带隔板底水油藏水平井见水时间预测方法

黄全华,陆 云*,付云辉,陈 冲,童 凯
(西南石油大学 石油工程学院,四川 成都 610500)

摘要:底水脊进是底水油藏水平井开发过程中经常遇到的重要问题,准确地预测底水脊进的时间对于底水油藏合理开发至关重要。针对带隔板底水油藏水平井,基于油水两相渗流理论及流体在多孔介质中的流动规律,建立物理模型,并利用镜像反映和势叠加原理得到底水油藏水平井势分布,推导了带隔板底水油藏水平井见水时间公式。实例计算结果表明,该公式计算结果与实际见水时间相对误差为5.39%,隔板的存在大大延缓了水平井底水脊进的时间,且随着隔板半径增大和避水高度的增加,见水时间越长;水平井见水时间随着水平井段长度的减小和产油量 的增大而缩短。该研究对于带隔板底水油藏中水平井段长度和避水高度的设计以及油藏合理开发具有一定指导意义。

关键词:底水油藏 隔板 水平井 水脊 镜像反映 见水时间
中图分类号:TE341 **文献标识码**:A **文章编号**:1009-9603(2016)06-0082-05

Prediction method of water breakthrough time of horizontal wells in bottom water reservoir with barrier

Huang Quanhua, Lu Yun, Fu Yunhui, Chen Chong, Tong Kai
(*Petroleum Engineering Institute, Southwest Petroleum University, Chengdu City, Sichuan Province*, 610500, *China*)

Abstract: Bottom water coning is one of the important problems in the development process of horizontal wells in bottom water reservoir. To accurately predict the time of bottom water coning is vital for reasonable development of the bottom water reservoir. For the horizontal wells in bottom water reservoir with barrier, physical model was establish based on oil-water two phase flow theory and the law of fluid flow in porous media, and potential distribution of horizontal wells in bottom water reservoir was obtained through the mirror image and potential superposition principle. The formula for water breakthrough time of horizontal wells in bottom water reservoir with barrier was deduced. Case calculation shows that the relative error between the formula calculation results and the actual water breakthrough time is 5.39%. The existence of the barrier greatly delays the bottom water coning time, and the water breakthrough time increases with the increase of the barrier radius and water avoidance height. With decrease of horizontal section length and increases of daily oil production, the water breakthrough time of horizontal well decreases. The research has certain guiding significance for the design of the horizontal well length and water avoidance height and development of the bottom water reservoir with barrier reservoir.

Key words: bottom water reservoir; barrier; horizontal well; water coning; mirror image; water breakthrough time

水平井具有泄油面积大、生产压差小等特点,能有效延缓底水脊进和延长无水开采期,在底水油藏开发过程中得到广泛应用[1-2]。但水平井一旦见水,含水率将快速上升且产油量骤减,大大降低了油气田的采收率,因此准确地预测底水脊进时间对于底水油气藏合理开发至关重要。中外许多学者对水平井开采底水油藏做了大量研究[3-4]。Giger建立二维水平井底水脊进模型,推导出水平井见水时

收稿日期:2016-07-06。
作者简介:黄全华(1968—),男,四川营山人,副教授,博士,从事油气藏工程研究。联系电话:13540319656,E-mail:swpuhqh@126.com。
*通讯作者:陆云(1990—),男,湖北天门人,在读硕士研究生。联系电话:18117833889,E-mail:454637893@qq.com。
基金项目:国家科技重大专项"亚太及南美地区复杂油气田渗流机理及开发规律研究"(2011ZX05030-005-06)。

间公式[5]；Yang等通过数值模拟技术研究水平井底水脊进规律及影响因素[6]；范子菲等运用保角变换和势函数理论推导出底水油藏水平井的产能公式和见水时间公式[7]；程林松等利用镜像反映和势叠加理论推导出底水油藏水平井见水时间预测公式[8]。这些研究均是以无隔板底水油气藏水平井模型为基础，而对于带隔板底水油气藏中水平井的研究较少，有少数学者通过实验和数值模拟方法对底水油藏中隔板进行了相关研究[9-12]。笔者针对带隔板底水油藏水平井，以油水两相渗流理论及质点在多孔介质中的流动规律为基础，运用镜像反映和势叠加理论，推导带隔板底水油藏中水平井见水时间预测公式，并通过实例分析产油量、水平井长度和避水高度以及隔板半径对见水时间的影响。

