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改进的低渗透带隔板底水油藏油井见水时间的预报式

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摘 要 底水油藏开发面临的核心问题是底水的锥进,准确的预测底水油藏油井的见水时间至关重要,它可为合理地制定油藏的开发方案提供依据。基于底水锥进和低渗透非达西渗流原理,考虑隔板下部底水锥进的垂向渗流方式和沿隔板的径向渗流方式,推导出低渗透带隔板的底水油藏油井见水时间的预测公式。对于低渗透带隔板的底水油藏,由于考虑了启动压力梯度和应力敏感等因素的影响,计算出的油井见水时间要比不考虑以上因素的值大。经鄂尔多斯盆地某油井的实际计算,预测的见水时间与实际见水时间较接近。该公式为准确预测此类油井的见水时间提供了借鉴和指导意义。

关键词 低渗透油藏 隔板 底水油藏 启动压力梯度 应力敏感

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低渗透砂岩底水油藏储量丰富,底水在低渗透油藏的开发中起着重要的作用:一方面,相比于常规油藏的开发,底水在油水压力差的作用下向上锥进,可以为低渗透油藏的开发提供驱动能量;另一方面,底水油藏油井容易较早的见水,致使油井含水过高而较早关井;同时,产出的底水增加了额外的地面处理水的费用。至关重要的是,由于底水的产出,地层能量降低,导致油藏的采出程度降低[1]。关于底水油藏,人们关注的核心是油井何时见水,以便为合理的安排油井的日常管理工作提供参考依据[2]。在底水油藏的开发过程中,隔板对抑制底水锥进具有明显的效果。但关于低渗透带隔板的底水油藏油井见水时间的研究较少。

自从隔板理论提出以来,众多研究学者对有无隔板的底水油藏的见水时间进行了研究[3—8]。朱圣举[9]基于底水锥进和低渗透非达西渗流原理,推导出了低渗透无隔板底水油藏油井见水时间的预报公式。李传亮[10]提出了带隔板底水油藏油井见水时间预报公式,在该公式的基础上,文献[11]对其进行了改进,根据物质平衡原理,将隔板下部的底水锥进假设为圆台形,预测了该假设条件下底水油井的见水时间。赵新智[12]将该改进公式应于低渗透油藏,并考虑了启动压力梯度对见水时间的影响。但是,在低渗透油田开发中,储层的应力状态发生变化,从而引起储层渗透率和日产油量的降低,即存在着应力敏感现象[13,14]。以上研究者均未涉及应力敏感对低渗透带隔板底水油藏油井见水时间的影响。因此,在计算带隔板底水油藏油井见水时间时,不应忽略启动压力梯度和应力敏感对见水时间的影响。

基于低渗透非达西渗流理论,并结合底水锥进原理,推导了同时考虑启动压力梯度和应力敏感的低渗透底水油藏油井见水时间的计算式。由于综合考虑了以上因素的影响,推导出的低渗透带隔板底水油藏油井见水时间的预报式,能够比较准确地预测此类油藏油井的见水时间。

1 物理模型和基本假设

对于带隔板的低渗透底水油藏,在油井投产之后,底水在压力差的作用之下向上锥进[15—18],在稳态情况下底水锥进到临界状态(即底水锥进到油井底部)时的油水运动形态如图1(蓝色箭头)所示。

假设隔板近似于圆形且比较厚,井位于圆形隔板中心位置,h_p表示储层射孔段厚度。当油井投产后,底水将向上锥进。在隔板下面,底水沿箭头AB所示,垂向锥进;当底水到达B点时,底水沿隔板从B点向C点的流动为平面径向渗流。

油井生产过程中,底水首先从油水界面上的A点锥进到隔板边缘的B点,接着沿B点径向流动到生产井底C点。该油井总的见水时间为t_{AB}和t_{BC}之和。为了简化数学分析,在推导过程中作如下假设:

