手段, 而确定水平井最优垂向位置是获得最佳开发效果的关键。针对这一问题, 从水平井垂向位置对气顶油藏临界产量和见气时间的影响入手, 得出了临界产量和见气时间与水平井垂向位置的关系曲线; 在综合考虑临界产量和见气时间的基础上, 得到了水平井垂向位置与临界产量和见气时间乘积的关系曲线, 由曲线趋势得到了气顶油藏水平井最优垂向位置的范围。研究表明, 水平井越靠近气顶, 临界产量越大, 而见气时间越短; 水平井距油气界面的距离为含油厚度的 80% ~ 90% 时开发效果最优。该研究结果为气顶油藏水平井的油藏工程设计提供了依据。

关键词: 水平井; 气顶油藏; 临界产量; 见气时间; 最优位置

中图分类号: TE349 文献标识码: A

水平井的垂向位置是影响开发效果的关键因素之一, 国内许多学者进行过相关探讨^[1,2]。目前对气顶油藏水平井垂向位置和开采井段的优化一般仅从临界产量的角度进行研究^[3,4], 与现场实际存在较大差距, 有必要重新认识。水平井在气顶油藏中的开发效果与其临界产量和见气时间密切相关, 而此二者均受水平井在油藏中垂向位置的影响。通常认为, 水平井水平段距离油气界面越远, 水平井临界产量越高, 但实际上水平井越靠近油藏底部, 气顶驱动油藏中渗流阻力越大, 水平井产量会降低而见气时间则相对延长。因而水平井水平段在气顶油藏中存在一个最优位置, 可使水平井开采效果最好。

式中, q_c 为水平井临界产量, m^3/d ; ρ_o 为地下油气的密度差, g/cm^3 ; h_w 为油藏底面到水平井筒的距离, m ; k_h 、 k_v 分别为水平方向和垂直方向渗透率, $10^{-3} \mu m^2$; μ_o 为原油黏度, $mPa \cdot s$; B_o 为原油体积系数, m^3/m^3 ; h 为储层厚度, m ; r_w 、 L 分别为水平井的井眼半径和水平段长度, m 。

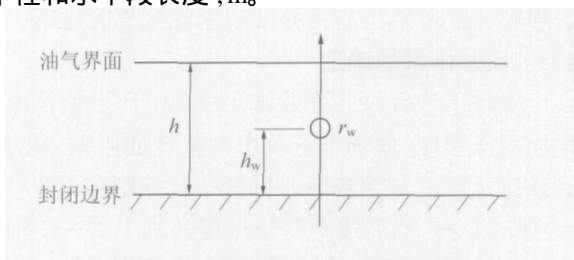


图 1 气顶油藏水平井示意图

为了便于研究, 在式 (1) 中定义无量纲量

$$\Phi = \frac{q_c \mu_o B_o}{5.32 k_c L (h - h_w)}, \quad h_D = \frac{h_w}{h}$$

则

$$\Phi = \frac{1}{\ln \frac{4h}{r_w} + \ln \tan \frac{(1 - h_D)}{2}} \quad (2)$$

由公式 (2) 计算并绘制水平井无量纲产量与无量纲水平井位置关系曲线, 如图 2 所示。由图 2 可见, 当生产压差和水平与垂向渗透率比一定时, 水平

1 气顶油藏水平井临界产量

假设地层如图 1 所示, 下面封闭, 油气边界为恒压, 且认为供油半径为无限大。考虑地层水平和垂向渗透率差异时, 气顶油藏水平井的临界产量的计算公式^[1]为

$$q_c = \frac{5.32 k_c L (h - h_w) \rho_o B_o}{\ln \frac{4h}{r_w} + \ln \tan \frac{(h - h_w)}{2h}} \quad (1)$$

其中 $k_c = \sqrt{k_h / k_v}$, $k_e = \sqrt{k_h k_v}$

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作者简介: 吕爱民, 1970 年生。1994 年毕业于石油大学 (华东) 油藏工程专业, 博士研究生, 主要从事油气田开发方面的教学和研究工作。电话: 0546 - 8391192, E-mail: hdpulam@163.com。

