改进型水驱特征曲线计算技术可采储量的公式推导及其应用

王 华
(中国石化股份胜利油田分公司 地质科学研究院，山东 东营 257015)

摘要：水驱特征曲线法是水驱油藏计算技术可采储量的重要方法之一，在中高含水开发阶段得到广泛应用。然而，油田进入特高含水开发后期，水驱特征曲线会出现上翘现象，导致计算该时期的技术可采储量具有明显的不适应性。针对特高含水开发后期的开发特征，对水驱特征曲线进行了改进，推导出适用于特高含水开发后期的技术可采储量计算公式，拓宽了水驱特征曲线适用范围。利用改进型水驱特征曲线计算孤东油田七区西 $Ng5^4$—6^1 注水区的技术可采储量为 555×10^4 t，采收率为39.1%，符合矿场实际。为验证改进方法的适用性，筛选出胜利油区6个处于特高含水期且水驱特征曲线上翘的注水单元进行试验，结果表明，改进方法的计算结果更符合油田实际。

关键词：特高含水开发后期 水驱特征曲线 技术可采储量 最小二乘法
中图分类号：TE319 文献标识码：A 文章编号：1009-9603(2012)04-0084-03

水驱特征曲线法是天然水驱和人工注水开发油田所特有的实用方法，被广泛应用于油藏动态分析、技术可采储量计算及开发指标预测[1-2]，其理论依据是累积产油量和累积产水量在半对数坐标系中表现出的直线关系，根据直线关系外推可得到技术可采储量。矿场实践表明，这种直线关系在中高含水开发阶段具有很好的适应性，但在特高含水开发阶段，水驱特征曲线会出现上翘现象，使得水驱特征曲线偏离直线，表现出非线性。陈元千等研究了曲线上翘的原因[3]，于波等研究了曲线上翘的时机、影响因素和校正方法[4-13]，但上述研究都是基于传统方法进行的。笔者对传统水驱特征曲线公式进行改进，并在改进公式的基础上推导出技术可采储量的计算公式，以期为特高含水期技术可采储量的计算提供参考。

1 公式推导

矿场实践表明：特高含水开发后期，甲型和乙型水驱特征曲线会出现上翘现象，这一现象会导致传统水驱特征曲线表达式出现明显的不适应性，因此需要对其进行改进，以甲型水驱特征曲线为例说明改进过程。

传统的甲型水驱特征曲线的表达式[3]为

$$\lg W_p = A + BN_p \tag{1}$$

式中：W_p 为累积产水量，10^4 t；A，B 为系数；N_p 为累积产油量，10^4 t。

传统公式对于中高含水阶段的直线规律拟合效果较好，但对特高含水阶段的非线性规律，拟合效果较差，因此需要对其进行改进，以满足特高含水阶段计算技术可采储量的需要。研究发现，将式(1)右边增加一个非线性项，能较好地拟合特高含水阶段的非线性规律，即

$$\lg W_p = A + BN_p + Ce^{DN_p} \tag{2}$$

式中：C 和 D 为系数。

式(2)两边对时间求导，可得

$$\frac{1}{2.303W_p}\times\frac{dW_p}{dt} = B\frac{dN_p}{dt} + CDe^{DN_p}\frac{dN_p}{dt} \tag{3}$$

其中

$$\frac{dW_p}{dt} = Q_w \tag{4}$$

$$\frac{dN_p}{dt} = Q_o \tag{5}$$

式中：t 为时间，a；Q_w 为水相流量，m^3/s；Q_o 为油相流量，m^3/s。

收稿日期：2012-05-10。
作者简介：王华，男，工程师，硕士，从事油田开发综合研究。联系电话：(0546)8715298，E-mail：409875733@qq.com。
基金项目：国家科技重大专项“胜利油田特高含水期提高采收率技术”(2011ZX05011)。

