低渗透油藏启动压力梯度的应力敏感性实验研究

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摘要:低渗透油藏由于天然能量不足、岩性致密和压力传导能力差,导致开发过程中地层压力下降幅度较大。地层压力的下降会造成岩石变形而影响其物性和渗流能力,岩石表现出应力敏感性特征。借助室内岩心流动实验,模拟再现地层压力的下降过程,研究了低渗透油藏有效上覆压力对岩石启动压力梯度的影响。结果表明,当地层压力下降时,启动压力梯度随着岩石骨架承受的有效上覆压力的增加而增加,即启动压力梯度具有应力敏感性;且岩石的渗透率越低,当地层压力下降幅度相同时,启动压力梯度的增幅越大,即启动压力梯度的应力敏感程度越强。因此,在根据启动压力梯度计算低渗透油藏合理井距时,要充分考虑地层压力保持水平对启动压力梯度的影响。

关键词:低渗透 启动压力梯度 应力敏感性 有效上覆压力 孔喉
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室内岩心分析和油田现场监测资料均表明[1-2],在油藏开采过程中,地层压力的变化会导致岩石的力学和物性等参数发生相应的变化,从而影响岩石的单相及多相渗流特征,油藏参数随着地层压力的变化而变化的特性就是油藏参数的应力敏感性。前人研究成果表明[3-13],低渗透油藏具有岩性致密、粘土矿物含量高、孔喉细小及压力传导能力差等特点,其渗透率和孔隙度具有应力敏感性,低渗透油藏渗流还普遍存在启动压力梯度,并且启动压力梯度与岩石的渗透率密切相关。为此,笔者选择胜利油区滨 425 井作为研究对象,进行低渗透油藏启动压力梯度应力敏感性的室内实验研究。

1 实验器材及实验步骤

实验岩心 从取自滨 425 井的全直径岩心上水平钻取直径为 2.5 mm、长径比大于等于 2 的柱塞状岩心,分别采用体积比为 1∶3 的酒精苯和甲醇利用索氏抽提法去除岩心中的油和盐,在 85 ℃下烘干后置于干燥器中待用。岩心的长度、直径、物性和粘土含量等基础参数见表 1。

实验用水 根据滨 425 井的地层水分析资料,配制与地层水矿化度(170 g/L)相当的 KCl 溶液作为实验用水,保证实验过程中岩心不会发生水敏。

表 1 实验岩心基础参数

岩心编号	长度/cm	直径/cm	孔隙度,%	空气渗透率/$10^{-3}\mu m^2$	粘土含量,%
1	5.87	2.52	13.87	1.56	11.0
2	6.24	2.52	16.75	4.01	10.0
3	5.02	2.50	18.79	9.52	11.0
4	6.41	2.52	19.16	16.1	9.0
5	5.15	2.50	21.72	25.9	9.0
6	5.52	2.50	23.04	43.5	11.0

实验用油 实验用油为粘度与滨 425 井原油相当的机械油,其 23 ℃时的为 8.06 mPa·s。

实验仪器 实验仪器主要由动力系统(ISCO 泵)、压力采集系统(差压传感器)、出口计量系统(电子天平)、岩心夹持器及高压容器组成。

实验条件 由于启动压力梯度几乎不受温度影响,实验在室温下进行,但考虑到实验流体粘度受温度影响较大,因此实验过程中保持室内温度恒定在 23 ℃。根据滨 425 井的平均岩石密度(2.3 g/cm^3)和取样深度(2 600 m),计算得到岩石的上覆压力为 59 MPa,试油资料表明,该井的原始地层压力为 32 MPa,因此在未投入开发前岩石骨架承受的有效上覆压力为上覆压力与原始地层压力之差,即 27 MPa,随着地层压力的下降,有效上覆压力上升,若

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地层压力下降 50% 时，有效上覆压力增至 43 MPa，故有效上覆压力定为 27 ~ 43 MPa。

