开采工艺

裂缝性非均质底水油藏含水变化规律研究

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摘　要：针对裂缝性油藏中裂缝发育程度不同、非均质性强的特点，将其储层抽象成渗透率渐变的地质模型，并应用油气渗流理论推导出了部分打开裂缝性非均质底水油藏的水相分流量方程，同时对分流量曲线的影响因素进行了分析。分析表明，该方程可准确描述不同储层条件、不同生产压差下的含水变化规律。该理论的建立为裂缝性非均质底水油藏开发动态分析和预测提供了依据。

关键词：裂缝性油藏；底水油藏；非均质；分流量方程
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我国的大部分碳酸盐岩油田，其流体流动空间以裂缝为主，且油藏内裂缝发育程度不一，非均质性强，有些同时有底水存在。目前适合这种类型油藏的油藏工程方法较为缺乏，国内外的研究多集中在均质底水油藏的临界产量、见水时间方面[1]，而对其含水变化规律的研究相对较少，对含水的预测主要根据水淹厚度来粗略估算[2]、[3]，对裂缝性非均质底水油藏含水变化的理论研究几乎还是空白，远远满足不了现场的要求。

一、裂缝性非均质底水油藏理想地质模型的建立

鉴于裂缝性储层的裂缝发育程度不一、非均质性强的特点，可将其抽象为渗透率渐变的地质模型，以反映油藏内由大缝到小缝的过渡特点。渗透率渐变地层剖面流动示意图如图 1所示，假设油井位于地层中心，打开厚度为 b，油井半径为 R_w，油藏避水高度为 H，井底压力为 P_w，边缘压力为 P_e。假设渗透率沿径向变化系数为 a，则各点渗透率为：

$$K(r) = K + ar \tag{1}$$

其中：K—井点渗透率，μm^2。

该模型适用于裂缝发育程度不同的非均质底水油藏，若油井打在裂缝发育区，则可取 $\alpha > 0$；若油井偏离裂缝发育区，则可取 $\alpha > 0$；若储层裂缝发育相对均匀，则可取 ，即变为均质模型。

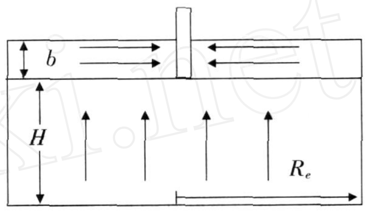

图 1 部分打开的底水油藏剖面流动示意图

二、油藏的产量及其压力分布

由达西定律[4]，油藏顶部径向流在 r处的流量为

$$Q = \frac{K + ar}{\mu} \times 2\pi rb \frac{dP}{dr} \tag{2}$$

对式 (2)分离变量得

$$dP = \frac{Q\mu}{2\pi b} \cdot \frac{dr}{r(K + ar)} = \frac{Q\mu}{2\pi Kb}\left(\frac{1}{r} - \frac{\alpha}{K + \alpha r}\right) dr \tag{3}$$

取积分限 $r = R_w$, $P = P_w$; $r = R_e$, $P = P_e$，故

$$\int_{P_w}^{P_e} dp = \frac{Q\mu}{2\pi Kb}\int_{R_w}^{R_e}\left(\frac{1}{r} - \frac{\alpha}{K + ar}\right) dr \tag{4}$$

完成积分并整理得

$$Q = \frac{2\pi Kb(P_e - P_w)}{\mu\left(\ln\frac{R_e}{R_w} - \ln\frac{K + \alpha R_e}{K}\right)} \tag{5}$$

改变积分限：

$$\int_{P_w}^{P(r)} dp = \frac{Q\mu}{2\pi Kb}\int_{R_w}^{r}\left(\frac{1}{r} - \frac{\alpha}{K + ar}\right) dr \tag{6}$$

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将式 (5)代入式 (6),完成积分得:

$$P(r)=P_w+\frac{P_e-P_w}{\ln\frac{R_e}{R_w}-\ln\frac{K+\alpha R_e}{K}}\left(\ln\frac{r}{R_w}-\ln\frac{K+ar}{K}\right) \tag{7}$$

式 (7)即为沿径向各点的压力公式,由此可得各点的垂向流动压差为

$$\Delta P(r)=P_{owi}-P(r)=P_{owi}-P_w-\frac{P_e-P_w}{\ln\frac{R_e}{R_w}-\ln\frac{K+\alpha R_e}{K}}\times\left(\ln\frac{r}{R_w}-\ln\frac{K+ar}{K}\right) \tag{8}$$