将式(4)和式(5)代入式(3)可得

$$\frac{Q_w}{2.303W_p} = BQ_o + CDe^{DN_p}Q_o \tag{6}$$

含水率的表达式为

$$f_w = \frac{Q_w}{Q_w + Q_o} \tag{7}$$

式中:f_w 为含水率。

将式(7)代入式(6)可得

$$\frac{1}{2.303W_p} \times \frac{f_w}{1-f_w} = B + CDe^{DN_p} \tag{8}$$

由式(2)和式(8)可得

$$N_p = \frac{\ln\left(\frac{f_w}{1-f_w} \times \frac{1}{2.303 \times 10^{A+BN_p+Ce^{DN_p}}} - B\right) - \ln CD}{D} \tag{9}$$

令 $f_w = f_{wi}$(f_{wi} 为极限含水率,一般取值为 0.98),代入式(9)可得技术可采储量,即

$$N_R = \frac{\ln\left(\frac{f_{wi}}{1-f_{wi}} \times \frac{1}{2.303 \times 10^{A+BN_R+Ce^{DN_R}}} - B\right) - \ln CD}{D} \tag{10}$$

其中

$$N_R = NR^* \tag{11}$$

式中:N_R 为技术可采储量,10^4 t;N 为动用储量,10^4 t;R^* 为采收率。

由采出程度的定义可得

$$R = \frac{N_p}{N} \tag{12}$$

式中:R 为采出程度。

将式(12)代入式(9)可得

$$f_w = \frac{2.303(B + CDe^{DNR}) \times 10^{A+BNR+Ce^{DNR}}}{1 + 2.303(B + CDe^{DNR}) \times 10^{A+BNR+Ce^{DNR}}} \tag{13}$$

式(13)为改进型水驱特征曲线对应的理论含水率与采出程度的关系式。

2　参数求解方法

2.1　系数的求解方法

由于改进型水驱特征曲线是非线性方程,直接求解系数难度较大,可通过公式变换简化方程后再求解。令 $x = DN_p$,代入式(2)可得

$$\lg W_p = A + \frac{B}{D}x + Ce^x \tag{14}$$

假定已知某区块的累积产油量和累积产水量,D 任取一个初值(如 $D = 0.01$),计算对应的 x,然后绘制 $\lg W_p$ 与 x 的关系曲线,利用最小二乘法求出最佳拟合系数,即相关系数最大时的系数 A,B,C。取 N_p 最大值,计算 e^x 最大值,如果数据不溢出,则 A,B,C,D 为改进型水驱特征曲线的解;否则,改变初值 D,重新计算系数 A,B,C,直到满足要求为止。

2.2　技术可采储量计算方法

取极限含水率为 0.98[7],代入式(10),用牛顿迭代法计算技术可采储量。具体过程为:N_R 任取一个初值(例如 $N_R = 0.01$),代入式(10)的等号右边项,计算得到 N_{R1}(即式(10)左边的 N_R),如果 $|N_R - N_{R1}| < \delta$(δ 为允许的最大误差),则 N_{R1} 为所求的技术可采储量;否则,令 $N_R = N_{R1}$,重复上面的计算过程,直到 $|N_R - N_{R1}| < \delta$ 为止,此时得到的 N_{R1} 即为所求的技术可采储量。

3　应用实例

孤东油田七区西 $Ng5^4$—6^1 注水区动用储量为 1 421 × 10^4 t,技术可采储量为 567 × 10^4 t,采收率为 39.9%,综合含水率为 97.6%,采出程度为 37.7%,目前已进入特高含水开发后期(表 1)。

