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稠油油藏储层伤害产能预测新模型及表皮因子研究

何勇明[1], 王允诚[1], 董长银[2], 赵子刚[3]
(1. 成都理工大学 油气藏地质及开发工程国家重点实验室, 四川 成都 610059;
2. 中国石油大学(华东) 石油工程学院, 山东 东营 257061; 3. 中国石油青海油田 采油一厂, 甘肃 敦煌 736202)

摘要: 基于幂律流体的流变特性方程, 推导了幂律流体储层污染前后的垂直井的产能预测模型; 推导了适合稠油油藏的表皮因子和非牛顿流体污染井井底压力损失的表达式, 并验证了非牛顿流体公式可以还原为牛顿流体公式, 分析了非牛顿流体流变特性参数对模型的影响。计算结果对比表明, 储层流体的非牛顿特性对模型预测结果具有明显的影响。

关键词: 稠油; 迂曲度; 产能预测; 幂律流体; 表皮因子
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稠油是典型的非牛顿流体, 幂律流型和宾汉流型基本包括了所有的稠油油藏类型。正是由于稠油的非牛顿特性, 使得开采稠油油藏变得十分困难。在目前的稠油油藏开采中, 无论是进行产能预测还是进行酸化压裂增产效果预测, 所用到的理论大多是基于普通油藏适用的达西定律, 只有个别文献[1-2]运用非牛顿参数从理论上来研究稠油的产能预测。用达西定律研究非牛顿性稠油油藏, 给其开发效果的预测带来了不准确的因素。为了更好地预测稠油油藏的开发效果, 本文基于幂律流体的流变特性方程, 推导了稠油油藏受污染前后的产能模型, 并进行了表皮因子研究, 为稠油油藏的开发提供理论依据。

1 稠油油藏(幂律型)储层的产能预测模型

流变特性方程的推导基础是一个简化的毛细管模型[3-4], 庞兴河等基于迂曲毛细管模型推导了幂律流体的流变特性方程为[5]

$$\gamma = \frac{(3n+1)Q_m}{nAt\sqrt{8k\phi}} \tag{1}$$

式中: γ 剪切速率, 1/s; n 为幂律指数; Q_m 为毛细管流量, cm^3/s; A 为毛细管横截面积, cm^2; t 为迂曲度; k 为有效渗透率, μm^2; ϕ 为有效孔隙度。

根据公式(1), 可推导出受污染前后储层的产能预测模型, 这将更适合于地层的实际情况。

对于平面径向流, 假设圆形定压边界地层中心有一口生产井, 其产能公式为

$$Q_c^n = \frac{2\pi kh}{K\left(\dfrac{3n+1}{2\pi hnt\sqrt{8k\phi}}\right)^{n-1}} r^n \frac{dp}{dr} \tag{2}$$

式中: Q_c 为生产井的产量, m^3/d; h 为油藏厚度, m; K 为稠度系数, $mPa\cdot s^n$; r 为井底到油藏边界任意处的距离, m; p 为井底到油藏边界任意处的压力, MPa。

污染前的产能模型

污染前的边界条件: 当 r 为泄油半径时, p 为边界压力; r 为井半径时, p 为井底压力。

对式(2)分离变量积分为

$$Q_w^n = \frac{(p_e - p_w)M k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}} (n-1)}{r_w^{1-n} - r_e^{1-n}} \tag{3}$$

其中

$$M = \frac{2\pi h}{K\left(\dfrac{3n+1}{4\pi hnt\sqrt{2}}\right)^{n-1}} \tag{4}$$

收稿日期 2005-09-30; 改回日期 2006-11-23。
作者简介: 何勇明, 男, 2004年毕业于石油大学(华东)油气田开发专业, 现为成都理工大学博士研究生, 现从事油气田开发方面的研究工作。联系电话: 13086693020, E-mail: hymhym.hym@163.com。
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式中: Q_w为未污染的产量, m^3/d; p_e为边界压力, MPa; p_w为井底压力, MPa; r_w为井半径, m; r_e为泄油半径, m。

污染后的产能模型

污染区外的边界条件: 当 r为泄油半径时, p为边界压力; 当 r为污染半径时, p为污染区压力。

对式(2)分离变量积分为

$$Q_1^{\,n} = \frac{(p_e - p_d) M k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}} (n-1)}{r_d^{\,1-n} - r_e^{\,1-n}} \tag{5}$$