井产量随油井位置 h_D 的增加而增加,即水平井距离油气界面越近,水平井的产量越高;当无因次距离 $h_D < 0.1$ 和 $h_D > 0.8$ 时,随着 h_D 的增加,水平井产量增加较快;当 $0.1 < h_D < 0.8$ 时,随着 h_D 的增加,水平井临界产量增加较平缓。

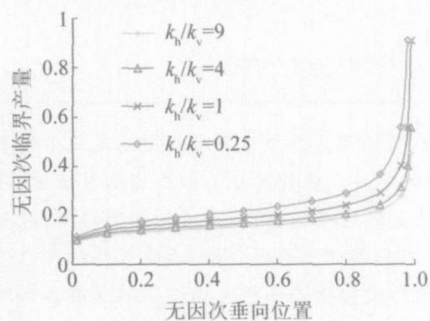


图2 水平井无因次临界产量与无因次垂向位置关系

图2还表明了油藏渗透率各向异性对水平井临界产量的影响。在生产压差一定时,随着水平与垂向渗透率比的增加,水平井的临界产量减小,因此垂向渗透率的提高有利于气顶油藏水平井临界产量的提高。

2 气顶油藏水平井见气时间

在图1所示地层中,考虑水平和垂向渗透率差异时,气顶油藏水平井的见气时间计算公式^[1]为

$$t_{\tau} = \frac{4\phi L h^2}{q_b} \left\{ 1 - \cot \frac{(h - h_w)}{2h} \cos \frac{(h - h_w)}{2h} \right. \\ \left. \ln \left[\sec \frac{(h - h_w)}{2h} + \tan \frac{(h - h_w)}{2h} \right] \right\} \quad (3)$$

$$\text{令} \quad t_b = \frac{q_b t_{\tau}}{4\phi L h^2}, \quad h_D = \frac{h_w}{h}$$

$$\text{则} \quad t_b = 1 - \cot \frac{(1 - h_D)}{2} \cos \frac{(1 - h_D)}{2} \\ \ln \left[\sec \frac{(1 - h_D)}{2} + \tan \frac{(1 - h_D)}{2} \right] \quad (4)$$

式中, t_{τ} 为水平井见气时间, d; t_b 为无因次见气时间; ϕ 为孔隙度; q_b 为水平井的日产油量, m^3/d 。

由公式(4)计算并绘制水平井无因次见气时间与无因次水平井位置关系曲线,如图3所示。由图3可见,当水平井位置 h_D 增加时,无因次见气时间 t_b 减小,即水平井距油气界面越远,见气时间越长,并且当 $h_D < 0.1$ 和 $h_D > 0.8$ 时,随着水平井位置 h_D 的减小,无因次见气时间 t_b 增长较慢;当 h_D 在 0.1 和 0.8 之间时,随着水平井位置 h_D 减小,无因次见气时间 t_b 增长较快。

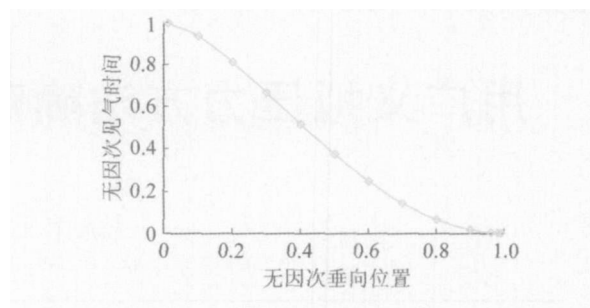


图3 水平井无因次见气时间与无因次垂向位置关系

3 气顶油藏水平井最优垂向位置

由图2和图3可见,水平井无因次位置 h_D 减小可延长见气时间,但不利于产量的提高。综合考虑水平井临界产量和见气时间这2个因素,得到无因次产量和无因次见气时间的乘积 $q_b h_D$ 与无因次位置 h_D 的关系曲线如图4所示。由图4可见, $h_D = 0.1 \sim 0.2$ 时,无因次产量与无因次见气时间的乘积达到最大值。该值可反映无气采油量的大小,该值越大,开发效果越好;另外,水平与垂向渗透率比不同,开发效果不同,垂向渗透率越大,开发效果越好;但图4中不同水平与垂向渗透率比下各曲线的变化趋势相同,说明水平与垂向渗透率差异不影响水平井最优垂向位置的选取。由此可见,气顶油藏水平井最优垂向位置应为 $h_D = 0.1 \sim 0.2$,即水平井距油气界面的距离为油藏含油厚度的 80% ~ 90%。