表 1　孤东油田七区西 $Ng5^4$—6^1 注水区开发数据

时间	累积产油量/10^4 t	累积产水量/10^4 t	含水率,%	采出程度,%
1991	224	111	84.2	15.7
1992	263	427	90.2	18.5
1993	294	758	91.9	20.7
1994	322	1 123	93.7	22.6
1995	347	1 544	94.9	24.3
1996	370	1 999	95.4	26.0
1997	388	2 438	96.3	27.3
1998	405	2 871	96.4	28.4
1999	421	3 312	96.8	29.5
2000	436	3 760	96.3	30.6
2001	451	4 157	96.2	31.6
2002	467	4 519	95.1	32.8
2003	483	4 843	95.2	33.9
2004	497	5 151	95.8	34.9
2005	510	5 443	96.4	35.8
2006	520	5 740	96.9	36.5
2007	529	6 049	97.4	37.2
2008	530	6 075	97.6	37.7

利用表 1 数据,进行曲线拟合求解水驱特征曲线系数(图1)。系数拟合结果为:$A = 3.26$,$B =$

0.063 6，$C=0.000\ 9$，$D=0.01$。取极限含水率为 0.98，代入式（10）—式（11）可得技术可采储量为 555×10^4 t，采收率为 39.1%，与矿场实际相符。而利用传统方法计算该区块的技术可采储量为 685×10^4 t，采收率为 48.2%，计算结果偏差较大。

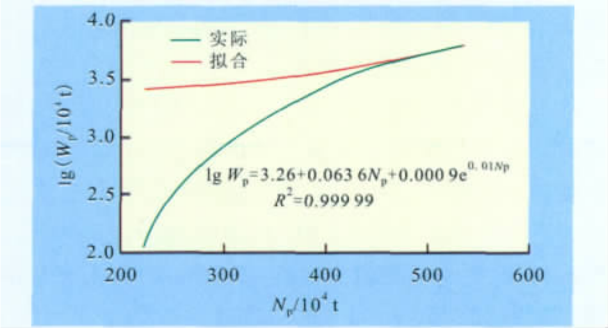

图1　孤东油田七区西 $Ng5^4$—6^1 注水区改进型水驱特征曲线系数拟合结果

将所得到的系数 A，B，C，D 和表 1 中的采出程度代入式（13），得到理论含水率，由理论含水率和实际含水率与采出程度的关系（图 2）可知：特高含水开发后期理论曲线和实际曲线拟合效果较好。

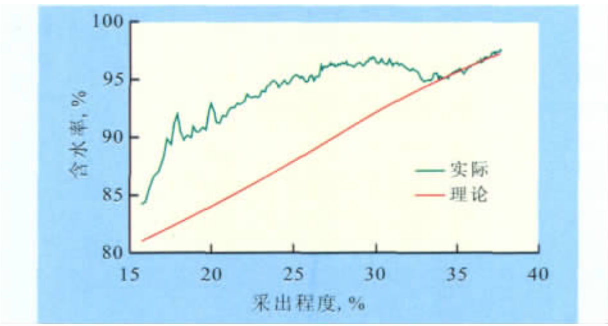

图2　孤东油田七区西 $Ng5^4$—6^1 注水区含水率与采出程度关系

为验证改进方法的适用性，筛选了胜利油区 6 个处于特高含水期且水驱特征曲线上翘的注水单元，分别用传统公式和改进公式进行技术可采储量计算，并与公报值进行对比，结果（表2）表明：特高含水期，水驱特征曲线出现上翘现象时，改进方法计算结果更符合油田实际。

表 2　胜利油区不同区块可采储量计算结果对比

单元名称	技术可采储量/10⁴ t			采收率，%		
	传统方法	改进方法	公报值	传统方法	改进方法	公报值
七区中	332.9	255.6	247.7	31.6	24.2	23.5
八区 Ng5—6	901	429	402.3	74.5	35.5	33.3
七区西 $Ng5^{2+3}$	660	515	569.4	50.2	39.1	43.3
七区中 Ng3—6	2 201	978	974.6	78.7	35	33.8
中一区 Ng3—4	4 709	2 859	2 766.4	93.4	56.7	54.9
中一区 Ng5—6	3 261	1 727	1 697	102.6	54.3	53.4