式中: Q_1为污染区外的产量, m^3/d; p_d为污染区压力, MPa; r_d为污染半径, m。

污染区内的边界条件: 当 r为污染半径时, p为污染区压力; 当 r为井半径时, p为井底压力。

对式(2)分离变量积分为

$$Q_2^{\,n} = \frac{(p_d - p_w) M k_d^{\frac{n+1}{2}} \phi_d^{\frac{n-1}{2}} (n-1)}{r_w^{\,1-n} - r_d^{\,1-n}} \tag{6}$$

由流体的连续性知

$$Q_1 = Q_2 = Q_h \tag{7}$$

$$Q_h^{\,n} = \frac{(p_e - p_w) M (n-1) k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}} k_d^{\frac{n+1}{2}} \phi_d^{\frac{n-1}{2}}}{(r_d^{\,1-n} - r_e^{\,1-n}) k_d^{\frac{n+1}{2}} \phi_d^{\frac{n-1}{2}} + (r_w^{\,1-n} - r_d^{\,1-n}) k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}}} \tag{8}$$

式中: Q_2为污染区内的产量, m^3/d; k_d为污染区渗透率, μm^2; ϕ_d为污染区的孔隙度; Q_h为污染后的产量, m^3/d。

根据文献[6], 牛顿型油藏垂直井平面径向流的产量公式为

$$Q_z = \frac{2\pi k h (p_e - p_w)}{\mu \ln \frac{r_e}{r_w}} \tag{9}$$

式中: Q_z为垂直井的产量, m^3/d; μ为地层油粘度, mPa·s。

2 表皮因子研究

污染前的产能为

$$Q_w^{\,n} = \frac{(p_e - p_{wf}') M k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}} (n-1)}{r_w^{\,1-n} - r_e^{\,1-n}} \tag{10}$$

污染后的产量为

$$Q_h^{\,n} = \frac{(p_e - p_{wf}) M (n-1) k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}} k_d^{\frac{n+1}{2}} \phi_d^{\frac{n-1}{2}}}{(r_d^{\,1-n} - r_e^{\,1-n}) k_d^{\frac{n+1}{2}} \phi_d^{\frac{n-1}{2}} + (r_w^{\,1-n} - r_d^{\,1-n}) k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}}} \tag{11}$$

式中: p_{wf}'为未伤害井底压力, MPa; p_{wf}为伤害井底压力, MPa。

为了研究污染井和未污染井之间的压降损失及相应的表皮因子, 假设污染后的产能和污染前的产能一样, 那么, 由公式(10)和(11)得

$$\Delta p_{sk} = p_{wf}' - p_{wf} = \frac{Q_w^{\,n} r_w^{\,1-n}}{M k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}} (1-n)} \cdot \left[\left(\frac{k}{k_d}\right)^{\frac{n+1}{2}}\left(\frac{\phi}{\phi_d}\right)^{\frac{n-1}{2}} - 1\right]\left[\left(\frac{r_d}{r_w}\right)^{1-n} - 1\right] \tag{12}$$

令

$$S = \left[\left(\frac{k}{k_d}\right)^{\frac{n+1}{2}}\left(\frac{\phi}{\phi_d}\right)^{\frac{n-1}{2}} - 1\right]\left[\left(\frac{r_d}{r_w}\right)^{1-n} - 1\right]\frac{1}{1-n} \tag{13}$$

则

$$\Delta p_{sk} = \frac{Q_w^{\,n} r_w^{\,1-n}}{M k^{\frac{n+1}{2}} \phi^{\frac{n-1}{2}}} S \tag{14}$$

式中: Δp_{sk}为井底压降损失, MPa; S为表皮因子。

根据文献[7], 没有考虑非牛顿因素的表皮因子为

$$S = \left(\frac{k}{k_d} - 1\right) \ln \frac{r_d}{r_w} \tag{15}$$

例如, 当 k/k_d为5, r_d/r_w为8, ϕ/ϕ_d为2时, 对不同的幂律指数按公式(13)和公式(15)计算其表皮因子; 当幂律指数为0.70, 0.80, 0.90和0.99时, 公式(13)的计算结果分别为8.45, 8.40, 8.35和8.32, 而公式(15)的计算结果为8.32, 这与公式(13)中n取0.99时的计算结果完全一致。因此当幂律指数为1时, 考虑非牛顿特性的表皮因子和经验的表皮因子的计算结果是一致的, 说明新的表皮因子在一定条件下可以还原为经验的表皮因子; 随着幂律指数的减小, 流体的非牛顿性越强, 新公式的表皮因子值越大, 说明幂律指数对表皮因子是有一定影响的; 但影响不是很明显, 甚至可以忽略。

