非均质致密砂岩应力敏感性的定量表征

雷 刚[1],王 昊[2],董平川[1],王 彬[1],杨 书[1],吴子森[1],莫邵元[1]
(1.中国石油大学(北京)石油工程教育部重点实验室,北京 102249;
2.中国石化胜利油田分公司 石油工程技术研究院,山东 东营 257000)

摘要:基于渗透率应力敏感实验研究非均质致密砂岩渗透率应力敏感性,根据颗粒Hertz接触变形法则,建立非均质致密砂岩毛管孔隙渗透率应力敏感定量表征模型,对孔隙度、渗透率和渗透率级差随有效应力变化规律进行了量化分析,并将理论计算结果与实验结果进行对比验证,从理论上对实验结果及规律进行了解释。结果表明,非均质致密砂岩的应力敏感性主要表现为渗透率应力敏感性,不同岩石渗透率随有效应力的变化具有不同步性,岩石渗透率越低,渗透率下降速度越快,非均质岩石渗透率下降速度介于岩石高渗透层与低渗透层渗透率下降速度之间;非均质岩石渗透率级差越大,渗透率应力敏感曲线越靠近岩石低渗透层渗透率应力敏感曲线,且渗透率级差随着有效应力的增大而不断增大。

关键词:致密砂岩 非均质性 渗透率 应力敏感 定量表征
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Quantitative analysis on stress sensitivity of heterogeneous tight sandstone

Lei Gang[1], Wang Hao[2], Dong Pingchuan[1], Wang Bin[1], Yang Shu[1], Wu Zisen[1], Mo Shaoyuan[1]
(1.*MOE Key Laboratory of Petroleum Engineering, China University of Petroleum(Beijing), Beijing City*, 102249, *China*; 2.*Research Institute of Petroleum Engineering, Shengli Oilfield Company, SINOPEC, Dongying City, Shandong Province*, 257000, *China*)

Abstract: The stress-dependent permeability in the heterogeneous tight sandstone has been studied based on the experiment of permeability stress sensitivity. Based on Hertz contact deformation principle, a capillary model for heterogeneous tight sandstone was established to characterize the stress sensitivity of capillary and porous media. The variation of porosity, permeability and permeability ratio under different effective stress was quantitatively analyzed. The theoretical calculation results were compared with the experimental ones as validation, and the experimental results were explained in theory. Research results show that the stress sensitivity of the heterogeneous tight sandstone is mainly presented as permeability stress sensitivity. Rock permeability varies with effective stress in different cores. The lower the rock permeability is, the faster the permeability declines. The permeability declining speed of the heterogeneous rock lies between those of the high permeability layer and the low permeability layer. When the permeability ratio increases, the stress-dependent permeability curves of heterogeneous rock are closer to that of the low permeability layer in rock. Heterogeneous tight sandstone permeability ratio becomes larger when effective stress increases.

Key words: tight sandstone; heterogeneity; permeability; stress sensitivity; quantitative analysis

随着低渗透致密储层开发力度的加大,中外学者对低渗透致密储层的研究日益加强,通过大量实验研究了储层物性参数随有效应力的变化关系[1-8]。但由于实验研究方法及岩石物性的差异,导

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作者简介:雷刚(1987—),男,湖北洪湖人,在读博士研究生,从事油气田开发工程方面的研究。联系电话:15011314843,E-mail:leigang5000@126.com。
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致研究成果存在许多不一致[9-11]。有必要建立储层应力敏感定量表征模型,从理论上对实验结果及规律进行解释,以对实验提供理论指导。

目前,中外学者对应力敏感理论模型的研究较少。刘仁静等采用变径毛管束模型,对低渗透储层孔隙度和渗透率随应力变化规律进行了研究[12];王厉强等采用不等径迂曲毛管束模型,根据弹性力学厚壁筒理论,对低渗透油藏应力敏感性进行了分析[13-14];董平川等基于岩石孔隙结构特征和颗粒接触变形理论,对致密砂岩应力敏感性进行了定量分析,并将理论计算结果与实验测试结果进行了对比验证[15];孙军昌等提出了毛管束孔隙网络模型,对致密砂岩应力敏感进行了解释[16],但不能定量分析受压前后岩石物性的变化。