实验步骤　实验步骤包括：①设定岩心承受的初始净围压为 27 MPa，通过油驱水建立束缚水饱和度，研究束缚水条件下单相油渗流时的启动压力梯度应力敏感性；②依次设定 ISCO 泵的流量为 0.002，0.005，0.01，0.02 和 0.05 mL/min，确定每个流量下流动稳定时对应的驱替压力，建立驱替压力梯度与渗流曲线，即低速非达西渗流曲线，获得有效上覆压力为 27 MPa 时的启动压力梯度；③根据选择的有效上覆压力变化区间，依次将净围压增至 31，35，39 和 43 MPa，重复步骤②，建立 4 种不同有效上覆压力下的低速非达西渗流曲线，获得相应压力下的启动压力梯度；④对于每块岩心，都通过稳定流法获得 5 个不同有效上覆压力下的启动压力梯度，分析启动压力梯度随有效上覆压力的变化规律，研究启动压力梯度的应力敏感性；⑤根据渗透率级别对岩心进行归类，研究不同渗透率级别岩心启动压力梯度的应力敏感性；⑥借助压汞和核磁共振等测试手段，分析有效上覆压力变化对样品孔喉结构的影响，研究启动压力梯度应力敏感性的作用机理。

2　实验结果分析

2.1　驱替压力梯度的应力敏感性

2.1.1　有效上覆压力对驱替压力梯度的影响

由图 1 可以看出，在相同的渗流速度下，岩心承受的有效上覆压力越大，渗流所需的驱替压力梯度也越大，即驱替压力梯度具有应力敏感性。岩心在不同有效上覆压力下的压汞测试表明，随着有效上覆压力的增加，岩石骨架颗粒会发生变形，使得孔喉缩小，部分孔喉甚至闭合，从而增大了渗流阻力和驱替压力梯度，表现为非达西渗流曲线的位置整体向上偏移。

2.1.2　渗流速度对驱替压力梯度应力敏感性的影响

分析图 1 发现，渗流速度越大，有效上覆压力增加导致的驱替压力梯度增幅也越来越大。原因在于：当驱替压力梯度较低时，岩心中参与渗流的主要为大孔喉，随着驱替压力梯度的增加，渗流速度也不断增大，岩心中参与渗流的小孔喉也越来越多。岩心在不同有效上覆压力下的压汞测试表明，随着有效上覆压力的增加，小孔喉更容易发生缩小、闭合，因此，随着渗流速度的增大，有效上覆压力增加导致的渗流阻力增幅也越来越大，造成驱替压力梯度的增幅也越来越大，表现为不同有效上覆压力下的非达西渗流曲线之间的间隔也越来越大。

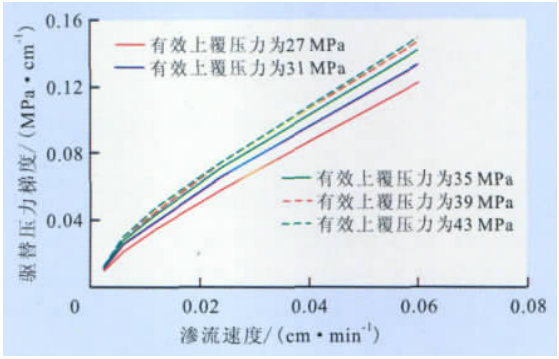

图 1　不同有效上覆压力下岩心的非达西渗流曲线

2.2　启动压力梯度的应力敏感性

2.2.1　有效上覆压力对启动压力梯度的影响

由图 2 可见，6 块不同渗透率的岩心均呈现有效上覆压力增加启动压力梯度增大的趋势。压汞资料表明，增加有效上覆压力，使得岩石的孔喉变形缩小，增大了渗流边界层在渗流通道中所占的比例，从而增加了流体在孔喉中的渗流阻力，导致渗流所需的启动压力梯度增大。