3 应用分析

3.1 算例

南海油田某井泄油半径为200m, 边界压力为12.03MPa, 井底压力为1.02MPa, 井半径为0.12m, 油藏厚度为50m, 稠度系数为60mPa·s^n, 渗透率为0.18μm^2, 迂曲度取2.5(迂曲度的确定见文献[8]), 孔隙度为0.25。

检验污染前的非牛顿流体公式(3)和污染后的非牛顿流体公式(8)是否可以还原为牛顿流体公式(9);由于公式(3)和公式(8)中 n 不能取 1,因此取各参数逼近值,n 取 0.999,r_d 为 0.121m,k_d 为 0.179 μm^2,ϕ_d 为 0.249,t 取 1。

利用公式(3)、公式(8)和公式(9)计算的产能分别为 120.05,120.08 和 120.71m^3/d。可以看出,三个公式计算结果吻合的非常好,证明非牛顿流体公式可以还原为牛顿流体公式,推导是正确的。

3.2 幂律指数和迂曲度对产能的影响

取迂曲度为 2.5 和 1(没有考虑迂曲度的影响);幂律指数分别为 0.9,0.8,0.7;r_d 为 1.0m,k_d 为 0.1μm^2,ϕ_d 为 0.13。从计算结果可以看出(图 1),①幂律指数对污染前后的产能模型影响很大,幂律指数越大,产量越大,因为幂律指数越大,非牛顿性越弱;②迂曲度对模型也有一定的影响,幂律指数相同时,考虑迂曲度的产能比没有考虑迂曲度($n=1$)的产能小,因为迂曲度越大,流体流动的阻力越大;③考虑非牛顿性的模型产能与牛顿流体公式的产能相差很大,这说明对于非牛顿性流体油藏,在采取增产措施计算污染前后的产能时,非牛顿性因素是不可以忽略的。

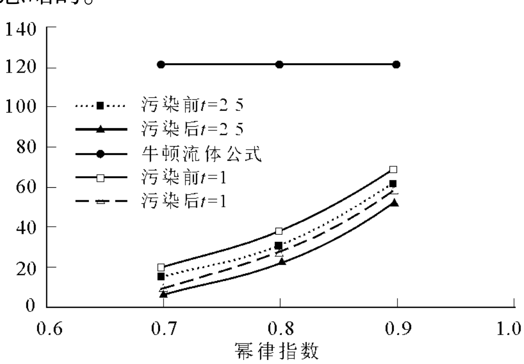

图 1 幂律指数对产能的影响

4 结束语

无论是普通油藏还是稠油油藏,流体的流动都是迂曲前进的,而不是理想的直进;应用迂曲度来修正理想毛细管模型,使幂律流体的流变特性更符合实际地层情况。对于非牛顿流体稠油油藏,在采取酸化增产措施时,不可忽略非牛顿因素;实践证实,对于幂律型流体,幂律指数是一个很重要的影响参数,如果用经验的牛顿流体公式来计算污染稠油油藏的产能,计算结果将严重背离实际情况。在对稠油油藏进行酸化增产效果预测时,表皮因子将是一个重要的影响因素;本文推导了适合稠油油藏的表皮因子,它受幂律指数的影响,这与经验的表皮因子表达式有很大的区别;幂律指数和表皮因子对酸化效果预测的具体影响将在以后的研究中进行重点分析讨论。

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tive evaluated by its thickness. It is feasible and can be referential to evaluate the storage - layer quality of meshwork - carpet type oil and gas pool - forming system in the same type of the oilfield.