中国大部分储层属于陆相沉积,非均质性强,而致密储层非均质性更强。对于纵向非均质储层,各层渗透率不同,应力敏感性也不同,开发过程中储层非均质性随着有效应力的变化而变化,从而影响开发效果[17]。目前中外学者对于非均质储层应力敏感性研究较少[17-18],非均质储层应力敏感性是否与均质储层规律相同,非均质储层应力敏感性与均质储层应力敏感性差异有多大,非均质储层的非均质性随着有效应力如何变化,这些问题尚待解决。为此,笔者通过渗透率应力敏感实验研究了不同渗透率级差非均质致密砂岩渗透率应力敏感性,并基于颗粒Hertz接触变形法则,建立了应力敏感性理论表征模型,对非均质致密砂岩孔隙度、渗透率和渗透率级差随有效应力变化规律进行了定量表征,从理论上对实验结果及规律进行了解释。

1　应力敏感实验结果

实验选用3组不同渗透率的人造致密砂岩岩心,每组岩心由2块均质岩心和1块非均质岩心组成,非均质岩心的渗透率级差为2块均质岩心渗透率的比值。各组岩样物性参数如表1所示。

按照SY/T 6385—1999[19],分别对各组实验岩心进行不同有效应力下的渗透率应力敏感实验,得到各组岩样渗透率应力敏感曲线。结果(图1)表明:在有效应力增大的过程中,致密砂岩岩心渗透率会产生一定的损失,但损失过程不同步,渗透率较低岩心渗透率下降速度较快,渗透率较高岩心渗透率下降速度较慢,非均质岩心渗透率下降速度介于两者之间;非均质岩心应力敏感性受岩心渗透率级差影响,渗透率级差越大,非均质岩心渗透率应力敏感

表1　岩心基本参数

Table1　Basic parameters of cores

编号	类型	直径/mm	长度/mm	孔隙度,%	渗透率/$10^{-3}\mu m^2$	渗透率级差
1	均质	25.00	43.64	15.68	18.02	185.77
	非均质	25.00	43.64	14.94	9.509	
	均质	25.00	43.64	11.04	0.097	
2	均质	25.22	45.34	14.81	4.631	54.48
	非均质	25.22	45.34	14.07	2.358	
	均质	25.22	45.34	10.87	0.085	
3	均质	25.04	49.45	13.42	1.260	22.91
	非均质	25.04	49.45	12.78	0.658	
	均质	25.04	49.45	10.57	0.055	

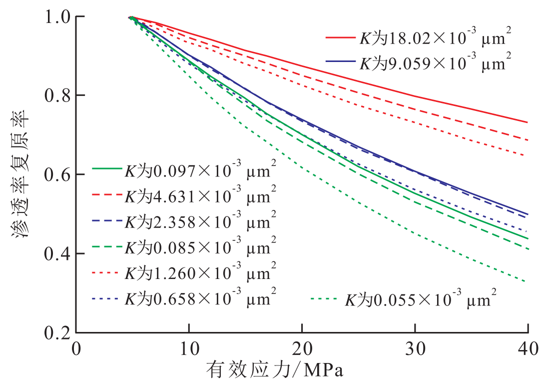

图1　3组不同岩心渗透率应力敏感曲线

Fig.1　Permeability stress sensitivity curves of three groups of cores

曲线越靠近渗透率低的均质岩心渗透率应力敏感曲线。

2　应力敏感性定量表征模型

2.1　模型建立

致密砂岩毛管孔隙由球状岩石颗粒堆积而成,颗粒受到有效应力影响产生变形(图2),变形符合Hertz接触变形法则[20]。

根据Hertz理论,球状岩石颗粒间接触半径为

$$a=\sqrt[3]{\frac{3F}{4}\times\frac{R_1R_2}{R_1+R_2}\times\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)} \tag{1}$$

非均质致密砂岩毛管孔隙由属性不同的颗粒堆积而成,基本堆积单元为4颗粒密堆积。颗粒受到有效应力影响产生变形,从而导致毛管孔隙产生变形(图3)。

颗粒变形前、后毛管孔隙渗流面积分别为

$$S=2\left(R_1+R_2\right)\sqrt{R_1R_2}-R_1^2\arccos\frac{R_1-R_2}{R_1+R_2}-R_2^2\left(\pi-\arccos\frac{R_1-R_2}{R_1+R_2}\right) \tag{2}$$

