低渗透油藏应力敏感实验数据处理方法对比

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摘要：低渗透油藏存在应力敏感现象，对17块低渗透岩心参照行业标准进行了应力敏感性实验，并对实验结果分别采用达西渗流规律公式和幂律渗流规律公式进行处理。由8块岩心实验数据获得流量与压力梯度的关系，回归得出幂律渗流规律公式中的参数。2种处理方法的实验结果表明：净围压越大，渗透率降低幅度越小；利用2种渗流规律处理方法得到的渗透率降低幅度相差不大；幂律渗流规律方法处理得到的渗透率为达西渗流规律方法处理的3.9倍；对于低渗透岩心实验数据，应该采用幂律渗流规律来处理。

关键词：低渗透油藏 应力敏感 达西定律 幂律渗流规律 压力梯度
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低渗透油藏存在应力敏感性[1－3]，许多石油工作者对其做了大量的实验研究[4－8]，也得到了很多经典公式和结论[7,9－12]。但低渗透油藏应力敏感性实验数据的处理还是基于达西定律，显然是不正确的。因为达西定律只适合中高渗透油藏，对于低渗透油藏，由于其独特的渗流规律[13－15]，即在低速段其渗流过程为曲线，不能用达西定律来表达其渗流过程，应该用幂律渗流规律来描述[16－17]。笔者通过对低渗透岩心进行应力敏感性实验，对实验数据分别采用达西渗流规律和幂律渗流规律2种方法进行处理，并对2种方法计算的渗透率进行了对比分析。

1 实验流程

参照储层敏感性流动实验评价方法[18]进行应力敏感性实验。采用改变围压的方式来模拟有效应力变化对岩心物性参数的影响。采用氮气作为流体，对某低渗透油田实取的9块岩心开展实验。

实验流程包括：①将制备好的岩心用游标卡尺测量长度和直径，并计算横截面积；②测定损害前的气体渗透率；③保持进口压力不变，缓慢增加围压，使净围压依次为3.5，5，7，9，11，15和20 MPa，每一个压力点稳定后，测定岩样渗透率；④缓慢减小围压，使净围压依次为20，15，11，9，7，5和3.5 MPa，每一个压力点稳定后，持续1 h，再测定岩样渗透率。

2 实验数据处理

2.1 利用达西渗流规律处理实验数据

实验用氮气作为通过岩心的介质，考虑气体在系统中要发生等温膨胀，即当压力从进口压力变化到出口压力时，气体的体积和流速都在变化，因此，流量应使用平均体积流量，可得渗透率计算公式为

$$K_{g1} = \frac{0.1\bar{Q}\mu L}{A(p_1 - p_2)} \tag{1}$$

式中：K_{g1}为利用达西渗流规律处理得到的渗透率，μm²；$\bar{Q}$为平均体积流量，cm³/s；μ为实验室温度和大气压力下通过岩心的氮气粘度，mPa·s；L为岩心长度，cm；A为岩心横截面积，cm²；p_1为进口压力，MPa；p_2为出口压力，MPa。

根据等温条件的理想气体状态方程可得

$$\bar{Q} = \frac{2Q_{sc}p_{sc}}{p_1 + p_2} \tag{2}$$

式中：Q_{sc}为气体体积流量，cm³/s；p_{sc}为标准大气压力，MPa。

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将式(2)代入式(1)并考虑量纲，得

$$K_{g1} = \frac{0.2Q_{sc}p_{sc}\mu L}{A(p_1^2 - p_2^2)} \tag{3}$$

在当前的实验中都采用式(3)来求取岩心渗透率。

2.2 利用幂律渗流规律处理实验数据

由于低渗透储层孔隙细小，其渗流规律不符合达西定律，而符合幂律渗流规律[16-17]，因此，考虑对实验数据进行非达西处理。流量的计算式为

$$Q = 0.1K\frac{A}{\mu}\left(\frac{\Delta p}{\Delta x}\right)^b \tag{4}$$

式中：Q 为流量，cm^3/s；K 为渗透率，μm^2；$\frac{\Delta p}{\Delta x}$为通过实验岩心的压力梯度，MPa/cm，相当于$(p_1-p_2)/L$；$b$ 为常数。

