低渗透储层应力敏感系数统一模型

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摘要：低渗透储层应力敏感性的研究虽已引起中外学者的关注，但目前仍未形成统一认识。为了更准确地描述低渗透储层的应力敏感性，通过保持围压不变、改变流体压力的实验方法，研究了低渗透储层渗透率随有效应力的变化规律及其影响因素。在此基础上，按照岩石压缩系数的定义方法，提出了渗透率应力敏感系数的概念，在综合考虑孔隙结构、有效压力及滞后效应等参数的基础上，结合分形理论，建立了应力敏感系数的统一模型。结果表明，渗透率随有效压力的增加呈阶梯状减小，且与孔隙结构及有效应力加压方式有关；渗透率应力敏感系数可以定量表征储层渗透率随有效应力变化的敏感程度，其值越大说明储层敏感性越强；所建模型考虑了岩石内部孔隙结构、外部有效应力变化及滞后效应等多种因素的综合影响，可以全面表征储层的应力敏感性，并预测不同孔隙结构岩石的渗透率随有效应力变化的规律。

关键词：低渗透储层 应力敏感性 孔隙结构 统一模型 滞后效应

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随着低渗透储层开发力度的加大，对低渗透储层的研究也日益加强。大量的研究表明，低渗透储层物性参数受地层应力的影响较大[1－4]，且许多储层物性参数随应力的变化而变化[5－9]，但是由于研究手段的差异，导致了研究结果存在许多不一致，而且目前大部分的流固耦合关系式只考虑了外应力的影响，拟合关系式繁多却没有物理意义，亟待改进。为此，笔者从室内实验出发，采用与实际油藏开发相一致的变流体压力的方法，研究渗透率与有效应力的关系及其影响因素，提出了渗透率应力敏感系数的概念，以实验与理论相结合的方式建立了具有物理意义并有普遍适用性的模型。

1 应力敏感性实验

不同于常规改变围压的方法，实验通过改变回压来控制流体压力，这样更符合油藏实际开发特征。实验流程及实验步骤详见文献[10]。实验岩心取自延长油田，渗透率为 $0.16\times10^{-3}\sim5.2\times10^{-3}$ μm^2，测试温度为 20 ℃，围压为 20 MPa。

应力敏感性实验结果表明，随着有效应力的变化，不同渗透率岩心的渗透率变化规律相同：随着有效压力的不断增加，渗透率不断减小，其减小程度不断减弱；随着有效应力的减弱，其渗透率难以恢复至初始值，说明其初始孔隙结构已发生塑性形变，岩石渗流能力受到破坏。

除外部有效应力之外，孔隙内部结构对应力敏感的影响也很大。在减小相同有效应力的情况下，渗透率越小，渗透率损害系数及永久伤害率越大，即使孔隙度比较接近，对于渗透率更小的岩心，由于其平均喉道更细小，渗透率伤害程度更大。

利用孔隙结构相近的 2 块岩心，研究快速和慢速 2 种不同加压方式下渗透率的变化。结果表明：在岩心的渗透率和孔隙度比较接近的条件下，慢速加压下的渗透率变化值比快速加压时小，这主要是由于有效应力增加速度越快，岩石颗粒变形越严重，对原始孔隙结构破坏越大，从而使岩石渗透率下降更迅速，并且渗透率恢复性也更差。

总之，流体在低渗透储层中流动时，由于应力场的改变，岩石的渗透率将发生显著变化。但这种有效应力敏感性受外部有效应力、内部孔隙结构及加压方式等多种因素影响。

2 渗透率应力敏感系数概念的提出

为了解决目前存在的流固耦合关系式无实际物

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理意义的问题，笔者按照孔隙度压缩系数的定义方法[11]，提出了渗透率应力敏感系数这一概念，它表示有效应力每改变单位压力时，单位渗透率的改变值，其表征了储层渗透率随应力变化的敏感程度，该值越大代表储层敏感性越强，表达式为

$$C_K = -\frac{1}{K_0} \times \frac{\Delta K}{\Delta p} \tag{1}$$

式中：C_K为渗透率应力敏感系数，MPa^{-1}；K_0为岩石初始渗透率，$10^{-3}\ \mu\mathrm{m}^2$；ΔK为渗透率改变值，$10^{-3}\ \mu\mathrm{m}^2$；Δp为有效应力改变值，MPa。