4　结束语

特高含水开发后期，水驱特征曲线会出现上翘现象，导致基于直线规律外推计算技术可采储量的传统方法计算结果偏大，改进方法使用非线性函数描述水驱特征曲线，拟合效果较好，计算结果符合实际。

改进型水驱特征曲线的系数直接求解比较困难，可进行公式代换，然后用最小二乘法求解，对应技术可采储量可用牛顿迭代法求解。

改进型水驱特征曲线解决了特高含水期传统水驱法计算技术可采储量结果偏大的问题，拓宽了水驱特征曲线法的使用范围，对水驱砂岩油藏特高含水开发后期技术可采储量计算具有重要意义。

参考文献：

[1] 冉启佑，胡建国，肖玉茹. 水驱特征曲线对原油粘度不存在选择性［J］. 油气地质与采收率，2006，13（6）：59－62.

[2] 陈元千. 水驱体积波及系数变化关系的研究［J］. 油气地质与采收率，2001，8（6）：49－51.

[3] 陈元千，陶自强. 高含水期水驱特征曲线的推导及上翘问题的分析［J］. 断块油气田，1997，4（3）：19－24.

[4] 于波，孙新敏，杨勇，等. 高含水期水驱特征曲线上翘时机的影响因素研究［J］. 石油天然气学报（江汉石油学院学报），2008，30（2）：127－131.

[5] 赵连素，金春洪，徐茂斌，等. 水驱特征曲线与产量衰减曲线在滨南油田利 7 块的综合应用［J］. 油气地质与采收率，2003，10（1）：45－47.

[6] 高丽，宋考平，马春华，等. 二段直线法预测高含水期油田开发指标［J］. 石油钻探技术，2008，36（5）：72－74.

[7] 杨勇. 高含水期水驱特征曲线上翘现象校正方法研究［J］. 石油天然气学报（江汉石油学院学报），2008，30（3）：120－123.

[8] 齐梅，侯建锋，蒋漫旗，等. 可采储量标定的合理确定性探讨［J］. 油气地质与采收率，2007，14（6）：62－65.

[9] 陈元千. 水驱特征曲线关系式的推导［J］. 石油学报，1985，6（2）：69－78.

[10] 陈元千. 油田可采储量计算方法［J］. 新疆石油地质，2000，21（2）：130－137.

[11] 王文环. 水驱特征曲线在特高含水油藏提高采收率研究中的应用［J］. 断块油气田，2003，10（1）：33－36.

[12] 高文君，彭长水，李正科. 推导水驱特征曲线的渗流理论基础和通用方法［J］. 石油勘探与开发，2000，27（5）：56－60.

[13] 王树华，杨凤波，孙继伟，等. 应用水驱特征曲线法计算可采储量应注意的几个问题［J］. 石油勘探与开发，2001，28（5）：53－55.

编辑　武云云

China

Wang Hua. Application of improved water drive curve in recoverable reserves. ***PGRE*****, 2012, 19(4): 84-86.**

Abstract: Water drive curve is one important method for estimate recoverable reserves of water drive reservoir, this method is widely used in high water-cut stage of development, but the water drive curve starts to rise upward at extra high water cut stage, it is an obvious non-adaptability that uses water drive reservoir to calculate recoverable reserves in this period. For the development characteristic of extra-high water cut development stage, it has improved the formula of water drive curve, and established a new formula for water drive curve at high water-cut stage to calculate recoverable reserves, which has widened the scope of water drive curve. The recoverable reserve is estimated to be 555 million tons in Gudong oilfield 54-61unit by the improved formula, and the recovery rate is 39.1%, and the result accords well with the field practice. To validate the applicability of improved method, it has screened 6 units of Shengli oilfield which is in extra high water cut stage and its water drive curve is upward to calculate recoverable reserves. The results prove that the improved method is more applicable to the oilfield production.