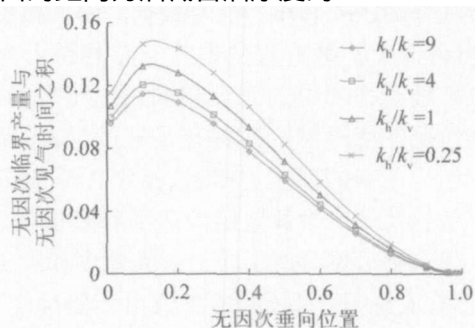


图4 气顶油藏水平井最优无因次垂向位置

4 结论及建议

水平与垂向渗透率比影响水平井的临界产量,但不影响水平井最优垂向位置的选取;气顶油藏水平井的最优垂向位置应为 $h_D = 0.1 \sim 0.2$,即水平井距油气界面的距离为油藏含油厚度的 80% ~ 90%,该研究结果为气顶油藏中水平井的油藏工程设计提供了依据。该结论是在油气界面的压力和位置均假

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3 应用实例

采用一实际气井参数: $p_0 = 117 \text{ MPa}$, $T = 401.15 \text{ K}$ 气体的相对密度 $\rho_g = 0.684$, 渗透率模量 $k = 0.05 \text{ MPa}^{-1}$, 由程序计算得到 $p_c = 4.617531 \text{ MPa}$, $T_c = 213.600590 \text{ K}$, 天然气视分子量 $M_g = 19.818377 \text{ g/(g} \cdot \text{mol)}$ 以及任一压力对应的气体黏度 μ 、偏差因子 Z 和广义拟压力值。

从计算结果可以看到, 当 $p < 12 \text{ MPa}$ 时, $\mu_i Z_i = 0.015 \text{ MPa}$ 。该结论和目前得到的认识是一致的。根据得到的拟压力值, 可得到广义拟压力和压力关系如图 1 所示。

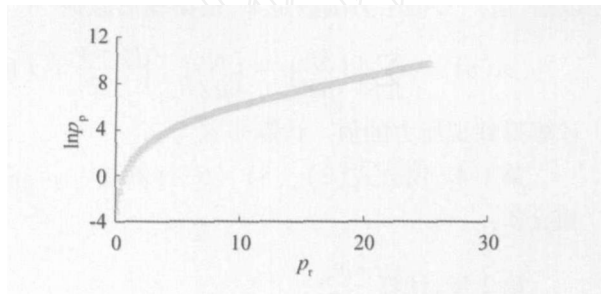


图 1 广义拟压力和压力关系

回归得其关系式为

$$\ln p_p = 0.4244889989 + 0.000374p_r^2 \ln p_r + 1.0179 \ln p_r$$

联合 (12)、(13) 式可得到该油藏压力形式下的相应的产能方程, 该方程是高压气井动态分析的基础。

4 结论

(1) 引入广义拟压力函数来表征压敏油藏气体

渗流过程中, 气体的黏度和偏差因子 Z 以及地层渗透率都是压力的函数这一特性, 使气体渗流扩散方程的形式得到简化。

(2) 提出定温条件下广义拟压力函数计算的数学方法, 回归其方程系数, 得出真实气体的拟压力计算关系式, 并将其用于气井流入动态的分析。

(3) 关系式 (11) 的提出, 为真实气体拟压力的计算提供了快速准确的方法, 对提高压敏气藏模拟具有重要意义。

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定为不变的条件得出的。对于油气界面压力及位置随开发时间变化的情况尚待进一步研究。

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field application

SUN Ling^{1,2}, 1. Faculty of Chemical Engineering in Shandong University, Jinan 250000, Shandong, China; 2. Huanghe Drilling and Cementing Company of Shengli Oilfield, Dongying 257064, Shandong, China

Application of plugging and film forming drilling fluid technology in Kun-2 well AI Guicheng ODPT, 2007, 29 (1):89-91

Abstract: Kuntayi depression of Qaidam Basin features in deeply buried oil reservoir and complex geologic structure. To realize safe, optimum and fast drilling in this high risk formation, plugging and film forming drilling fluid is developed on the theories of ideal packing, filming forming, and ultra-low permeability drilling fluid. Experiments of submerging depth of sand bed, sealing properties of membrane structure, pressure and filtration, and permeability recovery are conducted to test the properties of the drilling fluid. In addition, drilling fluid formulation is selected in accordance with the porosity, permeability, lithology, bottomhole temperature, drilling procedure of Kun-2 well. Application shows that this kind of drilling fluid has excellent wellbore stability and enables Kuntayi formation to realize no accidents, increase drilling speed, shorten drilling cycle, and successfully complete drilling tasks.