当储层有效应力从p_0变化到p时，其渗透率为

$$K = K_0 \exp\left(-\int_{p_0}^{p} C_K \mathrm{d}p\right) \tag{2}$$

式中：K为目前压力下的渗透率，$10^{-3}\ \mu\mathrm{m}^2$；p_0为原始压力，MPa；p为目前压力，MPa。

因此，对渗透率应力敏感性的研究就转化为对渗透率应力敏感系数的研究。

3 统一模型的建立

3.1 孔隙结构的定量表征

渗透率应力敏感性同时受岩石内部孔隙结构和外部有效应力的影响。孔隙结构是一种不规则的结构，但却具有统计均匀性、自相似的特点，分形理论对于岩石同样适用[12-13]。孔隙分维数常用毛管压力曲线方法确定，计算公式[14]为

$$\sum_{i=1}^{n} p_i \Delta V_i = c r_n^2 \left(\frac{V_n^{\frac{1}{3}}}{r_n}\right)^{D_f} \tag{3}$$

式中：i为进汞次数；n为进汞总次数；p_i为第i次进汞压力，MPa；ΔV_i为第i次进汞量，mL；c为常数；r_n为第n次进汞时所对应的孔隙半径，μm；V_n为总进汞量，mL；D_f为孔隙分维数。

令

$$W_n = \sum_{i=1}^{n} P_i \Delta V_i \tag{4}$$

$$Q_n = \frac{V_n^{\frac{1}{3}}}{r_n} \tag{5}$$

则

$$\ln \frac{W_n}{r_n^2} = C + D_f \ln Q_n \tag{6}$$

式中：C为常数，其值为$\ln c$。

根据延长油田延长组4块岩心的毛管压力曲线，求得孔隙分维数（图1）。由图1可见，孔隙分维数能很好地反映孔隙结构，但如果对每块岩心都进行毛管压力测试，不但工作量特别巨大而且成本非常高。通过对30块实际岩心的孔隙分维数的统计分析发现，孔隙分维数与储层品质系数（$\sqrt{K/\phi}$）具有很好的半对数关系（图2），其关系式为

$$\lg \sqrt{\frac{K}{\phi}} = -4.601\,4 D_f + 12.376\,5 \tag{7}$$

式中：ϕ为孔隙度。

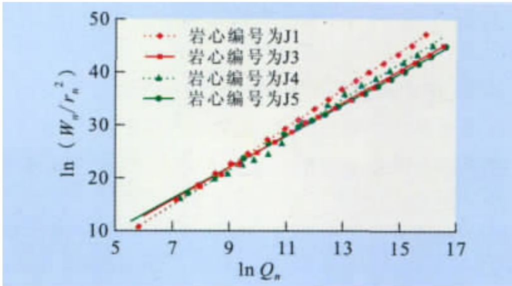

图1 $\ln(W_n/r_n^2)$与$\ln Q_n$的关系

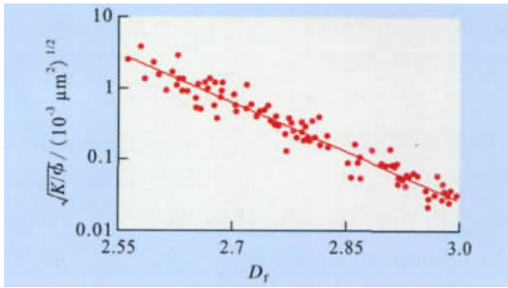

图2 孔隙分维数与储层品质系数的关系

储层品质系数是孔隙分维数的一种外在表现，也可以反映储层的孔隙结构特征，并且这2个参数易于获取，所以在求取渗透率应力敏感系数时，采用储层品质系数来表征孔隙结构的影响。

3.2 统一模型

随着有效压力的增加，由渗透率应力敏感系数随储层品质系数及有效应力的变化关系（图3）可得

$$C_K = a_1 \left(\sqrt{\frac{K_0}{\phi}}\right)^{-b_1} (\Delta p)^{-c_1} \qquad p > p_0 \tag{8}$$