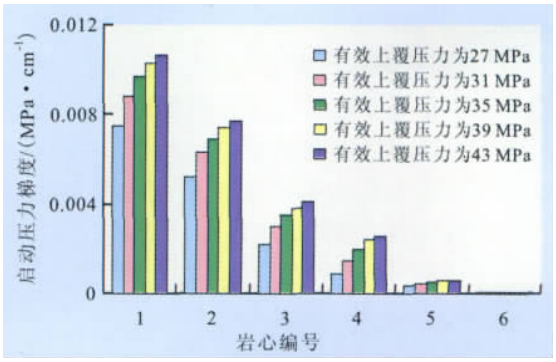

图 2　不同有效上覆压力下的启动压力梯度

2.2.2　渗透率对启动压力梯度应力敏感性的影响

分析图 2 发现，当有效上覆压力由 27 MPa 增至 43 MPa 时，1—6 号岩心的启动压力梯度分别增加了 3.2×10^{-3}，2.5×10^{-3}，1.9×10^{-3}，1.7×10^{-3}，2.0×10^{-4} 和 2.6×10^{-5} MPa/cm，表明岩心渗透率越低，有效上覆压力增加对启动压力梯度的影响越大。不同渗透率岩心的核磁共振测试表明，岩心的空气渗透率越低，小孔喉所占比例越高，且渗流空间主要为小孔喉所控制。岩心在不同有效上覆压力下的压汞测试也进一步表明，随着有效上覆压力的增加，小孔喉更容易发生缩小、闭合，造成启动压力梯度的应力敏感性更强。

2.3　渗透率对启动压力梯度的影响

由启动压力梯度与空气渗透率的关系(图 3)可见,在相同的有效上覆压力下,岩石的启动压力梯度随着空气渗透率的增大而减小。不同渗透率岩心的压汞及核磁共振测试表明,随着岩心渗透率的增大,孔喉平均半径也逐渐增大,导致孔喉渗流阻力减小,流体在孔隙中流动所需的最小驱动压力梯度减小,启动压力梯度下降。启动压力梯度与空气渗透率的关系可用指数函数来表征。当空气渗透率小于 25×10^{-3} μm^2时,曲线较陡,表明随着渗透率的增加,启动压力梯度快速下降;当空气渗透率大于 25×10^{-3} μm^2时,随着渗透率的增加,启动压力梯度变化幅度很小。因此,当空气渗透率大于 25×10^{-3} μm^2,可忽略渗透率对启动压力梯度的影响。

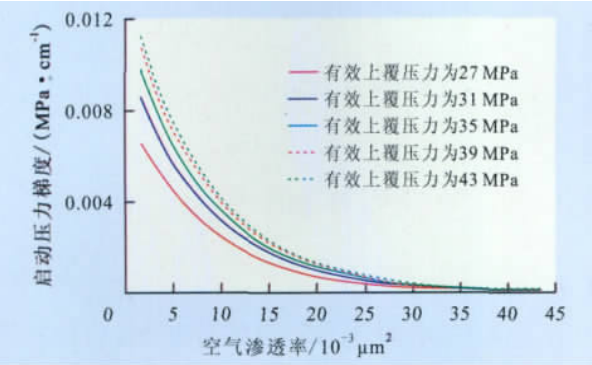

图 3　启动压力梯度与空气渗透率的关系

3　结束语

低渗透油藏的启动压力梯度具有应力敏感性,地层压力下降会导致岩石的孔喉变形闭合,平均孔喉半径减小,这是造成渗透率下降和渗流启动压力梯度增加的根本原因。岩石的渗透率决定启动压力梯度应力敏感性的强弱,渗透率越低,岩石中小孔喉所占比例越高,应力敏感性越强,地层压力下降导致的启动压力梯度增加幅度越大。因此,在根据启动压力梯度计算低渗透油藏、特别是特低渗透油藏合理井距时,要充分考虑地层压力下降对启动压力梯度的影响。

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application technology, the horizontal well has little production without fracturing. The flow rates of the fractured horizontal well with open hole completion are only more than that of perforation completion at the initial time. The gas production rises with the increasing number of fractures, and the flow rate in each fracture is approximately equal at the unsteady state. But, for the quasi-steady state, there is a "U" shape gas output distribution of fractures due to the interferences from fractures and wellbore. Taking the production technology and economic factors into consideration, the fractured horizontal wells with perforation completion should be more suitable for the tight gas reservoir. The interferences from fractures have to be paid enough attention in fracturing design, so, there should be longer fractures at both ends of horizontal wellbore.

Key words: tight gas reservoir; fractured horizontal well; unsteady state; quasi-steady state; fractures; completion methods

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Yang Xiaopei. Development techiniques of horiontal wells on heavy oil reservoir, Henan oilfield. *PGRE*, 2012, 19(2): 72-74.