1　模型的建立及势分布

1.1　模型的建立

假设有一带隔板的底水油藏，其隔板的存在改变了底水锥进的路线(图1)。底水先从A点垂直锥进到隔板边缘的B点，由于隔板的作用，底水并不会立即向井底流动，而是从B点流动到C点，再从C点流动到水平井筒D点。

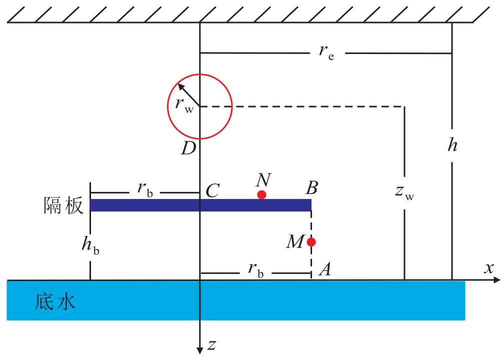

图1　带隔板底水油藏水平井水脊示意

Fig.1　Water coning of horizontal wells in bottom water reservoir with barrier

1.2　势分布

设油水界面为恒压界面，通过镜像反映和势叠加理论可得到底水油藏中xz平面内任意点的势分布[13-14]为

$$\Phi(x,z)=\Phi_e+\frac{q_{sc}B_o}{2L}\times\ln\frac{\left[\mathrm{ch}\frac{\pi x}{2h}-\cos\frac{\pi(z-z_w)}{2h}\right]\left[\mathrm{ch}\frac{\pi x}{2h}+\cos\frac{\pi(z+z_w)}{2h}\right]}{\left[\mathrm{ch}\frac{\pi x}{2h}+\cos\frac{\pi(z-z_w)}{2h}\right]\left[\mathrm{ch}\frac{\pi x}{2h}-\cos\frac{\pi(z+z_w)}{2h}\right]} \tag{1}$$

2　见水时间公式推导

由图1可知，带隔板底水油藏水平井见水时间可分为3部分：底水从A点上升到隔板边缘B点的时间、底水从隔板边缘B点沿着隔板流向C点的时间、最后底水从C点脊进到水平井筒D点的时间。

2.1　底水从A点到B点的时间

根据由式(1)求取获得的底水油藏中任意点的势分布，可求得AB直线($x=r_b$)上势函数梯度为

$$\left.\frac{\partial\Phi}{\partial z}\right|_{x=r_b}=\frac{\pi q_{sc}B_o\,\mathrm{ch}\frac{\pi r_b}{2h}\left\{\sin\frac{\pi(z-z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z+z_w)}{2h}\right]-\sin\frac{\pi(z+z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z-z_w)}{2h}\right]\right\}}{2hL\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z-z_w)}{2h}\right]\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z+z_w)}{2h}\right]} \tag{2}$$

沿AB方向上任意点M处(图1)底水的渗流速度为

$$v_z=-\left.\frac{\partial\Phi}{\partial z}\right|_{x=r_b}=\frac{\pi q_{sc}B_o\,\mathrm{ch}\frac{\pi r_b}{2h}\left\{\sin\frac{\pi(z+z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z-z_w)}{2h}\right]-\sin\frac{\pi(z-z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z+z_w)}{2h}\right]\right\}}{2hL\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z-z_w)}{2h}\right]\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z+z_w)}{2h}\right]} \tag{3}$$

根据油水两相渗流理论及流体在多孔介质中的流动规律可知

$$\mathrm{d}t=\left[\frac{\phi(1-S_{wi}-S_{or})}{v_z}\right]\mathrm{d}r \tag{4}$$

将式(3)代入式(4)并积分可得底水从A点到B点的时间为

$$t_{AB}=\int_0^{h_b}\frac{2hL\phi(1-S_{wi}-S_{or})\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z-z_w)}{2h}\right]\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z+z_w)}{2h}\right]}{\pi q_{sc}B_o\,\mathrm{ch}\frac{\pi r_b}{2h}\left\{\sin\frac{\pi(z+z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z-z_w)}{2h}\right]-\sin\frac{\pi(z-z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi r_b}{2h}-\cos^2\frac{\pi(z+z_w)}{2h}\right]\right\}}\mathrm{d}z \tag{5}$$