式中: P_{woi}—油水界面处的压力 (假定为定压), 10^{-1} MPa。

三、裂缝性底水油藏的油水运动方程

对于裂缝性油藏而言,毛管力的作用很小,一般可忽略。而对于块状底水油藏,重力的作用则必须加以考虑。在忽略毛管力作用而只考虑重力作用时两相渗流的运动方程[5]可写为:

$$v_w=\frac{KK_{rw}}{\mu_w}\left(\frac{dP}{dx}-\gamma_w\sin\theta\right) \tag{9}$$

$$v_o=-\frac{KK_{ro}}{\mu_o}\left(\frac{dP}{dx}-\gamma_o\sin\theta\right) \tag{10}$$

式中: θ—表示正的下倾角;

γ_o、γ_w—分别为油藏条件下油、水的重率。

对不可压缩、黏度不变和垂直一维的情况,上述方程采用达西单位制相应的变为:

$$v_w=-\frac{K_vK_{rw}}{\mu_w}\left(\frac{\Delta P}{H}-\frac{\gamma_w}{1000}\right) \tag{11}$$

$$v_o=-\frac{K_vK_{ro}}{\mu_o}\left(\frac{\Delta P}{H}-\frac{\gamma_o}{1000}\right) \tag{12}$$

四、裂缝性非均质底水油藏水相分流量方程的导出

令 $\beta=K_v/K_h$,在图 1中的下部渗流区域 r处取与井轴同心的圆环作为渗流微元,积分可得油相的流量:

$$Q_o=\frac{2\pi\beta K_{ro}}{\mu_o}\int_{R_w}^{R_e}(K+\alpha r)\left[\frac{P_{owi}-P_w}{H}-\frac{\gamma_o}{1000}-\frac{P_e-P_w}{H\left(\ln\frac{R_e}{R_w}-\ln\frac{K+\alpha R_e}{K}\right)}\times\left(\ln\frac{r}{R_w}-\ln\frac{K+\alpha r}{K}\right)\right]r\,dr \tag{13}$$

完成式 (13)中积分,考虑到 $R_e\gg R_w$,忽略 R_w^2,整理得

$$Q_o=\frac{\pi\beta K_{ro}}{\mu_o}\left\{\left(KR_e^2+\frac{2\alpha R_e^3}{3}\right)\left(\frac{P_{owi}-P_w}{H}-\frac{\gamma_o}{1000}-\frac{P_e-P_w}{H}\right)+\frac{P_e-P_w}{H\ln\frac{R_eK}{R_w(K+\alpha R_e)}}\left[\frac{KR_e^2}{12}-\frac{K^3}{3\alpha^2}\ln\frac{K+\alpha R_e}{K}+\frac{K^2(R_e-R_w)}{3\alpha}\right]\right\} \tag{14}$$

同理可得

$$Q_w=\frac{\pi\beta K_{rw}}{\mu_w}\left\{\left(KR_e^2+\frac{2\alpha R_e^3}{3}\right)\left(\frac{P_{owi}-P_w}{H}-\frac{\gamma_o}{1000}-\frac{P_e-P_w}{H}\right)+\frac{P_e-P_w}{H\ln\frac{R_eK}{R_w(K+\alpha R_e)}}\left[\frac{KR_e^2}{12}-\frac{K^3}{3\alpha^2}\ln\frac{K+\alpha R_e}{K}+\frac{K^2(R_e-R_w)}{3\alpha}\right]\right\} \tag{15}$$

由式 (14)、式 (15)可得水相的分流量方程:

$$f_w=\frac{Q_w}{Q_o+Q_w}=\frac{\frac{K_{rw}}{\mu_w}}{\frac{K_{rw}}{\mu_w}+\beta\frac{K_{ro}}{\mu_o}} \tag{16}$$

H的单位采用 m;压力的单位采用 MPa;记压力系数为 α′;记 $\Delta P=P_e-P_w$,注意到 $P_{owi}-P_e=\alpha' H$, $P_{owi}-P_w=\alpha' H+\Delta P$。可得式 (16)中 B 的表达式如下:

$$\beta'=1+\frac{(\gamma_w-r_o)H/100}{(\alpha'-\gamma_w)H/100+\frac{\Delta P\cdot\left[\frac{KR_e^2}{12}-\frac{K^3}{3\alpha^2}\ln\frac{K+\alpha R_e}{K}+\frac{K^2(R_e-R_w)}{3\alpha}\right]}{\left(KR_e^2+\frac{2\alpha R_e^3}{3}\right)\ln\frac{KR_e}{R_w(K+\alpha R_e)}}} \tag{17}$$