式(4)中 b 的取值方法为：取 8 块岩心，保持围压不变测量流量与压力梯度，并拟合回归曲线(图 1)，得出流量与压力梯度的关系，与式(4)相对比得出系数，从而得出完整的式(4)。拟合得到 b 值为 1.620 66。

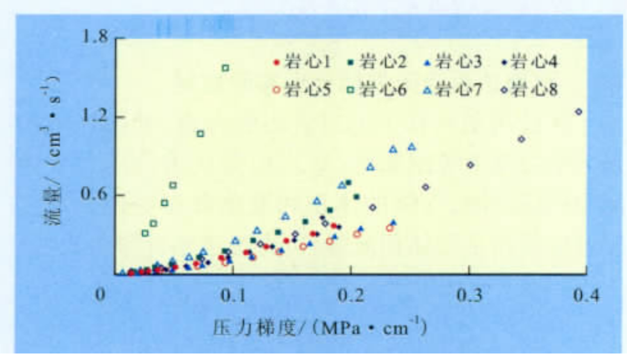

图 1　岩心 1—岩心 8 流量与压力梯度的关系

同时考虑气体通过岩心介质时，气体在系统中将发生等温膨胀，因此使用平均体积流量代入式(4)，则气体渗透率计算公式为

$$K_{g2} = \frac{0.1\bar{Q}\mu}{A\left(\frac{\Delta p}{\Delta x}\right)^{1.62066}} \tag{5}$$

式中：K_{g2}为利用幂律渗流规律处理得到的渗透率，μm^2。

将式(2)代入式(5)得

$$K_{g2} = \frac{0.2Q_{sc}p_{sc}\mu}{A(p_1+p_2)\left(\frac{\Delta p}{\Delta x}\right)^{1.62066}} \tag{6}$$

3 实验结果分析

由图 2—图 7 可以看出：①根据达西渗流规律处理的渗透率实验结果，当净围压从 3.5 MPa 升高到 15 MPa 时，渗透率降低幅度最大值为 82.46%，最小值为 34.55%，平均降低幅度为 54.02%；净围压从 15 MPa 升高到 20 MPa，渗透率降低幅度与初始阶段的降低幅度相比较小，平均为 14.01%；同时，由于岩心 190，79 和 104 的初始渗透率极小，只要渗透率稍微变小，就会产生非常大的应力敏感性，净围压由 3.5 MPa 升高到 20 MPa 时，其渗透率平均降低幅度为 84.97%。②根据幂律渗流规律处理的渗透率实验结果，当净围压从3.5 MPa升高到15 MPa