2.2 底水从*B*点到*C*点的时间

根据由式(1)求取获得的底水油藏中任意点的势分布,可以得到BC直线($z=h_b$)上势函数梯度的表达式为

$$\left.\frac{\partial\Phi}{\partial x}\right|_{z=h_b}=\frac{\pi q_{sc}B_o\,\mathrm{sh}\frac{\pi x}{2h}\left\{\cos\frac{\pi(h_b-z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b+z_w)}{2h}\right]-\cos\frac{\pi(h_b+z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b-z_w)}{2h}\right]\right\}}{2hL\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b-z_w)}{2h}\right]\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b+z_w)}{2h}\right]} \tag{6}$$

沿BC方向上任意点N处(图1)底水的渗流速度为

$$v_z=-\left.\frac{\partial\Phi}{\partial x}\right|_{z=h_b}=\frac{\pi q_{sc}B_o\,\mathrm{sh}\frac{\pi x}{2h}\left\{\cos\frac{\pi(h_b+z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b-z_w)}{2h}\right]-\cos\frac{\pi(h_b-z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b+z_w)}{2h}\right]\right\}}{2hL\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b-z_w)}{2h}\right]\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b+z_w)}{2h}\right]} \tag{7}$$

将式(7)代入式(4)并积分可得底水从B点到C点的时间为

$$t_{BC}=\int_{r_b}^{0}\frac{2hL\phi(1-S_{wi}-S_{or})\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b-z_w)}{2h}\right]\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b+z_w)}{2h}\right]}{\pi q_{sc}B_o\,\mathrm{sh}\frac{\pi x}{2h}\left\{\cos\frac{\pi(h_b+z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b-z_w)}{2h}\right]-\cos\frac{\pi(h_b-z_w)}{2h}\left[\mathrm{ch}^2\frac{\pi x}{2h}-\cos^2\frac{\pi(h_b+z_w)}{2h}\right]\right\}}\mathrm{d}x \tag{8}$$

2.3 底水从*C*点到*D*点的时间

根据由式(1)求取获得的底水油藏中任意点的势分布,可求得CD直线(x=0)上势函数梯度为

$$\left.\frac{\partial\Phi}{\partial z}\right|_{x=0}=\frac{\pi q_{sc}B_o\left[\sin\frac{\pi(z+z_w)}{2h}-\sin\frac{\pi(z-z_w)}{2h}\right]}{2hL\sin\frac{\pi(z+z_w)}{2h}\sin\frac{\pi(z-z_w)}{2h}} \tag{9}$$

沿CD方向上任意点(图1)底水的渗流速度为

$$v_z=-\left.\frac{\partial\Phi}{\partial z}\right|_{x=0}=\frac{\pi q_{sc}B_o\left[\sin\frac{\pi(z-z_w)}{2h}-\sin\frac{\pi(z+z_w)}{2h}\right]}{2hL\sin\frac{\pi(z+z_w)}{2h}\sin\frac{\pi(z-z_w)}{2h}} \tag{10}$$

将式(10)代入式(4)并积分可得底水从C点到D点的时间为

$$t_{CD}=\int_{h_b}^{z_w-r_w}\frac{2hL\phi(1-S_{wi}-S_{or})\sin\frac{\pi(z+z_w)}{2h}\sin\frac{\pi(z-z_w)}{2h}}{\pi q_{sc}B_o\left[\sin\frac{\pi(z-z_w)}{2h}-\sin\frac{\pi(z+z_w)}{2h}\right]}\mathrm{d}z \tag{11}$$

则带隔板底水油藏水平井见水时间为

$$t=t_{AB}+t_{BC}+t_{CD} \tag{12}$$

3 实例分析

某底水油藏的基本参数包括:油层厚度为20 m,水平井段长度为500 m,水平井避水高度为15 m,隔板到油水界面的高度为10 m,隔板到水平井筒的距离为5 m,隔板半径为10 m,油的体积系数为1.34,油井的井径为0.101 2 m,孔隙度为0.15,束缚水饱和度为0.35,残余油饱和度为0.2。油井初期平均产油量为60 m³/d。