Key words: Kun-2 well; wellbore stability; plugging and film forming drilling fluid; reservoir protection

AI Guicheng, Yumen Branch of Tuha Oilfield Drilling Company, Yumen 735200, Gansu, China

Cementing techniques for wells with salt formations used for underground gas storage YIN Xue-yuan. ODPT, 2007, 29 (1):92-94

Abstract: This paper analyzes technical challenges arising from cementing through salt formations and cavems used for the underground gas storage of the West-East Gas Pipeline project, such as no hole bottom, high downhole temperature, large hole size and strict requirements for long-term bonding properties of cementing sheath, etc. By employing techniques of cementing plug and semi-saturated salt-water-base slurry and improving displacement efficiency, preceding cementing problems are solved and cementing for no-bottom salt cavems is realized. Through improving properties of the semi-saturated salt-water-base slurry, good cementing results of newly drilled wells are achieved in salt-gypsum formations. Cementing through five salt cavems used for gas storage and in eight newly drilled wells in Jiangsu Jintan Salt Mine shows that this technique fulfills the need of cementing through salt formations and cavems used for gas storage and can be used to improve cementing quality.

Key words: gas storage well; salt cavern; no bottomhole; salt formation; displacement efficiency; cementing technique

YIN Xue-yuan, No. 1 Drilling Company of Liaohe Petroleum Exploration Bureau, Panjin 124010, Liaoning, China

Cementing technology of gas well in Shuangtuozi region of Jilin Oilfield QI Feng-zhong, WANG Shun-li, MAO Jing-xun, BU Yun-peng, YU Guo-dong ODPT, 2007, 29 (1):95-97

Abstract: Slurry loss and gas channeling between the formations often occur during cementing owing to the low pressure and easy lost circulation, impurity pressure gradient, long gas reservoir distribution interval, alternating with gas and water layers exist in the top formations in Shuangtuozi region of Jilin Oilfield. In this paper, solving methods to gas well cementing are presented, anti-channeling cement additives are selected based on analyzing the necessary conditions for the anti-channeling cement slurry system, and a new G302 cement slurry system is developed. What's more, a comprehensive anti-channeling technology is developed based on employing G302 anti-channeling cement slurry and separably setting cement slurry. Technical measures such as JSS-1 drilling fluid and NCH-2 spacer fluid are proposed to improve displacement efficiency suitable for low-pressure and easy lost circulation conditions. This technology has been applied in Shuangtuozi region for four well-times in 2005 and good cementing results have been achieved. For that, the problem of long production interval cementing in multiple series of strata of this region has been solved and a set of comprehensive systematic technologies have been developed to guide the gas well cementing in this region, providing an effective solution to similar gas well cementing problems.

Key words: gas well; cementing; anti-channeling; displacement efficiency; cement additive; test

QI Feng-zhong, Langfang Branch, PetroChina Research Institute of Petroleum Exploration and Development, Langfang 065007, Hebei, China

Study on optimal vertical position of horizontal well in gas-cap reservoir. Lv Aimin, YAO Jun. ODPT, 2007, 29 (1):98-99

Abstract: The horizontal well is an effective way to avoid early gas breakthrough of gas cap reservoir and the identification of its optimal vertical location is the key to obtain the best development result. Through analyzing the effect of the vertical locations of horizontal wells on the critical output and gas breakthrough time of the gas cap reservoir, the curve showing the relationship between the vertical locations of horizontal wells and the critical output as well as the gas breakthrough time is obtained in this paper. After taking both critical output and gas breakthrough time into consideration, the author obtains the curve showing the relationship between the vertical locations of horizontal wells and the arithmetic product of critical output and

gas breakthrough time. According to the curve tendency, the range of the optimal vertical locations of horizontal wells in gas cap reservoirs is obtained as well. The research shows that the critical output will increase and the gas breakthrough time will become shorter if the horizontal well gets closer to the gas cap. The best development effect will be achieved if the distance between the horizontal well and the oil-gas interface accounts for 80% to 90% of the oil bearing thickness. This can supply basis for reservoir engineering design of the horizontal wells in gas cap reservoir.

