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三重压敏介质油藏不稳态产能变化特征研究

王子胜,姚 军
(中国石油大学,山东 东营 257061)

摘要:建立由基岩系统、裂缝系统和溶洞系统组成,并考虑溶洞渗透率随压降的增加呈指数减小的压敏三重介质油藏不稳态产能模型,采用隐式差分格式对考虑井筒储存和污染效应的情况进行了求解,讨论了无因次渗透率模数、介质间窜流、弹性储容比、外边界条件以及表皮系数对不稳态产能的影响。结果表明:表皮系数对不稳态产能早期的影响较为显著,而无因次渗透率模数可导致不稳态产能明显下降,但其影响不如表皮系数;窜流系数决定着窜流出现的时机;裂缝弹性储容比影响着油藏早期不稳态产能的大小和窜流阶段出现的时机;封闭边界情况下产能急剧下降,定压边界情况产能最终会达到一个稳定的状态。

关键词:应力敏感;三重介质;不稳态产能;参数影响;塔河油田
中图分类号:TE319 **文献标识码**:A

前 言

压敏介质指容易发生部分或者全部不可逆变形的介质[1],这种变形对介质的物性产生明显影响。著名学者 Raghavan 和 Miller[2] 提出了"拟压力"模型,并进行了数值求解;Samaniego[3,4] 等人采用数值方法研究压敏介质渗流问题,绘制了瞬态产量递减曲线,给出了长时间渐进解析式,并将其应用于变流量常规试井分析之中;Pedrosa[5] 引入渗透率变异关系式,用小扰动方法求解压敏介质非线性渗流数学模型,给出了点源的一阶近似解,Kikani 和 Pedrosa[6] 用小扰动方法进一步给出了二阶近似解析式;2000 年,苏玉亮和栾志安[7] 等人也对变形介质油藏的开发特征进行了研究;但是对变形介质油藏的产能变化的研究甚少。

新疆塔河油田地层属于碳酸盐岩,埋深达 6 000 m。生产过程中,油井的初期产量较高,但递减较快,表现出压敏介质的特征。为此,对该油藏不稳态产能变化特征进行了研究。

1 数学模型的建立和求解

1.1 数学模型的建立

描述流体在地层中的不稳态流动时,一般假设渗透率不变,研究方法对于那些岩石性质随孔隙压力变化的地层常常忽略不计。而对于缝洞型油藏来说,由于缝洞孔隙尺寸较大,地层渗透率的有效应力敏感性较强。

地层孔隙压力的降低将导致有效应力的增加,进而使得渗透率减小。三重介质油藏由基岩孔隙系统、裂缝系统和溶洞系统组成[8],在考虑一般假设的基础上,又作如下假设:①地层岩石可压缩,并因此引起渗透率的变化;②油井以定井底压力生产。

定义一个和压缩系数类似的渗透率随压力变化模数,并假设其在生产过程中保持不变:

$$\gamma = \frac{1}{K_v} \cdot \frac{\mathrm{d} D_v}{\mathrm{d} p_v} \tag{1}$$

对式(1)进行积分得到:

$$K_v / K_{v0} = \mathrm{e}^{-\gamma(p_i - p_v)} \tag{2}$$

无限大三重介质油藏溶洞与井筒连通情况下无因次不稳态产能数学模型为[9]:

$$\begin{cases} \frac{1}{r_D} \cdot \frac{\partial}{\partial r_D}\left(r_D \mathrm{e}^{-\gamma_D p_{Dv}} \frac{\partial p_{Dv}}{\partial r_D}\right) - \omega_m \frac{\partial p_{Dm}}{\partial t_D} - \omega_f \frac{\partial p_{Df}}{\partial t_D} = -\omega_v \frac{\partial p_{Dv}}{\partial t_D} \\ -\lambda_{mv}(p_{Dm} - p_{Dv}) = \omega_m \frac{\partial p_{Dm}}{\partial t_D} \\ -\lambda_{vf}(p_{Df} - p_{Dv}) = \omega_f \frac{\partial p_{Df}}{\partial t_D} \\ p_{Dj}(r_D, t_D)|_{t_D=0} = 0 \ (j = m, f, V) \ 1 \le r_D \le +\infty \\ 1 = \left[p_{Dv} - S\mathrm{e}^{-\gamma_D p_{Dv}} \frac{\partial p_{Dv}}{\partial r_D} \right]_{r_D=1} \\ \lim_{r_D \to \infty} p_{Dv}(r_D, t_D) = 0 \end{cases} \tag{3}$$