通过MATLAB编程数值求解得到底水从A点到B点的时间、从B点到C点的时间和从C点到D点的时间分别为36.3,389.9和4.4 d,根据式(12)可计算出带隔板底水油藏水平井见水时间为430.6 d。若不考虑隔板的影响,可计算出水平井见水时间为27.3 d。

该底水油藏的水平井初期平均产油量为60 m³/d时,若以无隔板底水油藏水平井见水时间公式计算,油井应该很快见水,但实际该水平井生产408 d才见水(图2),根据式(12)计算的见水时间与实际见水时间相近,相对误差为5.39%,说明式(12)对于带隔板底水油藏水平井的见水时间预测具有较好的适用性。

从产油量及水平井段长度对水平井见水时间的敏感性分析(图3)可以看出,水平井见水时间随着产油量的增加和水平井段长度的减小而逐渐缩短。由式(3)、式(7)和式(10)可以得到,随着产油量的增加和水平井段长度的减小,底水脊进的速度变大,因此水平井见水时间变短。

当水平井产油量为60 m³/d时,计算分析水平

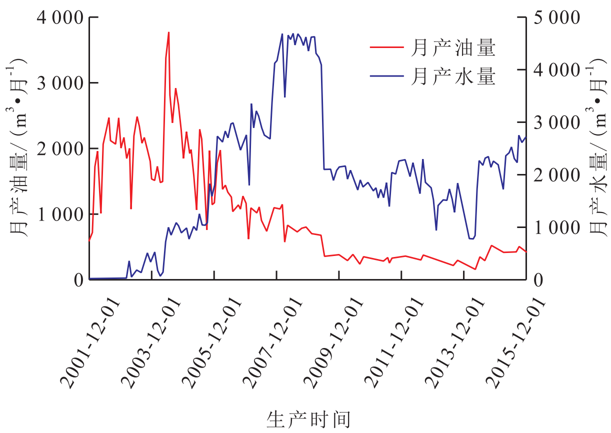

图2　带隔板底水油藏水平井油、水月产量随生产时间的变化曲线

Fig.2　Time-varying curves of monthly oil and water production of horizontal well in bottom water reservoirs with barrier

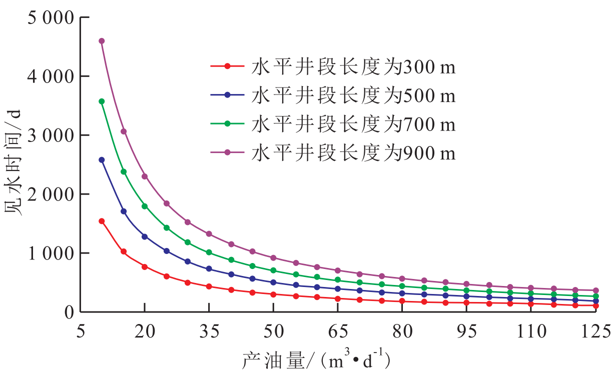

图3　带隔板底水油藏水平井见水时间与产油量的关系

Fig.3　Relationship between water breakthrough time and daily oil production of horizontal well in bottom water reservoirs with barrier

井避水高度和隔板半径对油井见水时间的影响，随着水平井避水高度和隔板半径的增加，水平井见水时间也变长(图4)。从图4可以看出，随着避水高度的增加，见水时间开始增长较缓慢，随后快速增加，当水平井快接近油层顶部时，见水时间基本不变；隔板半径对见水时间影响较大，当隔板半径增加

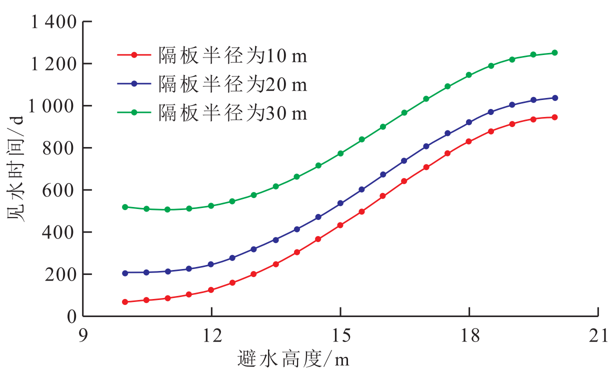

图4　带隔板底水油藏水平井见水时间与避水高度的关系

Fig.4　Relationship between water breakthrough time and height of water avoidance of horizontal well in bottom water reservoirs with barrier