Abstract: The development of steam stimulation in vertical wells has acquired preferable effects in the host area of Henan heavy oil reserves. But the technique of conventional vertical well, in thin layer of the heavy oil reserves with poor reserves abundance and banded edge water heavy oil distribution, has low single well recoverable reserves, and it is difficult to obtain economic benefits. In order to develop the reserves mentioned above, we consider the geologic characters of Henan heavy oil reserves and use numerical stimulation to carry out the research in horizontal well, and then optimize the deployment and production parameters of horizontal well in Henan heavy oil reserves. The results show that: the vertical depth of horizontal intended interval should be greater than 150 m; the best horizontal length is 80-150 m, and the oil production and oil-gas ratio have no increment; when the horizontal well away from oil-water boundary farther than 60 m, edge water invasion rarely occurs; when the horizontal well is greater than 20 m away from the fault, the fault will not open; when the dryness fraction of steam at bottom of the well is greater than 50%, the development effect has been significantly improved; when the first circle steam injection is 20 t/m, oil-water ratio and cyclical oil production have a high value, 0.54 t/t and 1 000 t, the effect of huff and puff is better; when steam inject speed is 300 t/d, the optimized injection pressure is about 14 MPa, and the rate of delivery at about 20 t/d is reasonable.

Key words: heavy oil reservoir; thin and shallow beds; edge water; horizontal well; injection-production parameter; Henan oilfield

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Wang Peixi, Liu Renjing. Universal model of stress sensitive coefficient for low permeability reservoir. *PGRE*, 2012, 19(2): 75-77.

Abstract: The study on stress sensitivity in low permeability reservoir has attracted more and more attentions of researchers home and abroad, but, there is so far no common understanding on it. To describe the stress sensitivity of low permeability more accurately, the relationship between permeability and effective pressure and its effect factors are studied by laboratory experiments with variable fluid pressures, while keeping confining pressure steady. On this base, a stress sensitive coefficient is presented according to the definition method of rock compressibility, and combined with fractal theory, a universal model of stress sensitive coefficient is built after taking into account of the effect of pore structure, effective stress and hysteresis effect. The results show that the permeability decreases in step shape with the rise of effective stress, and it is related to pore structure and effective stress loading way. The stress sensitive coefficient of permeability can characterize the rock sensitivity quantitatively: the larger the value, the stronger the stress sensitivity. The model built in this paper, taking into account of the effect of pore structure, the effective stress changes and hysteresis effect, can characterize the stress sensitivity in general, and it can forecast the permeability change laws with the change of effective stress, so, it has a wide adaptability. This result has important significance to the further study of stress sensitivity in low permeability reservoir.

Key words: low permeability reservoir; stress sensitivity; pore structure; universal model; hysteresis effect

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Wang Yong, Wu Xiaodong, Han Guoqing et al. Numerical simulation study on horizontal well in foamy oil reservoir. *PGRE*, 2012, 19(2): 78-80.

Abstract: Foamy oil is a kind of heavy oil containing dispersed little gas bubbles, showing different characteristics from conventional oil flow during natural depletion, and its oil production is high, gas oil ratio is low, and formation pressure declines slowly and recovery is high. The technique for simulating foamy oil using numerical simulation is proposed, and the model of foamy oil is established based on the laboratory study. The result comparison between the foamy oil and dissolved gas drive reservoir proves the reliability of the model qualitatively and quantitatively. An in-depth study of drive mechanism of foamy oil is carried out. The dispersed gas generated from the production of the foamy oil reservoir increases the flow capacity of crude oil, and also increases the expandability of the system, and ameliorates the draw down of the reservoir pressure, therefore, enhancing the elastic recovery.

Key words: foamy oil; cold heavy oil production; numerical simulation; component model; relative permeability

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Liu Li. Laboratory study on stress sensitivity of threshold pressure gradient in low permeability reservoir. *PGRE*, 2012,

19(2):81-83.

Abstract: Inadequate natural energy and poor transmission of pressure will give rise to deep pressure decline after putting into development in low permeable reservoir. Pressure decline will induce damages to rock physical properties and flowing character, i. e. reservoir rock presents stress sensitivity. Simulating changing process of reservoir pressure by flowing test, threshold pressure gradients at different effective overburden pressures are tested, and relationship between threshold pressure gradients and effective overburden pressures is studied. With mercury-injection test, nuclear magnetic resonance spectrometry analysis and rock mechanics test, changing mechanism for threshold pressure gradients in changing process of reservoir pressure is thoroughly analyzed. It was understood that, the threshold pressure gradients increases with reservoir pressure declines, i. e. threshold pressure gradients is sensitive to stress. It is also indicated that the lower the rock permeability, the bigger the increasing amplitude of threshold pressure gradients, which means that the stress sensitivity is stronger. It is suggested that, when calculating rational spacing between wells, it is necessary to consider the effect of reservoir pressure maintenance level on threshold pressure gradients.