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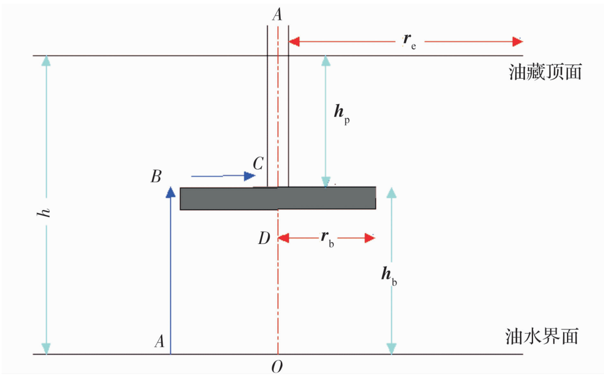

图 1 低渗透带隔板的底水油藏底水锥进示意图

1)流体在储层的流动为稳定流动。

2)忽略重力和毛细管力,油、水之间有明显的界面。

3)油、水的密度和黏度均为常数。

4)油井井底下的隔板为圆形。

5)油藏供给边界上压力保持恒定。

2 公式的推导

2.1 底水垂向流动的时间

由低渗透非达西渗流定律,油质点的垂向流速为[19]:

$$v = \frac{0.086\,4\alpha K}{\mu_o}\left(\frac{dp}{dz} - G\right) \tag{1}$$

式(1)中,v 为渗流速度,m/s;α 为油层垂向渗透率与水平渗透率之比,无量纲;μ_o 为地层流体黏度,mPa·s;p 为压力,MPa;G 为启动压力梯度,MPa/m。

对式(1)进行积分,得油井的生产压差为

$$\int_0^{h_b}\left(\frac{v\mu_o}{0.086\,4\alpha K} + G\right)dz = \int_{p_b}^{p_e} dp \tag{2}$$

$$\Delta p = p_e - p_b - Gh_b = \frac{v\mu_o h_b}{0.086\,4\alpha K} \tag{3}$$

式(3)中,Δp 为生产压差,MPa;p_e为供给压力,MPa;p_b为半渗透隔板边缘压力,MPa;h_b为油水界面到隔板上部的距离,m;K 为岩石渗透率,$\times 10^{-3}\mu m^2$。

根据油井的产能公式

$$q_o = \frac{2\pi Kh\Delta p}{\mu_o \ln\frac{r_e}{r_b}} \tag{4}$$

式(4)中,q_o为油井产量,m^3/d;r_e为油井泄油半径,m;r_b为隔板半径,m;h 为油藏厚度,m。

联立式(3)和式(4),得油井垂向锥进的流动时间为

$$t_{AB} = \frac{h_b}{v} = \frac{hh_b^2}{0.159\,\alpha q_o \ln\frac{r_e}{r_b}} \tag{5}$$

2.2 底水径向流动的时间

底水锥进到隔板时,平面径向渗流的压力梯度公式为

$$\frac{dp}{dr} - G = \frac{p_b - p_{wf}}{\ln\frac{r_b}{r_w}} \cdot \frac{1}{r} \tag{6}$$

式(6)中:r_w为油井半径,m。

由非达西渗流定律,结合式(6),得到渗流速度的公式为

$$v = \frac{K}{\mu_o}\frac{p_b - p_{wf} - Gr_b}{\ln\frac{r_b}{r_w}}\frac{1}{r} = \frac{dr}{dt} \tag{7}$$

对式(7)进行积分,得底水径向流动的时间:

$$\int_0^{t_{BC}}\left(\frac{K}{\mu_o}\frac{p_b - p_{wf} - Gr_b}{\ln\frac{r_b}{r_w}}\right)dt = \int_{r_w}^{r_b} r\,dr \tag{8}$$

$$t_{BC} = \frac{\mu_o}{K}\frac{\ln\frac{r_b}{r_w}}{(p_b - p_{wf} - Gr_b)}\frac{(r_b^2 - r_w^2)}{2} \tag{9}$$