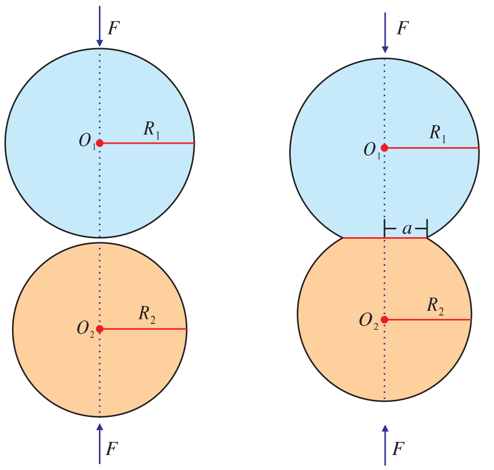

图2 球状岩石颗粒变形前后接触示意

Fig.2 A schematic showing the contact of sphere rock particle before and after deformation

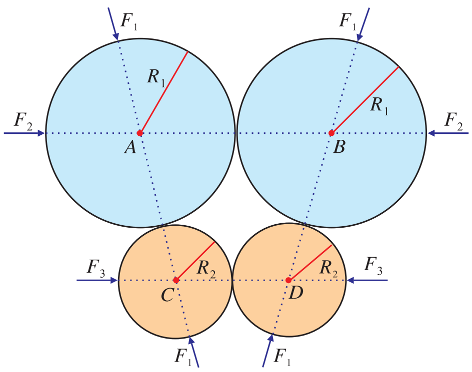

图3 非均质致密砂岩毛管孔隙变形示意

Fig.3 A schematic showing the deformation of the capillary pore in heterogeneous tight sandstone

$$S'=H\left(\sqrt{R_1^2-a_2^2}+\sqrt{R_2^2-a_3^2}\right)-a_1\left(\sqrt{R_1^2-a_1^2}+\sqrt{R_2^2-a_1^2}\right)-a_2\sqrt{R_1^2-a_2^2}-a_3\sqrt{R_2^2-a_3^2}-(\beta-\theta_1)R_1^2-(\pi-\beta-\theta_2)R_2^2 \tag{3}$$

其中

$$a_1=\sqrt[3]{\frac{3F_1}{4}\times\frac{R_1R_2}{R_1+R_2}\times\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)} \tag{4}$$

$$a_2=\sqrt[3]{\frac{3F_2R_1}{4}\times\frac{1-v_1^2}{E_1}} \tag{5}$$

$$a_3=\sqrt[3]{\frac{3F_3R_2}{4}\times\frac{1-v_2^2}{E_2}} \tag{6}$$

$$H=\sqrt{\left(\sqrt{R_1^2-a_1^2}+\sqrt{R_2^2-a_1^2}\right)^2-\left(\sqrt{R_1^2-a_2^2}-\sqrt{R_2^2-a_3^2}\right)^2} \tag{7}$$

$$\theta_1=\arcsin\frac{a_2}{R_1}+\arcsin\frac{a_1}{R_1} \tag{8}$$

$$\theta_2=\arcsin\frac{a_3}{R_2}+\arcsin\frac{a_1}{R_2} \tag{9}$$

$$\beta=\arccos\frac{\sqrt{R_1^2-a_2^2}-\sqrt{R_2^2-a_3^2}}{\sqrt{R_1^2-a_1^2}+\sqrt{R_2^2-a_1^2}} \tag{10}$$

颗粒之间所受应力应满足 $F_1:F_2:F_3=(R_1+R_2):2R_1:2R_2$，毛管孔隙受到的有效应力为

$$\sigma=\frac{1}{\pi}\left(\frac{F_1}{R_1^2-a_1^2}+\frac{F_1}{R_2^2-a_1^2}+\frac{F_2}{R_1^2-a_2^2}+\frac{F_3}{R_2^2-a_3^2}\right)+\sigma_0 \tag{11}$$