五、水相分流量曲线及影响因素分析

塔河油田 4区为典型的裂缝性底水油藏,地层水为高矿化度卤水,地层压力系数为 1.117 7,其 S48井钻遇裂缝发育区,为一口部分打开井,其相应的地层及流体参数见表 1,其相渗曲线见图 2。

表 1 塔河油田 4区 S48井参数表

油层厚度 (m)	钻开厚度 (m)	水平渗透率 (μm^2)	地层原油黏度 (mPa·s)	地层水黏度 (mPa·s)	地层水密度 (g/cm^3)	地层原油密度 (g/cm^3)	泄油半径 (m)	油井半径 (m)
100	7.0	3.55	21.7	0.64	1.154	0.8604	1000	0.0746

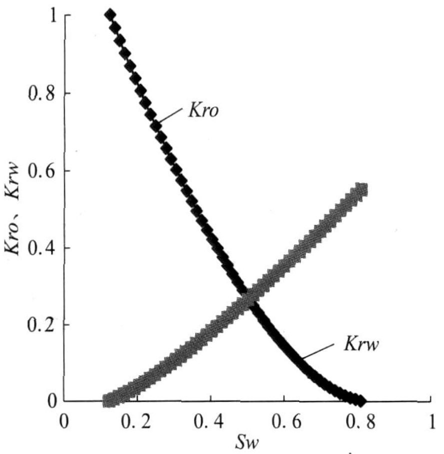

图2 塔河油田4区相对渗透率曲线

由式 (17)可计算得到不同生产压差下的 β值,将其代入式 (16)便可利用相对渗透率曲线计算水的分流量曲线。塔河油田 4区 S48井不同生产压差下的分流量曲线见图 3。

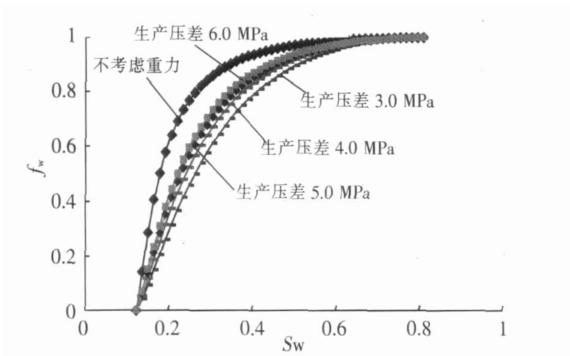

图 3 渗透率渐变模型分流量曲线(α=-0.001755)

由图 3可见,考虑重力影响的曲线均较不考虑重力的曲线缓,表明在开发底水油藏中,重力有利于减缓含水上升;同时不同生产压差下的含水变化趋势略有差异,生产压差越小,含水变化越缓。对于 S48井这类钻遇裂缝发育区的情况 (即近井渗透率大,外围渗透率较差的油藏),生产压差对含水的影响不明显。这也是该类井压锥效果较差的原因所在。

为了讨论式 (16)的适用性,同时做出了井偏离裂缝发育区情况下的水相分流量曲线 (参见图 4,涉及到的基础参数同表 1),图 4为井偏离裂缝发育区 (即近井区域渗透率小,远井区域渗透率大)时不同压差下的水相分流量曲线。由图可见,这种情况下生产压差对分流量的影响明显加剧 (与图 3相比),生产压差越小,重力的有利作用发挥越充分,含水变化越缓,且在中含水期各曲线的差别最大。该规律为缩嘴压锥提供了依据,且压锥时机选在中含水期,其效果最为明显,这已为现场的实践所证实。

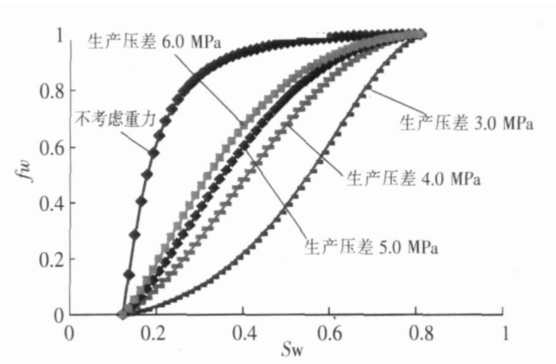

图 4 渗透率渐变模型分流量曲线(α=0.001755)