根据油井的产能公式

$$q_o = \frac{2\pi Kh\Delta p}{\mu_o \ln\frac{r_b}{r_w}} \tag{10}$$

将式(10)代入式(9),得底水径向流动的时间为

$$t_{BC} = \frac{\pi h(r_b^2 - r_w^2)}{q_o} \tag{11}$$

根据图 1 底水的流动路径所示,总的见水时间为

$$t_{AB} = \frac{hh_b^2}{0.159\,\alpha q_o \ln\frac{r_e}{r_b}} + \frac{\pi h(r_b^2 - r_w^2)}{q_o} = \frac{1}{q_o}\left[\frac{hh_b^2}{0.159\alpha\ln\frac{r_e}{r_b}} + \pi h(r_b^2 - r_w^2)\right] \tag{12}$$

考虑应力敏感的油井产量计算公式

$$q_o = \frac{2\pi Kh(p_e - p_{wf} - G r_e)}{\mu_o \ln\frac{r_b}{r_w}} e^{-b(p_e - \bar{p})} \tag{13}$$

$$q_o = q_i\, e^{-b(p_e - \bar{p})} \tag{14}$$

式(14)中,q_i为原始条件下的油井产量,m^3/d;p_{wf}为井底流压,MPa;$\bar{p}$ 为平均地层压力,MPa;b 为应力敏感常数,MPa^{-1}。

将式(14)代入式(12),得到新的低渗透带隔板底水油藏油井见水时间的预测公式为

$t_{AB} =$

$$\frac{1}{q_i e^{-b(p_e-\bar{p})}}\left[\frac{hh_b^2}{0.159\alpha\ln\frac{r_e}{r_b}}+\pi h(r_b^2-r_w^2)\right] \tag{15}$$

3　实例分析

以鄂尔多斯盆地某带隔板的底水油藏为例,计算油井见水时间。该低渗透砂岩底水油藏油井的有关参数如下:$h=8$ m,$\alpha=0.7$,$q_i=10$ m^3/d,$K=1\times10^{-3}$ μm^2,$p_e=18.5$ MPa,$\bar{p}=14$ MPa,$r_e=500$ m,$r_w=0.1$,$r_b=30$ m,$h_b=5$ m,$b=0.02$。

将以上参数代入式(15),即可得该井的见水时间为605.59 d,而该井的实际见水时间为589 d,二者仅相差16 d,如果忽略应力敏感的影响,计算的见水时间为543.47 d,与实际见水时间相差46 d。由此可见,考虑应力敏感和启动压力梯度的计算公式,相比于不考虑以上因素的时间长,计算的见水时间与实际见水时间比较接近。