时，见水时间快速增长，这说明隔板能有效地延缓底水脊进。

4　结论

针对带隔板底水油藏水平井，推导带隔板底水油藏中水平井见水时间预测公式，通过实例计算，该公式计算结果与实际见水时间相近，相对误差为5.39%，具有较好的适用性。水平井见水时间随着水平井段长度的减小和产油量的增加而缩短，随着水平井避水高度和隔板半径的增大而变长。对于具体的带隔板底水油藏，可综合考虑产油量和水平井段长度以及避水高度对水平井见水时间的影响，并以此确定合理的水平井长度、避水高度及产油量。

符号解释：

$\Phi(x,z)$——任意一点的势，μm²·MPa/(mPa·s)；Φ_e——油水界面的初始势函数，μm²·MPa/(mPa·s)；q_{sc}——气井日产油量，m³/d；B_o——油的体积系数；L——水平井长度，m；x——水平方向的距离，m；h——油层的厚度，m；z——垂直方向的距离，m；z_w——避水高度，m；r_b——隔板的半径，m；v_z——底水锥进的速度，m/s；t——底水移动的时间，d；ϕ——孔隙度；S_{wi}——束缚水饱和度；S_{or}——残余油饱和度；r——底水移动的距离，m；t_{AB}——底水从A点到B点的时间，d；h_b——隔板距油水界面的高度，m；t_{BC}——底水从B点到C点的时间，d；t_{CD}——底水从C点到D点的时间，d。

参考文献：

[1]　王庆，刘慧卿，曹立迎.非均质底水油藏水平井水淹规律研究[J].岩性油气藏，2010，22(1)：122-125.
Wang Qing，Liu Huiqing，Cao Liying.Water flooding law of horizontal well in heterogeneous bottom water reservoir[J].Lithologic Reservoirs，2010，22(1)：122-125.

[2]　王涛，赵进义.底水油藏水平井含水变化影响因素分析[J].岩性油气藏，2012，24(3)：103-107.
Wang Tao，Zhao Jinyi.Influencing factors of water cut for horizontal wells in bottom water reservoir[J].Lithologic Reservoirs，2012，24(3)：103-107.

[3]　Chaperon I.Theoretical study of coning toward horizontal and vertical wells in anisotropic formations：Subcritical and critical rates[C].SPE 15377，1986.

[4]　朱维耀，黄小荷，岳明.底水气藏水平井见水时间研究[J].科技导报，2014，32(8)：27-31.
Zhu Weiyao，Huang Xiaohe，Yue Ming.Prediction of water breakthrough time of horizontal wells in gas reservoirs with bottom water[J].Science & Technology Review，2014，32(8)：27-31.

[5]　Giger F M.Analytic 2-D models of water cresting before break-

through for horizontal wells[C].SPE 15378,1986.

[6] Yang W,Wattenbarger R A.Water coning calculations for vertical and horizontal wells[C].SPE 22931,1991.

[7] 范子菲,傅秀娟.气顶底水油藏水平井产能公式和见水时间研究[J].中国海上油气:地质,1995,9(6):46-53.
Fan Zifei,Fu Xiujuan.A study of productivity and breakthrough time of horizontal well in a reservoir with gas-cap and bottom-water drive[J].China Offshore Oil and Gas:Geology,1995,9(6):46-53.

[8] 程林松,郎兆新,张丽华.底水驱油藏水平井锥进的油藏工程研究[J].石油大学学报:自然科学版,1994,18(4):43-47.
Cheng Linsong,Lang Zhaoxin,Zhang Lihua.Reservoir engineering problem of horizontal wells coning in bottom-water driven reservoir[J].Journal of the University of Petroleum,China:Edition of Natural Science,1994,18(4):43-47.