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作者简介:王子胜(1980 -),男,博士,讲师,2002 年毕业于石油大学石油工程专业,主要从事试井解释和数值模拟方法的研究工作。

对于有界圆形封闭地层,外边界条件为:

$$\frac{\partial p_{Dv}}{\partial r_D}\Big|_{r_D = r_{eD}} = 0 \tag{4}$$

对于有界圆形定压力地层,外边界条件为:

$$p_{Dv}(r_{eD}, t_D) = 0 \tag{5}$$

则压敏介质油藏无因次产量表达式为:

$$q_D = -e^{-\gamma_D p_{Dv}}\frac{\partial p_{Dv}}{\partial r_D}\Big|_{r_D = 1} \tag{6}$$

其中:$r_D = \frac{r}{r_w}$,$r_{eD} = \frac{r_e}{r_w}$,$t_D = \frac{3.6K_{v0}}{\mu r_w^2 \phi_t C_t}t$,$\gamma_D = [p_i - p_v(r,t)]\gamma$,$p_{Dj}(r_D, t_D) = \frac{[p_i - p_j(r,t)]}{[p_i - p_{wf}]}$ $(j = m, f, v)$,$q_D = \frac{q\mu}{2\pi K_{v0} h(p_i - p_{wf})}$,$\omega_j = \frac{\phi_j C_j}{\phi_t C_t}$ $(j = m, f, v)$,$\lambda_{jv} = \frac{\alpha_j K_j r_w^2}{K_{v0}}$ $(j = m, f)$。

式中:下标 m、f、v、t 分别代表基岩、裂缝、溶洞和总系统;K_{v0} 为溶洞初始渗透率,μm^2;K_v 为溶洞渗透率,μm^2;$p = p(r,t)$ 为地层瞬时压力,MPa;ϕ 为孔隙度,%;C 为压缩系数,MPa^{-1};λ_{mv}、λ_{vf} 分别为基岩系统和裂缝系统与溶洞系统之间的窜流系数;ω 为弹性储容比;μ 为流体粘度,mPa·s;r 为径向距离,m;r_D 为无因次径向距离;r_w 为井筒半径,m;r_e 为外边界半径,m;r_{eD} 为无因次外边界半径;h 为油层有效厚度,m;q 为地面流量,m^3/d;p_i 为原始地层压力,MPa;p_{wf} 为井底压力,MPa;γ 为溶洞渗透率模数,MPa^{-1};γ_D 为无因次溶洞渗透率模数;S 为表皮系数;t 为测试时间,h;t_D 为无因次测试时间;α 为介质形状因子,m^{-2}。

1.2　数学模型的求解

式(3)中的非线性扩散方程为典型的非线性抛物型方程[10],采用全隐式的差分格式进行求解,结合式(6)即可以对产能进行求解。

2　参数影响分析

2.1　无因次渗透率模数的影响

渗透率模数影响着地层溶洞的渗透率。生产过程中,由于地层压力的降低使得溶洞渗透率减小,在一定井底压力的情况下,无因次不稳态产能也相应地减小。当条件为定井底压力时,开始生产时即建立了一定的压差,使得早期无因次不稳态产能有一定程度的降低(图 1)。

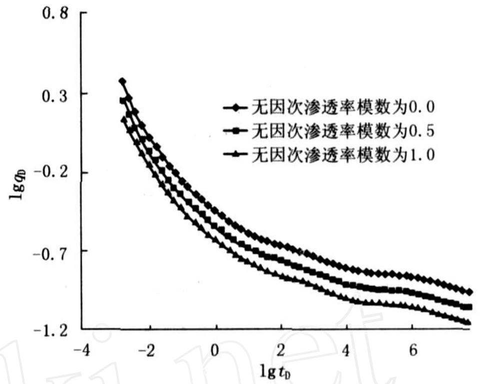

图 1　无因次渗透率模数对不稳态产能的影响

2.2　窜流系数的影响

窜流系数的大小决定着窜流阶段出现的时机,表现在无因次不稳态产能和时间的双对数曲线上则是平缓段出现的早晚。由于窜流的发生,基岩和裂缝开始向溶洞窜流供液,这使得仅靠溶洞供液的无因次不稳态产能的减小趋势变缓;在窜流阶段结束之后,油藏进入总系统流阶段,这时基岩、裂缝和溶洞同时参与流动,其减小趋势较纯溶洞供液阶段有所变缓(图 2)。