式中：a_1为有效应力增加条件下的综合系数；b_1为有效应力增加条件下孔隙结构的影响系数；c_1为有效应力增加条件下有效应力的影响系数。

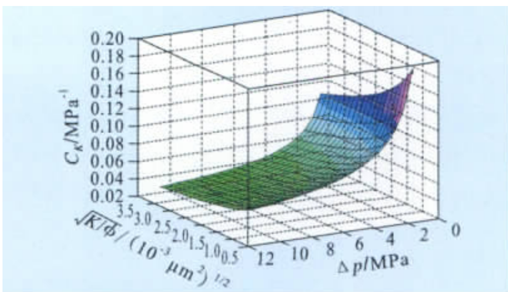

图3 有效压力增加时渗透率应力敏感系数变化

对于此次研究,a_1,b_1和c_1分别为0.162 5,0.365 7和0.519 4。由式(8)可以看出,在有效应力增加的条件下,渗透率应力敏感系数与储层品质系数和有效应力改变值成反比,储层品质越好,应力敏感程度越低,在有效应力改变初期,渗透率对应力变化的敏感性越强,渗透率变化程度越大。

当有效压力减小时,岩石的渗透率也随之增加,但存在滞后效应。由渗透率应力敏感系数变化关系(图4)可得

$$C_K = a_2\left(\sqrt{\frac{K_0}{\phi}}\right)^{-b_2}(\Delta p)^{c_2} \qquad p < p_0 \qquad (9)$$

式中:a_2为有效应力减小条件下的综合系数;b_2为有效应力减小条件下的孔隙结构影响系数;c_2为有效应力减小条件下有效应力的影响系数。

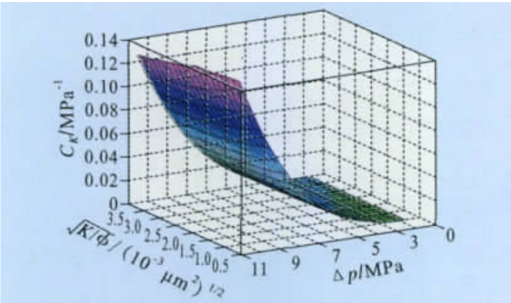

图4　有效压力减小时渗透率应力敏感系数变化

对于此次研究,a_2,b_2和c_2分别为3.935 2,0.152 3和3.486 5。由式(9)可见,在有效应力减小的条件下,渗透率应力敏感系数与储层品质系数成反比,而与有效应力改变值成正比。储层品质越好,应力敏感程度越低,在有效应力减小初期,渗透率的恢复程度较低,而在后期渗透率的恢复程度较大。

因此,式(8)和式(9)即为考虑孔隙结构、有效压力及滞后效应等影响因素的渗透率应力敏感系数的统一模型。

将式(8)和式(9)代入式(2),可得储层渗透率随有效压力的变化关系为

$$K = \begin{cases} K_0\exp\left[-\int_{p_0}^{p} a_1\left(\sqrt{\frac{K_0}{\phi}}\right)^{-b_1}(p-p_0)^{-c_1}\mathrm{d}p\right] & p > p_0 \\ K_0\exp\left[-\int_{p_0}^{p} a_2\left(\sqrt{\frac{K_0}{\phi}}\right)^{-b_2}(p-p_0)^{c_2}\mathrm{d}p\right] & p \leqslant p_0 \end{cases} \qquad (10)$$

4　结论

对于低渗透岩心,渗透率随有效压力增加呈阶梯状减小,存在应力敏感性,喉道越细小,加压越快,应力敏感性越强,而且渗透率存在永久伤害。

渗透率应力敏感系数表示有效应力每改变单位压力时,单位渗透率的改变值,可以定量表征储层渗透率随有效应力变化的敏感程度,其值越大代表储层越敏感。

储层品质系数与孔隙分维数成半对数关系,是孔隙分维数的一种外在表现,也可以反映储层的孔隙结构特征。

所建模型可以反映孔隙结构、有效压力及滞后效应等因素对岩石渗透率的综合影响,全面表征储层的应力敏感性,并预测不同孔隙结构岩石的渗透率随有效应力变化的规律。

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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,