Key words: migration trace of hydrocarbon, storage - layer thickness, Dongying Sag, meshwork - carpet type oil and gas pool - forming system

Jiang Suhua, College of Marine Geosciences, Ocean University of China, Qingdao City, Shandong Province, 266003, China

Xu Xiaoping, Su Yinghong. Research of abandoned oil recovery rate in the course of oilfield development. ***PGRE***, **2006, 13(1): 69 ~ 70**

Recoverable reserves are limited in the course of oilfield development. The production rate is a factual problem that decision - maker and reservoir engineer care about when oilfield is abandoned. Abandoned oil recovery rate was analyzed in the middle and last period of oilfield development from the aspects of technology and economy. Based on a great deal of examples, the abandoned oil recovery rates under different conditions were gotten . The result is that the higher the oil price, the lower the economic abandoned oil recovery rate; the higher the cost, the higher the economic abandoned oil recovery rate; and the corresponding quantitative relation was gained. It has certain guiding significance on how to determine the abandoned oil recovery rate reasonably and to improve the economic benefit of oilfield development.

Key words: recoverable reserves, recovery percent of reserves, technical abandoned oil recovery rate, economic abandoned oil production rate

Xu Xiaoping, Dongsheng Petroleum Development Stock Co., Ltd., SLOF, Dongying City, Shandong Province, 257000, China

Gao Chunguang, Wang Xiaodong, Liu Hefu et al. Optimization of perforation project for inhibiting water coning by water recovery with single tube in the bottom water drive reservoir. ***PGRE***, **2006, 13(1): 71 ~ 73**

Inhibiting water coning by water recovery from the oil reservoir with active bottom water can inhibit or slow down bottom water coning, stabilize oil production and control water cut. Water coning inhibiting technology with single tube was put forward then. The radial reservoir model of single well was established, and the well production performance for different thicknesses and various positions of perforation were predicted by means of numerical simulation. Optimum perforation project was provided. In addition, the influence of water body size and anisotropy of permeability on bottom water coning was analyzed. These results provided theoretical foundation for selecting measures of controlling water cut and enhancing the ultimate recovery efficiency of bottom water oilfield.

Key words: bottom water drive reservoir, inhibiting water coning by water recovery with single tube, perforation project

Gao Chunguang, Energy Faculty, China University of Geosciences, Beijing, 100083, China

Zhang Dezhi, Wang Zisheng, Yao Jun. Pressure behavior character of interference well test in tri - media oil reservoir. ***PGRE***, **2006, 13(1): 74 ~ 76**

Based on construction of well test interpretation model of tri - media oil reservoir, pressure performance variation of the interference well test was studied. The influence of wellbore storage, skin factor, interporosity flow coefficient and elastic storativity ratio to the bottom hole pressure of the observation well were analyzed. The result showed that skin factor had no effect on the bottom hole pressure of the observation well, whether the wellbore storage had effect on the pressure depended on its magnitude and the distance between active and observation wells, the influence of the interporosity flow coefficient and the elastic storativity ratio to the bottom hole pressure of the observation well was just like the single well test result.

Key words: tri - media oil reservoirs, interference well test, wellbore storage, skin factor, interporosity flow coefficient, elastic storativity ratio

Zhang Dezhi, College of Petroleum Engineering, China University of Petroleum (East China), Dongying City, Shandong Province, 257061, China

Mao Wei. New computing method for radius of investigation based on flow rate. ***PGRE***, **2006, 13(1): 77 ~ 78**

Radius of investigation is the location of pressure wave front in oil reservoir at certain production time. In view of existing question of contradiction between computing formula for current radius of investigation and hypothesis, influence range and sandbody size can not be obtained correctly during the production. In order to get accurate computing formula for radius of investigation, flow rate distribution formula in formation was derived according to partial differential equation of non - steady flow for determining downhole flow rate in infinite formation. Based on pressure response time and well distance of active well received from observation well during interference well testing in Daqing periphery oilfield, the computing formula of radius of investigation was derived from the viewpoint of the flow rate. The example showed that the computing results of new formula was reliable, and could provide basis for determining sandbody size.

Key words: radius of investigation, flow rate, sandbody size

Mao Wei, Exploration and Development Research Institute of Daqing Oilfield Company Ltd., Daqing City, Helongjiang Province, 163712, China

He Yongming, Wang Yuncheng, Dong Changyin et al. Research on new productivity prediction model and skin factor during formation damage in heavy oil reservoir. ***PGRE***,

2006,13(1):79~81

Productivity prediction model of power – law fluid in the reservoir before and after pollution had been deduced based on rheological behavior equation of the power – law fluid. The formulae were deduced for skin factor avaiable to heavy oil reservoir and the bottom – hole pressure loss of the polluted well with non – Newton fluid. It proved that non – Newtonian fluid formula could be returned to Newtonian fluid formula. The effect of the rheological behavior parameters of the non – Newtonian fluid on the model was analyzed. Comparing the results to the formula, non – Newtonian behavior of the reservoir fluid had obvious influence on the model prediction results.