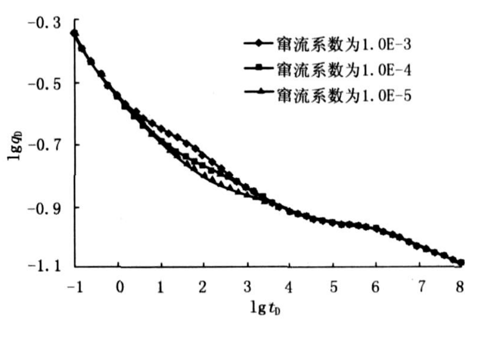

图 2　窜流系数对不稳态产能的影响

2.3　介质弹性储容比的影响

溶洞弹性储容比的大小表明了溶洞中的弹性储量占系统总弹性储量的比例。由于早期只有溶洞中流体流动,当溶洞的弹性储容比较小时,油井开始生产,其无因次不稳态产能相应较低,减少的幅度较大,同时达到窜流的时间越短,但是其窜流段的长度也就越长,否则变化相反(图 3)。

2.4　外边界条件的影响

油井在无限大油藏中生产时最终会达到无限

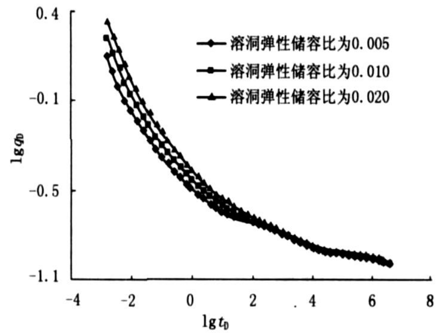

图3 溶洞的弹性储容比对不稳态产能的影响

作用径向流段,此时压力的变化同样会导致渗透率的变化,进而影响不稳态产能的变化;而在有限油藏中生产时则会受到边界的影响。封闭边界在压力动态的影响到达边界之后会加剧压力的变化,同时使得渗透率的减小更加剧烈,从而导致不稳态产能的急剧下降;当达到定压边界条件后,油藏的生产会达到稳定状态,地层中的压力不再变化,压力变化对渗透率的影响相应停止,不稳态产能也会达到一个稳定的状态(图4)。

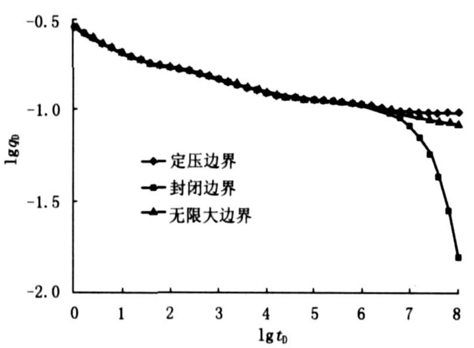

图4 外边界对不稳态产能的影响($\gamma_D=0.5$)

2.5 表皮系数的影响

表皮系数是钻井、洗井等作业过程中液体对油藏造成污染的表征参数,它对无因次不稳态产量的影响是全程的。如果表皮系数存在,则会造成附加压力降,使得在一定井底压力下的油井的不稳态产能大幅度地降低(图5)。

2.6 无因次渗透率模数和表皮系数对不稳态产能影响的差别

如前所述,表皮系数对无因次不稳态产能影响是全程的,而无因次渗透率模数对不稳态产能的影响虽然也是全程的,但是其在早期和后期的影响幅度不一样。因为油井在继续生产过程中压力持续地降低,由于渗透率模数的影响,渗透率持续地降低。越到后期,其影响越大;由图6可以看出,虽然二者最终的无因次不稳态产能相等,但在早期却有着相当大的差别。