由式 (5)可知,井钻偏离裂缝发育区时,渗透率外大内小 (即 α>0),很难获得较高的初产,但含水变化较缓 (如图 4),这可较好的解释一些井产量不高,但生产及含水较稳定的实际;而当井钻遇裂缝发育区时,渗透率内大外小,其初期产量往往较高,但含水上升较快 (如图 3),且在后期容易出现供液不足,产量大幅度递减的现象。

六、结论和认识

(1)油藏的含水变化规律是由地质因素 (裂缝是否发育)和开发因素 (井是否钻遇裂缝发育区及生产压差等)决定的。

(2)井偏离裂缝发育区时生产压差对含水变化的影响要比井钻遇裂缝发育区时显著,可选择中含水期实施压锥。

(3)井偏离裂缝发育区时含水变化较缓,但难于获得较高的产量;井钻遇裂缝发育区时,容易获得初期高产,但含水上升较快,且在后期容易出现供液不足,产量大幅度递减的现象。

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pattern projects in two production rates were also simulated and calculated, and the oil recovery rate, formation pressure, composite water ratio and degree of reserve recovery index in different well patterns were compared. In the end, the reasonable development well pattern was decided for the Shuanghe oilfield reservoir.

Key words: Shuanghe oilfield, low permeability reservoir, well pattern, numerical simulation

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FEASIBILITY STUDY ON SINGLE WELL CO_2, N_2 HUFF AND PUFF IN SMALL FAULT BLOCK RESERVOIR

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Abstract: Aiming at technical process of gas injection huff and puff in ZY oilfield, the numerical simulation model was established at the foundation of geologic research. Numerical simulation was done in the example well, first the parameters sensibility was analyzed of CO_2、N_2 huff and puff, and the influence of cycle injection volume, injection rate, stew well time, production rate etc. on gas injection huff and puff effect was evaluated, then optimal operation parameters of CO_2、N_2 huff and puff were obtained, and production index forecast was carried out. After going into production, daily oil production was restored soon injecting rather N_2 than CO_2, but duration was longer rather CO_2 than N_2. The quantity of the cumulative recovery and accumulative increasing oil were larger rather injecting N_2 than CO_2. Through comparative analysis, it is showed that this well gained greater increase oil quantity, oil change rate by injecting N_2 rather than injecting CO_2, so preferable benefit would be obtained.

Key words: small fault block oil reservoir, CO_2 huff and puff, N_2 huff and puff, numerical simulation, contrast

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STUDY ON THE VARIATION OF WATER-CUT IN FRACTURED HETEROGENEOUS RESERVOIR WITH BOTTOM WATER

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Abstract: A gradually varied permeability geologic model based on the different fracture development and strong heterogeneity of the reservoirs was presented. Utilizing oil & gas flow theory, the fractional flow equation of the water phase in partially perforated fractured heterogeneous reservoir with bottom water was derived and some analysis of influencing factors on fractional flow curve were given. The study showed that the derived equation could predict the variations of the water-cut under different reservoir conditions and different dropdown pressures. The proposed theory in the paper could act as a guideline for the dynamic analysis and predictions of the development in fractured heterogeneous reservoir with bottom water.

Key words: fractured reservoir, reservoir with bottom water, heterogeneous, fractional flow equation

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ENHANCING RE-FRACTURING EFFECT WITH ARTIFICIAL TEMPORARY PLUGGING TECHNOLOGY

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Abstract: The effect of enhancing productivity by conventional hydraulic re-fracturing for Xinjiang old Oilfield decreases year by year, which could not meet the developing demand of the field. Based on the investigation the mechanisms of fracture generation & fracture re-orientation, artificial fracture temporary-blocking agent and diverted-fracturing technology for the well and stratum selection were studied. Refracturing could generate artificial fractures of various directions by using high strength temporary blocking agent, and new flow channels would be got through, thus the enrichment area of remaining oil could be explored and the recovery ratio of the field could be improved. Adopting temporary blocking agent plugged primary fracture, the fracture orientation of refracturing could generate departure and change direction, it not only could enhance the stimulation of refracturing, but also change waterflooding direction and improve the utilization factor of injecting water.

Key words: refracturing, temporary plugging, fracture re-orientation, field application

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PROCESS MATCHING TECHNOLOGY TO PROLONG OIL WELL EXEMPTION PERIOD IN XIASIWAN OIL FIELD

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