[9] 魏绍蕾,程林松,张辉登,等.夹层对加拿大麦凯河油砂区块双水平井蒸汽辅助重力泄油开发的影响[J].油气地质与采收率,2016,23(2):62-69.
Wei Shaolei,Cheng Linsong,Zhang Huideng,et al.Physical simulation of the interlayer effect on SAGD production by dual horizontal well in Mackay River oil sands block,Canada[J].Petroleum Geology and Recovery Efficiency,2016,23(2):62-69.

[10] 朱德顺,王勇,朱德燕,等.渤南洼陷沙一段夹层型页岩油界定标准及富集主控因素[J].油气地质与采收率,2015,22(5):15-20.
Zhu Deshun,Wang Yong,Zhu Deyan,et al.Analysis on recognition criteria and enrichment factors of interlayer shale oil of Es_1 in Bonan subsag[J].Petroleum Geology and Recovery Efficiency,2015,22(5):15-20.

[11] 屈亚光,丁祖鹏,潘彩霞,等.厚油层层内夹层分布对水驱效果影响的物理实验研究[J].油气地质与采收率,2014,21(3):105-107,110.
Qu Yaguang,Ding Zupeng,Pan Caixia,et al.Physical experiment on distribution of interlayers impact on water flooding recovery efficiency[J].Petroleum Geology and Recovery Efficiency,2014,21(3):105-107,110.

[12] 党胜国,冯鑫,闫建丽,等.夹层研究在水平井开发厚层底水油藏中的应用——以曹妃甸11-6油田Massive砂体为例[J].油气地质与采收率,2015,22(1):63-67.
Dang Shengguo,Feng Xin,Yan Jianli,et al.Interlayer research application in horizontal well development of thick bottom water reservoir-a case of Massive sand in Caofeidian11-6 oilfield[J].Petroleum Geology and Recovery Efficiency,2015,22(1):63-67.

[13] 陈明,沈燕来,杨寨.底水油藏水平井合理位置的确定方法研究[J].西南石油学院学报,2003,25(6):31-34.
Chen Ming,Shen Yanlai,Yang Zhai.Method of determining optimum well location for horizontal well in bottom-water reseroir[J].Journal of Southwest Petroleum Institute,2003,25(6):31-34.

[14] 时宇,杨正明,张训华,等.底水油藏水平井势分布及水锥研究[J].大庆石油地质与开发,2008,27(6):72-75.
Shi Yu,Yang Zhengming,Zhang Xunhua,et al.Studies of the potential distribution and water coning of horizontal well in a bottom- water driven oil resrvoir[J].Petroleum Geology & Oilfield Development in Daqing,2008,27(6):72-75.

编辑 王 星

(上接第81页)

[12] Lu X,Jiang H,Smørgrav E,et al.A new thermal degradation model of polymer in high- temperature reservoirs[C].SPE 176460-MS,2015.

[13] Flory P J,Fox T G.Principles of polymer chemistry[M].Ithaca:Cornell University Press,1953.

[14] 林春阳,张贤松,刘慧卿.聚合物溶液老化作用数值模型研究[J].石油天然气学报,2012,34(12):143-147.
Lin Chunyang,Zhang Xiansong,Liu Huiqing.Study on numerical model considering polymer solution aging process[J].Journal of Oil and Gas Technology,2012,34(12):143-147.

[15] Hægland H,Dahle H K,Eigestad G T,et al.Improved streamlines and time-of-flight for streamline simulation on irregular grids[J].Advances in Water Resources,2007,30(4):1 027-1 045.

[16] Parsons R W.Directional permeability effects in developed and unconfined five-spots[J].Journal of Petroleum Technology,1972,24(4):487-494.

[17] Pollock D W.Semianalytical computation of path lines for finite-difference models[J].Ground Water,1988,26(6):743-750.

[18] Jimenez E,Sabir K,Datta-Gupta A,et al.Spatial error and convergence in streamline simulation[C].SPE 92873-MS,2005.

[19] Martin J C,Woo P T,Wagner R E.Failure of stream tube methods to predict waterflood performance of an isolated inverted five-spot at favorable mobility ratios[J].Journal of Petroleum Technology,1973,25(2):151-153.

[20] Krogstad S,Lie K A,Møyner O,et al.MRST-AD-an open-source framework for rapid prototyping and evaluation of reservoir simulation problems[C].SPE 173317-MS,2015.

编辑 王 星