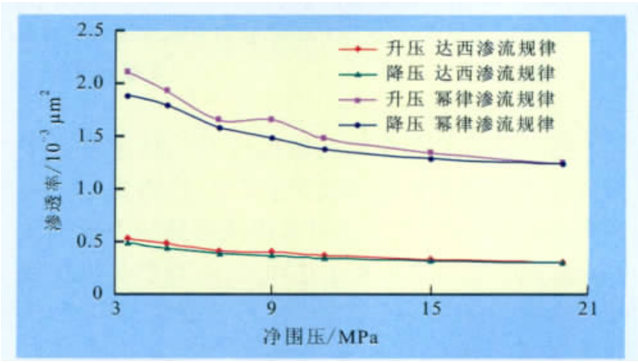

图 2　岩心 103 净围压与渗透率的关系

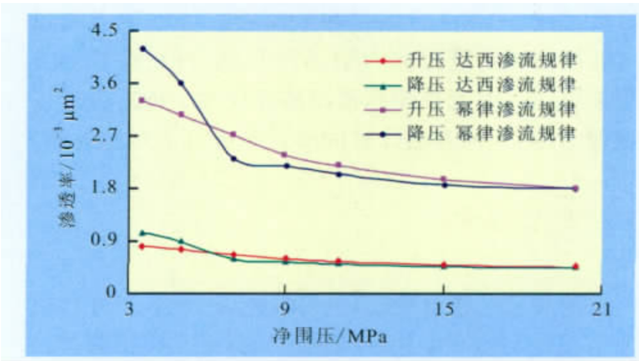

图 3　岩心 48 净围压与渗透率的关系

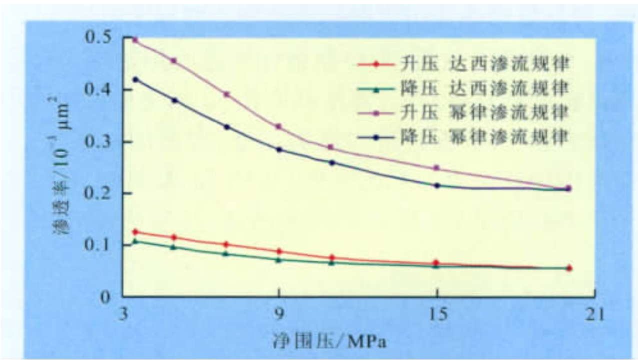

图 4　岩心 149 净围压与渗透率的关系

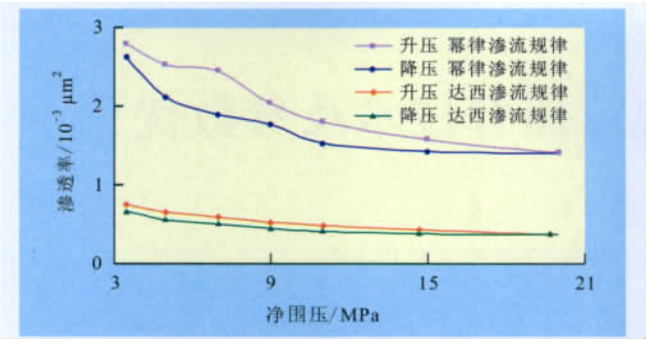

图 5　岩心 176 净围压与渗透率的关系

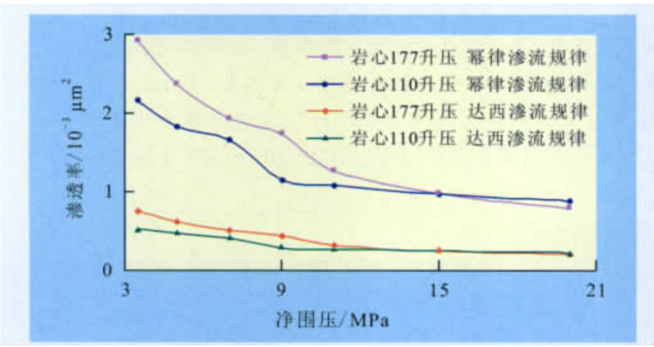

图 6　岩心 177 和 110 净围压与渗透率的关系

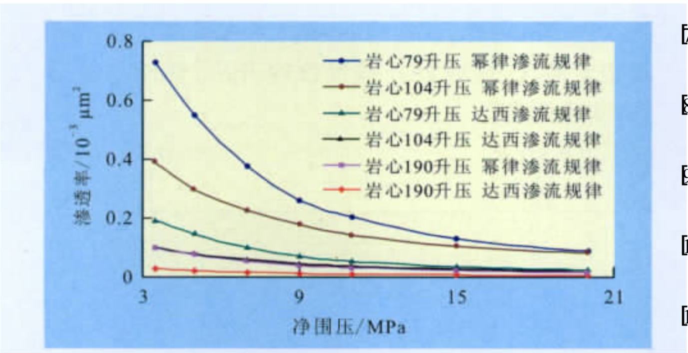

图 7　岩心 190,79 和 104 净围压与渗透率的关系

时,渗透率降低幅度最大值为 82.49%,最小值为 31.57%,平均降低幅度为 54.47%; 净围压从 15 MPa 升高到 20 MPa,渗透率降低幅度与初始阶段的降低幅度相比也较小,平均为 13.42%; 初始渗透率小的岩心,渗透率平均降低幅度为 84.73%。

对比幂律渗流规律与达西渗流规律处理的渗透率实验结果可知,前者处理得到的渗透率是后者的 3.9 倍,结果差异比较明显。

4　结论

针对低渗透油藏的渗流特点和应力敏感性特征,进行了低渗透油藏应力敏感性实验,并且用达西渗流和幂律渗流 2 种不同渗流规律方法来处理实验数据。由岩心实验的流量与压力梯度的关系可以得出幂律渗流规律处理方法公式的未知参数; 渗透率随着净围压的增大而变小,用达西渗流规律和幂律渗流规律计算的渗透率降低幅度相差不大; 净围压越大,渗透率降低幅度越小; 幂律渗流规律方法处理得到的渗透率是达西渗流规律方法的 3.9 倍。

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Liu Shun, He Heng, He Yanxiang et al. Data processing correlation on stress sensitivity experiment for low-permeability reservoirs. *PGRE*, 2012,19(4):71-73.