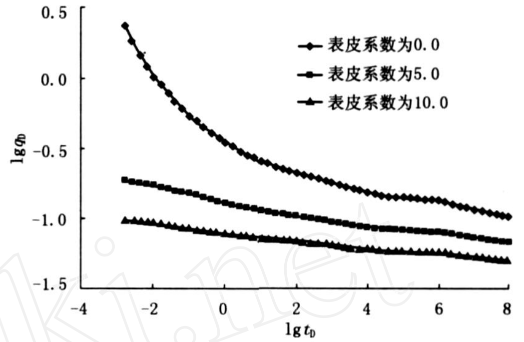

图5 表皮系数对不稳态产能的影响

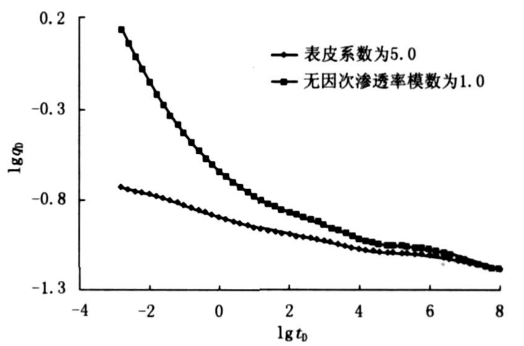

图6 无因次渗透率模数和表皮系数对不稳态产能影响的区别

3 结 论

(1) 无因次渗透率模数对不稳态产能影响较大。无因次渗透率模数增加,则不稳态产能下降。

(2) 介质间的窜流系数影响着窜流阶段出现的时机。窜流系数越大,窜流出现越早。

(3) 溶洞的弹性储容比决定着油藏早期不稳态产能的大小、介质间窜流阶段出现的时间和窜流阶段持续的时间。溶洞弹性储容比越小,油藏早期不稳态产能越小,窜流阶段出现的时间越早,同时窜流阶段持续的时间也就越长。

(4) 表皮系数越大,不稳态产能越低。表皮系数影响着不稳态产能的全程,且对早期影响较大;无因次渗透率模数虽然也影响着不稳态产能的全程,但其后期影响较大。

(5) 当边界为封闭情况时,由于压力的快速下降会使得渗透率的减小幅度更大, (下转第64页)

3.4 指标预测

在参数优化的基础上,对试验井组进行了生产指标预测(表 6)。预测结果表明,试验井组水气交替驱开发近 6 a,累计产油 10.8 ×10^4t,采出程度达到 17.12 %。

表 6 试验井组烟道气驱开发效果预测

时间 /a	产油量 /10^4t	产水量 /10^4t	注水量 /10^4t	注气量 /10^4t	采出程度 / %	采油速度 / %	油水比
1	2.76	5.41	8.59	8.64	4.37	4.37	0.321
2	3.22	7.50	8.64	8.64	9.47	4.74	0.373
3	1.91	7.03	8.64	8.64	12.5	4.17	0.221
4	1.34	6.89	8.84	8.64	14.62	3.64	0.151
5	1.03	7.01	8.93	8.64	16.25	3.23	0.115
6	0.55	4.54	5.75	5.76	17.12	2.85	0.095
合计	10.80	38.38	49.39	48.96	17.12	/	0.219

4 结 论

(1) 数值模拟计算结果表明,薄互层普通稠油油藏蒸汽吞吐后期,烟道气驱是蒸汽吞吐后一种有效的产能接替方式,该阶段预计采出程度可达到 17.12 %。

(2) 杜 66 块杜家台油层下层系烟道气驱的最优参数为: 段塞大小为 0.45 PV (对应瞬时含水 90 %左右),注(气) 水速度为 120～140 t/d,注入水温度为 60 ℃,采注比为 1.0～1.1,气液比为 1∶1,水气交替时间应为 30～45 d,CO_2 在烟道气中比例越大,开发效果越好。

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(上接第 54 页)从而导致产能急剧下降;而当压力动态达到定压边界后,油藏的生产会达到稳定状态,不稳态产能也会达到一个稳定的状态。

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编辑 姜 岭

XIU Nai - ling , XIONG Wei , GAO Shu - sheng , BAN Fan - sheng , XUE Hui
(*Institute of Porous Flow and Fluid Mechanics* , *CAS* , *Langfang* , *Hebei* 065007 , *China*)

Abstract :Solution cavity and fractures constitute major reservoir space in Tahe Oilfield. Fractures and cavities are highly heterogeneous , with fluid flow mechanism and water cut quite different from common sandstone reservoirs. A new flow model is set up based on conduit flow theory , and is used to simulate development performance and water cut of fracture - cavity constant volume reservoirs developed respectively by elastic drive and water flooding. This study is a reference in understanding fluid flow mechanism in fracture - cavity reservoirs.

Key words :fracture - cavity reservoir ; hydrodynamics ; constant volume ; conduit flow theory ; Tahe Oilfield

Study on transient productivity in pressure sensitive triple media reservoir

WANG Zi - sheng , YAO Jun
(*China University of Petroleum* , *Dongying* , *Shandong* 257061 , *China*)

Abstract :Transient productivity model is established for pressure - sensitive triple media reservoir composed of basement system , fracture system and cavity system with consideration of cavity permeability declining exponentially with the increasing of pressure drawdown. Implicit diffence equation is used to solve the situation with consideration of wellbore storage and pollution effect. The impact of dimensionless permeability modulus , interporosity flow channeling , elastic reserve/volume ratio , exterior boundary conditions and skin factor on transient productivity is discussed. The result shows that : skin factor has an evident impact on early productivity , while dimensionless permeability modulus can apparently reduce transient productivity but with less impact than skin factor ; channeling factor decides the timing of channeling ; elastic reserve/volume ratio of fractures affects the size of transient productivity in early stage and the timing of channeling ; productivity declines drastically when boundary sealed , and productivity will finally be stable under constant pressure boundary.