Key words: heavy oil, detour index, productivity prediction, power – law fluid, skin factor

He Yongming, State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu City, Sichuan Province, 610059, China

Sun Yeheng, Lv Guangzhong, Wang Yanfang et al. A method of state equation for determining minimum miscible pressure of CO_2. *PGRE*, 2006, 13(1):82~84

The miscible pressure is an important foundation of adopting miscible flooding or not in the reservoir. The best method of miscible pressure determination is slim – tube test, but it takes more time and effort. Based on slim – tube test results and the concept of "miscible function", a new method using component segmentation and combination was presented, in which component C_7^+ was segmented into several components. After that, the method was improved applying modified Redlich – Kwong equation of state to determine CO_2 minimum miscible pressure. It overcomes the shortcoming of the original method in which the critical value of heavy components was difficult to determine and it also improves the sensitivity of the calculated results to temperature. The contrast between calculated results and experimental ones indicates that the errors in determined minimum miscible pressure are less than 5%, and the validity of this method is proved.

Key words: minimum miscible pressure, slim – tube test, component segmentation, component recombination, equation of state, miscible function

Sun Yeheng, Geological Scientific Research Institute, Shengli Oilfield Co., Ltd., Dongying City, Shandong Province, 257015, China

Li Dongxia, Su Yuliang. Research on influence factors of capillary force in immiscible displacement. *PGRE*, 2006, 13(1):85~86

Capillary imbibition oil displacement as an important factor should be analyzed emphatically in the fractured oil reservoir with low permeability. The dimensional analysis method was used to the research of 1D immiscible displacement process considering the capillary force and the dimensionless expression of the capillary force was obtained. Influence factors of the capillary force during the displacement process were analyzed. The result shows that the influences of the capillary force on displacement are relative to the factors of rock wettability, crude oil viscosity, percolation rate, well spacing, porosity, rock permeability etc. In the development practice of the low permeability oilfield, the influence of the capillary force on the displacement should be sufficiently considered.

Key words: displacement, capillary force, dimensional analysis, low permeability oil reservoir

Li Dongxia, China University of Petroleum (East China), Dongying City, Shandong Province, 257061, China

Guan Wenlong, Wang Shihu, Cao Junhe et al. Analysis for difference between laboratory experiment results and analytical model solution of in – situ combustion in Zheng 408 block. *PGRE*, 2006, 13(1):87~89

In order to study the combustion drive mechanism of the sensible heavy oil reservoir, a series of physical simulation experiments of in – situ combustion were carried out by adoption of real formation cores and real crude oil of Zheng 408 pilot test block. There was an evident difference between experiments and calculated results of 1D mathematical model by dry combustion. The theoretical analysis showed the existence of mechanism of wet combustion was confident in high water saturation reservoir which contributed to the overhead advance of the combustion front and improved combustion drive effect.

Key words: in – situ combustion, dry combustion, wet combustion, physical simulation, mathematical model

Guan Wenlong, Postdoctor Research Station of Shengli Oilfield, SINOPEC, Dongying City, Shandong Province, 257000, China

Wang Jian, Huang Yun, Gu Hongjun et al. Optimization study of injection parameters for weak gel displacement control in conglomerate oil reservoir. *PGRE*, 2006, 13(1):90~91

For the special pore structure of various conglomerate reservoirs in Kelamayi Oilfield, we should do more study about injection parameters in weak gel profile control and flooding technology. The influencing rule of main agent concentration, slug size, injection rate and slug combination way on recovery efficiency were studied by physical simulation experiments and numerical simulation technology aiming at the condition of the conglomerate oil reservoir in Keshang formation of Qizhong area. The optimum injection parameters were chosen when the recovery efficiency was the highest, that is, the main agent concentration was 1100mg/L, slug size was 0.30PV, injection rate was 400mg/L · PV, slug assemblage way was high concentration ahead slug and main slug and low concentration slug.

Key words: weak gel, in – depth displacement control, physical simulation, numerical simulation, parameter optimization, recov-