Abstract: Stress sensitivity presents in low-permeability reservoirs. Choose 17 blocks low-permeability cores to stress sensitivity experiment according to SY/T 5358-2010 standard. The Darcy law equation and power-law non-linear percolation equation are adopted to analyze the experimental data. The parameter of power-law non-linear percolation equation is regressed from the relations between rate and stress gradient derived from other 8 blocks experimental cores. The results show that the peripheral pressure numbers are greater and the permeability number reduces less. Also, the conclusion can be achieved that the reduced ratio of permeability number from the two correlated calculated methods is nearly same. But, the permeability number based on power-law percolation method is quadruple to Darcy law method. So, the power-law non-linear percolation equation suggests to be used to data analysis in low-permeability reservoir.

Key words: low-permeability reservoirs; stress sensitivity; Darcy law; power-law non-linear percolation; pressure gradient

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Liu Yongge, Liu Huiqing, Pang Zhanxi et al. Study on nitrogen foam anti-water-cresting by double horizontal wells for bottom water heavy oil reservoir. *PGRE*, 2012,19(4):74-77.

Abstract: By means of numerical simulation, below the producing horizontal well, another horizontal well is placed to put off water cresting. When water cresting reached up to the height of producing horizontal well, we shut in the producing horizontal well and inject nitrogen foam into the horizontal well below. After two days'soaking, the upper horizontal well is opened to produce again. This process can be repeated for many times. The results of numerical simulation show that the development efficiency by double horizontal wells is much better, and the effect of water cresting can be alleviated greatly comparing to injecting nitrogen foam and producing oil only by a single well. The development style, distance away from the bottom water, length, liquid producing rate and the moment of injecting nitrogen foam are optimized by simulation. After optimization, the quantity and amplitude of incremental oil can reach up to 19,000 cubic meters and 48.7% respectively.

Key words: horizontal well; foam; bottom water heavy oil reservoir; water cresting; numerical simulation

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Li Nan, Cheng Linsong, Chen Hongquan et al. Study on water injection in ultra low permeability reservoir. *PGRE*, 2012,19(4):78-80.

Abstract: This article starts from the mechanism of advanced water injection, combining with the numerical simulation and actual production data, it contrasts the pressure profiles between the water injection well and oil well under the different water injection timing, then, optimizes the water injection timing in ultra low permeability reservoirs, and under the optimal water injection timing, it analyzes the effect on transmission of pressure by different ways of advanced water injection. Based on low permeability reservoirs property of start-up pressure gradient, stress the sensitive, thin pore throats, we analyze the effect on the lifting amplitude of oil wells, water wells and reservoir pressure by the different ways of advanced water injection. At the condition of the maximum of spread coefficient and under the rock breakdown pressure, screening and combining different ways of advanced water injection, we found that, it could be able to get the best development performance in ultra low permeable reservoir by anti-step mild water injection. Taking Changqing BMZ oilfield as example, the development effect has been analyzed under different water injection, and we evaluated the development effect of the method of anti-step mild water injection, which has certain directive significance to make the technology policy.

Key words: ultra low permeability reservoir; advanced water injection; stepped injection; mild injection; anti-step mild water injection; pressure profile

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Wang Jian. Study on technical policy limits of layer recombination in edge water fault block reservoir. *PGRE*, 2012,19(4):81-83.

Abstract: Fault block reservoir possesses the characteristics of many oil-bearing strata, serious heterogeneity. In addition, for the layers in the edge water fault block reservoirs, their oily strip width and edge water body multiples are different. The combination of the layers with different oily strip width and edge water body multiples have great impact on the development effect of the development unit. Therefore, in addition to considering the policy limits of permeability differences and oil viscosity differences, such the policy limits as oily strip width differences and edge water body multiples differences should be considered during the layers recombination. In this paper, the effect of the combination of different layers with oily strip width differences and edge water body multiples differences on the reservoir performance is analyzed. And, the policy limits of oily strip width differences and edge water body multiples differences are set up. The research result was applied to the actual fault block reservoir development, and achieved good results.

Key words: edge water reservoir; layer recombination; oil stripe width; water body multiples; policy limits

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