Key words: low permeability; threshold pressure gradient; stress sensitivity; net overlying pressure; pore throat

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Zhang Xing, Yang Shenglai, Zhang Ling et al. Experimental study on factors of KlinKenberg permeability in low permeable gas reservoir. *PGRE*, 2012, 19(2): 84-86.

Abstract: CNPC found a low-permeability gas reservoir with CO_2 in Jilin oil fields. Because the rock properties and fluid properties are unique, it is not accurate to analysis the effects of gas slippage effect on KlinKenberg permeability and penetration capacity. In view of this specificity, they are determined and analyzed by single-phase gas flow laboratory experiments. Experimental studies show that the KlinKenberg effect is found in the gas flow process in core and the influence factors are important including the core type, confining pressure, gas type and temperature. The KlinKenberg permeability of porosity core is higher than that of micro-fracture core. With the increasing of confining pressure, the slop of permeability-mean pressure curve is not changed, but the KlinKenberg permeability and its amplitude are decreased. Because of the different molecular weights, the KlinKenberg permeability of carbon dioxide (big molecular weight) is higher than that of natural gas and nitrogen gas (small molecular weight). The influence of temperature on gas flow at low temperature is greater than that at high temperature, that is, the KlinKenberg permeability of 20 ℃ is higher than that of 50, 80 and 140 ℃.

Key words: low-permeability gas reservoir; KlinKenberg permeability; gas slippage effect; influence factor; KlinKenberg effect

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Li Lianjiang. Study on drainage gas pattern for offshore gas wells, Chengdao oilfield. *PGRE*, 2012, 19(2): 87-89.

Abstract: After the condensate gas wells have been flooded, the choice of drainage gas recovery plan must be considered with the specific production environmental restrictions. In the paper, according to different stages conditions of the liquid production and gas production in a condensate gas well, the approximate drainage gas process pattern for offshore gas wells is studied by the wellbore temperature and pressure drop models. And, an effective feasible and economic drainage gas technology, the electric pump drainage gas recovery scheme, is put forward. Through the implementation of drainage gas recovery scheme, the natural gas output of the well is improved. The drainage gas schemes adopted by the gas well at different production stage can also be referenced for other gas wells nearby.

Key words: condensate gas wells; pressure drop model′ temperature drop model; water-out gas production technique; Chengdao oilfield

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Zhuang Li, Zhang Ling. Growth trend study of proved oil and gas reserves based on the upgrade rate of probable reserves. *PGRE*, 2012, 19(2): 90-92.

Abstract: Oil and gas reserves growth trend prediction research is the key factor for the oil company to make exploration and development strategy. From the study of contribution of probable reserves to the increased proved reserves of one oil company for ten years, it shows a steady rate at about 50% in the last three years. Upgrade rate of probable reserves can be classified into yearly increased and accumulative probable reserves upgrade rate. Research shows that the accumulative probable reserves upgrade rate has more significant meaning for the prediction of the growth of incased proven reserves next year. Considering the quality of increased probable reserves is very close in the recent years, based on the relationship of increased proved reserves with the accumulative probable reserves, a formula is summarized for the prediction of increased proved reserves, with convincing results tested with actual data. This method can be used by the exploration and development decision-making departments.

Key words: controlled reserve; proved reserve; contribution of controlled reserve; upgrading of controlled reserve; reserve prediction

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Wang Shuhua, Wei Ping. SEC reserves dynamic evaluation and analysis. *PGRE*, 2012, 119(2): 93-94.

Abstract: Since Sinopec′s public offering in New York and London in 1999, there are great challenges to bring domestic reserves management more in line with international practice, SEC methods and concepts of oil and gas reserves evaluation are having great shock on the domestic reserves calculation and management. Based on our decade years′ experiences in domestic reserves calculation, examination and SEC reserves evaluation, this paper analyzes 5 methods in SEC reserves evaluation: analogy, volume, production decline, material balance and reservoir modeling methods; herein, we present the object, basis, scope and conditions in