毛管孔隙变形后孔隙度复原率和渗透率复原率计算式分别为

$$\frac{\phi'}{\phi}=\left[1-\frac{\sqrt{S(R,\sigma)}-\sqrt{S'(R,\sigma)}}{\sqrt{S(R,\sigma)}}\right]^3=\left[\frac{S'(R,\sigma)}{S(R,\sigma)}\right]^{\frac{3}{2}} \tag{12}$$

$$\frac{K'}{K}=\frac{\phi'S'(R,\sigma)}{\phi S(R,\sigma)}=\left[\frac{S'(R,\sigma)}{S(R,\sigma)}\right]^{\frac{5}{2}} \tag{13}$$

2.2 模型分析

计算参数包括：渗透率较高岩石颗粒粒径为0.25 mm，泊松比为0.20，弹性模量为18.9 GPa；渗透率较低岩石颗粒粒径为0.15 mm，泊松比为0.25，弹性模量为6.04 GPa，储层初始有效应力为5 MPa。根据新建计算模型，采用Matlab编程计算，得到岩石毛管孔隙度及渗透率随有效应力变化曲线。计算结果（图4）表明：①随着有效应力的增大，毛管孔隙度复原率与渗透率复原率不断下降；②不同毛管孔隙度与渗透率的下降程度不同，致密程度较高（渗透率较低）岩石毛管孔隙度复原率和渗透率复原率下降速度较快，致密程度较低（渗透率较高）岩石毛管孔隙度复原率和渗透率复原率下降速度较慢，非均质岩石毛管孔隙度复原率和渗透率复原率下降速度介于两者之间；③渗透率复原率下降的幅度大于孔隙度复原率的降幅，说明岩石渗透率比孔隙度具有更强的应力敏感性。

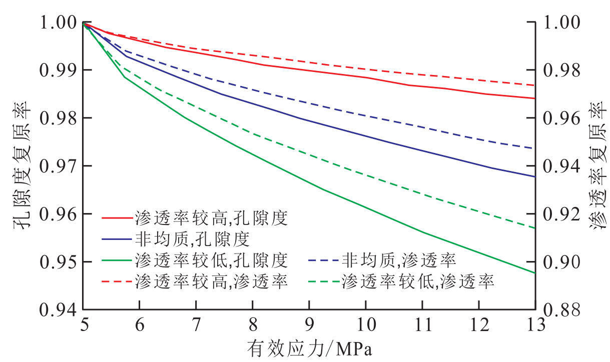

图4 毛管孔隙度复原率、渗透率复原率与有效应力的关系

Fig.4 Relationship between the effective stress and the recovery rates of capillary porosity and permeability

选取5组由不同粒径颗粒堆积而成的毛管孔隙，5组岩石颗粒泊松比均为0.22，弹性模量均为12.9 GPa，每组毛管孔隙由粒径分别为0.25，0.20和0.15 mm的3种均质颗粒与颗粒粒径比值分别为4∶3（0.20 mm∶0.15 mm）和5∶3（0.25 mm∶0.15 mm）的2种混合颗粒堆积组成。根据式(13)，可得到5组毛管渗透率随有效应力变化关系。由图5可看出：当颗粒粒径比值为4∶3时，混合颗粒堆积而成的毛管渗透率应力敏感曲线靠近粗颗粒堆积而成毛管渗透率应力敏感曲线；当有效应力为35 MPa时，颗粒粒径比值为4∶3曲线上点到粒径为0.15 mm曲线上点的距离是粒径为0.15 mm曲线上的点到粒径为0.2 mm曲线上点距离的2/3，而颗粒粒径比值为5∶3曲线上点到粒径为0.15 mm曲线上点的距离是粒径为0.15 mm曲线上点到粒径为0.25 mm曲线上点的距离的1/2，说明随着颗粒粒径比值的增大，混合颗粒堆积而成毛管渗透率应力敏感曲线有向细颗粒堆积而成毛管渗透率应力敏感曲线靠近的趋势。