Key words: horizontal well; gas cap reservoir; critical output; gas breakthrough time; optimal location

LV Aimin, College of Petroleum Engineering, China University of Petroleum, Dongying 257061, Shandong, China

Evaluation on inflow performance relationship of gas wells in pressure-sensitive reservoir using generalized pseudo pressure YANG Yong-zhi, LIAO Xin-wei, SHEN Ping-ping ODPT, 2007, 29 (1): 100-102

Abstract: To precisely describe the permeability characteristics of real gas in pressure-sensitive reservoir, the generalized pseudo pressure function is introduced to characterize the gas flow in pressure-sensitive reservoir. Thus the gas seepage-diffusion equation has the same expression with the diffusion equation of the slightly compressible liquid flow with single direction. While evaluating the generalized pseudo pressure function, corresponding models can first be used to calculate the gas velocity, the deviation factors and the formation permeability under constant temperature and various pressures. Secondly, the step-size pressure is calculated according to the trapezoidal rule. Numerical integration is applied to evaluate the generalized pseudo pressure fit to a constant temperature and any pressure and regress the coefficients to the gas seepage-diffusion equation. The expression for the relation between the pseudo pressure and the pressure of real gas is obtained and then applied to analyze the inflow performance relationship of gas wells. Results show that the expression of the gas seepage-diffusion equation can be simplified by introducing generalized pseudo pressure coefficients to describe the permeability characteristics of real gas in pressure-sensitive reservoir. Then a method to calculate the pseudo pressure for real gas is proposed, which makes the calculation of more rapid and accurate. It lays a solid foundation for analyzing gas-well inflow performance relationship and is very important in improving stimulated precision of pressure-sensitive reservoir.

Key words: pressure-sensitive reservoir; generalized pseudo pressure function; inflow performance relationship; deliverability equation

YANG Yong-zhi, China University of Petroleum, Changping 102249, Beijing, China

Application of dual completion technology to improve development effect of bottom-water reservoir WU Zeng-gui, ZHANG Huijun, ZHANG Yitang ODPT, 2007, 29 (1): 103-106

Abstract: Dual completion technology means producing oil and water in the same oil well, with the aim to eliminate bottom water coning and accelerate the process of developing bottom-water reservoir. This paper thoroughly discusses the principle, critical parameters design, theoretical and experimental research methods, and field application results of the dual completion technology. Two sets of production system are installed in oil zone and water zone separately and separated by a conventional packer, with the oil flowing to surface through tubing/casing annulus and the water flowing to surface through tubes. Oil production rate and ultimate recovery will be improved remarkably if the two different completion zones are optimized and controlled reasonably. The dual completion technology has been applied in oil field, showing that it can not only be used for effective development of new wells but is also capable of restoring abandoned wells caused by water flooding. If operation parameters are controlled effectively, produced water-free oil can be piped to oil tanks directly and oil-free water can be discharged directly or re-injected into formation after simple processing, which brings good economic results and is beneficial to environmental protection.

Key words: dual completion; downhole discharging water; bottom water coning; selective production system of oil and water

WU Zeng-gui^{1, 2}, 1. PetroChina Research Institute of Petroleum Exploitation and Development, Beijing 100083, China; 2. China University of Petroleum, Dongying 257061, Shandong, China

Field application of gas power casing patch technology MEN Yan-ping ODPT, 2007, 29 (1): 107-108

Abstract: As of leakage casing, a new casing patch method-gas power casing patch technology- is developed. The high-temperature and high-pressure gas energy produced from energetic materials works as the power source to propel the relative motion of pistons and piston cylinders. Then the taper sleeves at two ends of the reinforced tubes are kept in relative motion. The process makes metal anchors and metal sealing rings be firmly set on the internal wall of the casing through radial expansion. Finally the reinforced tubes are fixed on the casing deformation and make it be well repaired. This new technology has the following advantages of simple operation and good technical performance as compared to the conventional bellows extension casing technology and the water power casing patch technology. The field application in Yanchang Oilfield shows that the anchorage force of gas power patched casing is more than 800 kN and its pressure