4　结语

(1)建立了新的低渗透带隔板底水油藏油井见水时间的预测公式。考虑了启动压力梯度和应力敏感对见水时间的影响,计算的油井见水时间与实际见水时间比较接近。

(2)由于考虑了低渗透油藏的启动压力梯度和应力敏感等影响因素,相比于不考虑以上因素,新公式计算的见水时间较长。

参　考　文　献

1　唐人选.底水油藏水锥动态模拟及见水时间预测.新疆石油地质,2003;246):572—573
2　李传亮.油藏工程.北京:石油工业出版社,2005:337—339
3　MORADI B, DASTKHAN Z, ROOZBEHANI B. The design and preparation of a simulator for the water coning phenomenon applying in fractured reservoirs. Petroleum Science and Technology,2012; 30: 1579—1590
4　Di L G, Rae P. New insights into water control: a review of the state of the art. SPE 77963, 2002
5　Sobocinski D P, Cornelius A J. A correlation for predicting water coning time. J Pet Technol,1965;17: 594—600
6　Hongen D, Guan Changzhi, Lian Shengjiang. The experimental studies of physical simulation of bottom water reservoirs with barrier and permeable interbed on horizontal well. SPE 55995, 1999
7　Tu Xingwan, Peng Xiaolong, Chen Zhaohui. Research and field application of water-coning control with production-balanced method in bottom water reservoir. SPE 105033, 2007
8　王　庆,刘慧卿,李华释,等.底水油藏水平井见水时间影响因素研究.油气田地面工程,2010;29(9):6—7
9　朱圣举.低渗透无隔板底水油藏油井见水时间预测.新疆石油地质,2001;22(2):153—154
10　李传亮.带隔板底水油藏油井见水时间预报公式.大庆石油地质与开发,1997;16(4):49—50
11　朱圣举.带隔板底水油藏油井见水时间预报公式的改进.大庆石油地质与开发,1999;18(3):36—37
12　赵新智,朱圣举.低渗透带隔板底水油藏油井见水时间预测.石油勘探与开发, 2012;39(04):471—474
13　郭　肖,伍　勇.启动压力梯度和应力敏感效应对低渗透气藏水平井产能的影响.石油与天然气地质,2007;28(4):523—527
14　刘　峰,王裕亮,陈小凡,等.考虑应力敏感的低渗透油藏油井产能分析.石油与天然气地质,2013;34(1):124—128
15　Si S S, Wojtanowicz A K. A study of water coning control in oil wells by injected or natural flow barriers using scaled physical model and numerical simulator. SPE 77415, 2002
16　Wibowo W, Permadi P, Mardisewojo P, *et al*. Behavior of water cresting and production performance of horizontal well in bottom water drive reservoir: a scaled model study. SPE 77415, 2004
17　陈朝晖,邓　勇,许　博,等.缝洞型底水油藏油井底水突破时间预测方法—以塔河油田4区$48井为例.石油与天然气地质,2012;33(5):791—794
18　刘振宇,程　博.水平井开发研究—底水油藏的水脊变化及见水时间预测.大庆石油学院学报,2002;26(4):100—103
19　李晓平.地下油气渗流力学.北京:石油工业出版社,2008:54—59

A Modified Water Breakthrough Time Prediction Formula for Low-permeability Bottom Water Reservoirs with Barrier

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[**Abstract**] The main problem of bottom water reservoir development is water coning, it is very important to predict accurately the oil well water breakthrough time which can provide basis for reasonable development scheme for reservoir. Based the water coning and low-permeability non-Darcy seepage principle, considered the coning of bottom water vertical seepage and the radial flow along the barrier, the prediction formula of water breakthrough time of low permeability bottom water reservoir with barrier was derived. For low permeability bottom water reservoir with barrier, because of considering the influence of the starting pressure gradient and stress sensitivity factors, the calculated water breakthrough time is larger than that without considering the above factors. Through the actual calculation of oil wells in Erdos Basin, the prediction water breakthrough time is close to the actual. The formula can provide reference and guidance for predicting such wells water breakthrough time accurately.

[**Key words**] low permeability reservoir barrier bottom water reservoir starting pressure gradient stress sensitivity

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Research of Sandstone Reservoir Physical Properties Estimation Based on Elman Neural Networks with Hybrid Dimensionality Reduction

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[**Abstract**] For the high economic cost of rock physical properties tested in laboratory, an intelligent method which based on Elman neural networks with the hybrid dimensionality reduction, was proposed to estimate the properties of sandstone. With grey correlation analysis method, the correlation between rock slice characteristic parameters and physical properties were built. Then the appropriate parameters with high correlation would be chosen, and the second dimensionality reduction process was utilized for these parameters by principal component analysis method. Finally, the mapping relationship between rock slice characteristic parameters and physical properties had been found through Elman neural networks. The estimation validity and reliability for this method were tested with practical data from Xuecha, Wuqi region in Ordos Basin. The result showed that the average relative errors of porosity and permeability estimation for this method were 7.28% and 6.25% respectively, and this method had the better convergence speed and more accuracy than others. Therefore, by using the cheap rock slice related information, the rock reservoir physical parameters can be estimated efficiently and accurately, and it is of high reliability, practicability and application prospect.

[**Key words**] hybrid dimensionality reduction Elman neural networks sandstone reservoir physical properties intelligent computing