Key words :stress sensitive ; triple media ; unstable productivity ; parameter impact ; Tahe Oilfield

A new method of fuzzy comprehensive evaluation of water flooding response based on G1 method

ZHANG Jian - ye[1] , XIONG Yu[1] , HUANG Lan[1] , LIU Yan - dong[2]
(1. *Southwest Petroleum University* , *Chengdu* , *Sichuan* 610500 , *China* ;
2. *Gas Pipeline Engineering Co.* , *Ltd* , *PetroChina* , *Langfang* , *Hebei* 065000 , *China*)

Abstract : Inadaptability and weight determination are common problems when performing fuzzy comprehensive evaluation of reservoirs with maximum subordinate principle. It is proposed to use approximate rule to substitute maximum subordinate principle , thus overcoming the drawbacks of maximum subordinate principle and reducing misjudging. G1 method is introduced to determine weight vector , remedy the shortcomings of analytical hierarchy process such as a large amount of calculation , needing consistency check and complicated calculation , thus established a new fuzzy comprehensive evaluation model. This model has been used in an actual reservoir and proved a simple , practical and scientific method of water flooding response evaluation.

Key words :development response ; fuzzy comprehensive evaluation ; weight ; G1 method ; approximate rule

Future - oriented water injection in Guyunji Oilfield

LI Yan - tao , LIU Zheng - yun , LU Qing - he , WU Xu - guang , ZHANG Zhi - yong
(*Zhongyuan Oilfield Company* , *SINOPEC* , *Puyang* , *Henan* 252429 , *China*)

Abstract :Guyunji Oilfield is a waterflooding low permeability reservoir. This paper studies fluid percolation through numerical simulation and field mathematical statistics , analyzes the mechanism and response of future - oriented water injection in low permeability oilfield , and optimizes rational reservoir pressure , injection pressure , injection rate and timing , etc. , during future - oriented water injection. Field practice shows that future - oriented water injection can be very effective.

Key words :future - oriented water injection ; mechanism analysis ; rational reservoir pressure ; injection pressure ; injection rate ; injection timing ; Guyunji Oilfield

Numerical simulation of flue gas drive in conventional heavy oil reservoirs with thin interbeds

BAO Jun - gang
(*Liaohe Oilfield Company* , *PetroChina* , *Panjin* , *Liaoning* 124010 , *China*)

Abstract : Dujiatai reservoir in Block Du66 is a conventional heavy oil reservoir with thin interbeds , and has been recovered by cyclic steam stimulation. Current SOR is almost approaching economic limit , operation cost is increasing year on year , and development scheme must be converted without delay. Numerical simulation has been conducted for injection and production parameters of converting to flue gas drive , which are : slug size 0.45PV (corresponding instantaneous water cut about 90 %) , water (gas) injection rate 120～140t/d , injected water temperature 60 ℃,production factor 1.0～1.1 , gas - liquid ratio 1∶1 , WAG timing 30～45d , and CO_2 proportion is the higher the better. Index prediction indicates that , by the time of reaching economic water cut limit , the recovery factor of the well group can improve 17.12 %.

Key words : heavy oil reservoir with thin interbed ; flue gas drive ; numerical simulation ; reservoir engineering ; EOR ; Block Du66

Compound recovery by in situ combustion slug + steam flooding

ZHANG Rui , PU Jing - ming , DENG Ming
(*Research Institute of Petroleum Exploration & Development* , *PetroChina* , *Beijing* 100083 , *China*)

Abstract :After cyclic steam stimulation in mid - deep heavy oil reservoirs in Liaohe Oilfield , steam flooding is usually adopted to improve recovery factor. However , in early steam flooding stage , there is a long period of low production , and both oil - steam ratio and commercial rate are low. How to improve steam flooding has become an urgent need in Liaohe oil province for converting to steam flooding in a large scale. Feasibility study of compound recovery by "in situ combustion slug + steam flooding" has been conducted with Block Gao3 as an ex-