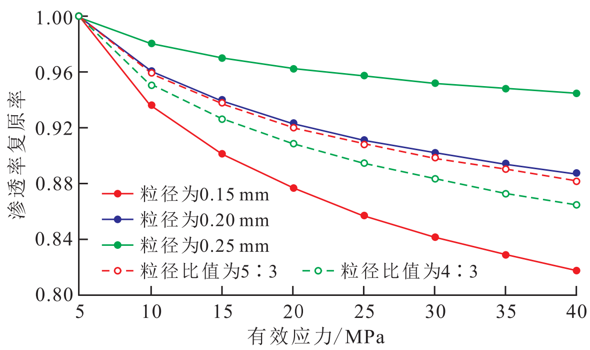

图5　不同颗粒堆积毛管渗透率复原率与有效应力的关系

Fig.5　Relationship between effective stress and permeability of different particles formed capillaries

由于不同渗透率岩石的渗透率随有效应力变化不同步，非均质岩石渗透率级差会随着有效应力的变化而发生变化。由图6可见，随着有效应力的增大，混合颗粒堆积毛管渗透率级差倍数增大，说明随着有效应力的增大，非均质岩石渗透率级差变

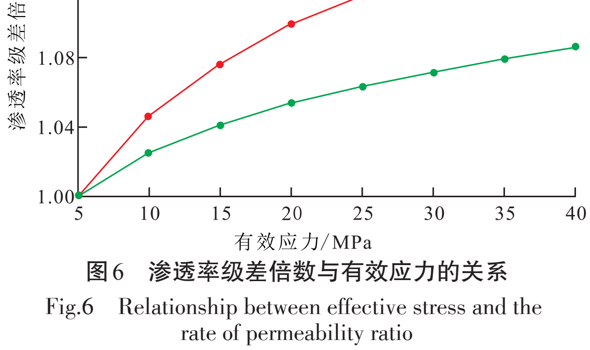

图6　渗透率级差倍数与有效应力的关系

Fig.6　Relationship between effective stress and the rate of permeability ratio

大，非均质岩石非均质性增强。在非均质致密砂岩储层开采过程中，有效应力过度增大会加剧储层非均质性。另外，颗粒粒径比值越大，混合颗粒堆积毛管渗透率级差变化倍数越大，说明相对于非均质性较弱储层，非均质性较强储层受到有效应力影响后，非均质性加剧程度更大。

3　结论

基于颗粒Hertz接触变形法则，对非均质致密砂岩孔隙度、渗透率和渗透率级差随有效应力变化规律进行了定量表征，并对非均质致密砂岩应力敏感性进行了分析。随着有效应力的增大，不同渗透率岩石的渗透率变化具有不同步性，渗透率较低岩石渗透率下降速度较快，渗透率较高岩石渗透率下降速度较慢，非均质岩石渗透率下降速度介于两者之间。非均质岩石渗透率级差越大，岩石渗透率应力敏感曲线越靠近低渗透层渗透率应力敏感曲线。非均质致密砂岩渗透率级差随着有效应力增大而不断增大。因此，有效应力的过度增大，会加剧致密砂岩储层非均质性，且致密砂岩储层非均质性越强，受压后储层非均质性加剧程度越大。

符号解释：

a——球状岩石颗粒间接触半径，mm；F——颗粒上所受应力，N；R_1——渗透率较高岩石颗粒粒径，mm；R_2——渗透率较低岩石颗粒粒径，mm；υ_1——渗透率较高岩石颗粒泊松比；E_1——渗透率较高岩石颗粒弹性模量，GPa；υ_2——渗透率较低岩石颗粒泊松比；E_2——渗透率较低岩石颗粒弹性模量，GPa；S——颗粒变形前毛管孔隙渗流面积，mm²；F_1——颗粒A和颗粒C中轴线上所受应力，N；F_2——颗粒A和颗粒B中轴线上所受应力，N；F_3——颗粒C和颗粒D中轴线上所受应力，N；S'——颗粒变形后毛管孔隙渗流面积，mm²；a_1——颗粒A和颗粒C的接触半径，mm；a_2——颗粒A和颗粒B的接触半径，mm；a_3——颗粒C和颗粒D的接触半径，mm；σ——毛管孔隙所受有效应力，MPa；σ_0——储层初始时刻所受有效应力，MPa；ϕ'——毛管孔隙变形后的孔隙度；ϕ——毛管孔隙变形前的孔隙度；K'——毛管孔隙变形后的渗透率，10^{-3} μm²；K——变形前毛管孔隙初始渗透率，10^{-3} μm²。

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