Key words: extra high water cut period; water drive curve; technical recoverable reserve; least square method curves

Wang Hua, Geoscience Research Institute, Shengli Oilfield Company, SINOPEC, Dongying City, Shandong Province, 257015, China

Huang Wenfen, Qin Xuejie, Du Xiaoyong. Study on development effectiveness of water injection and gas injection for reservoirs with low volatile black oil. ***PGRE*****, 2012, 19(4): 87-89.**

Abstract: The crude oil in O72&O73 reservoirs of Plutonio oil field has good properties and low volatility. The saturation pressure of reservoirs is very near to the initial formation pressure. Injecting fluid to maintain the formation pressure is an effective way to enhance the recovery of this kind of reservoir. Analyzing the balance between injecting and producing and flooding effects of different injecting fluids will be helpful for adjusting injection volume timely and enhancing the development performance. Studies on the ratio of injection-production show that there is fluid communication between two reservoirs. Research on relative permeability curves and the simulation model show that the water-flooding has higher oil displacement efficiency and the gas-flooding sweeps larger area. Both water and gas are injected to maintain the reservoir pressure since the very beginning of the development in field. It turns out that, after 3 years production, the recovery degree of two reservoirs is up to 18.5% and 10.9% respectively, with the average production rate of 3.3% and 5.5%.

Key words: low volatility black oil; GOR; injection-production ratio; oil displacement efficiency; recovery rate

Huang Wenfen, Sinopec International Petroleum Exploration and Production Corporation, Beijing City, 100083, China

Yin Junlu, Zhao Dingnan, Dong Jiashan et al. Numerical simulation on factors affecting flooding mechanism of bottom-water reservoir in horizontal wells. ***PGRE*****, 2012, 19(4): 90-92.**

Abstract: Bottom water reservoir, often with a big water body and enough fluid supply, can supply its formation energy used in exploiting crude oil immediately by bottom water. The production rate will be seriously affected once water breakthrough in horizontal wells during the development process. Based on the numerical simulation, the relationship of horizontal section length, height of water avoidance, producing pressure drop and water breakthrough time, cumulative recovery of water-free period and water cut has been studied in this paper, and the reasonable dimensionless horizontal section length, dimensionless height of water avoidance and producing pressure drop are respectively 0.75, 0.9 and 1.0 MPa. The results show that the influence degree on water breakthrough from high to low is respectively producing pressure drop, dimensionless height of water avoidance and dimensionless horizontal section length; and the influence degree on cumulative recovery of water-free period from high to low is respectively height of water avoidance, horizontal section length and producing pressure drop. A big height of water avoidance and a small producing pressure drop and a long horizontal section length could prolong the water breakthrough time and increase the cumulative recovery of water-free period and is more beneficial to develop the bottom water reservoir.

Key words: bottom water reservoir; horizontal well; water-flooding pattern; numerical simulation; horizontal well parameters.

Yin Junlu, CNPC Chuanqing Drilling Engineering Company Limited, Xi'an City, Shaanxi Province, 710018, China

He Yifan, Liao Xinwei, Xu Mengya et al. Deduction and application of deliverability prediction model for low permeability fractured horizontal gas well. ***PGRE*****, 2012, 19(4): 93-96.**

Abstract: Because of the existence of fractures in fractured horizontal well, gas converges in the wellbore with high velocity and large capacity, this would cause extra turbulent pressure drop. So, the deliverability equation of fractured horizontal gas well should consider the influence of non-Darcy flow rule. This paper adopts complex potential theory and superposition principle to deduce the seepage equation of fractured horizontal well and finally obtain the binomial deliverability equation of fractured horizontal gas well after considering the additional pressure drop caused by turbulent flow in the fractures. This equation is verified by field data and the elements which can influence the turbulent flow of fractured horizontal gas well are analyzed. The result is that this equation deduced in the paper fits the demand of field production and can guide the development and production of oilfield.

Key words: low permeability reservoir; fractured horizontal well; binomial deliverability equation; influence factor; non-Darcy flow; flow conductivity

He Yifan, College of Petroleum Engineering, China University of Petroleum (Beijing), Beijing City, 102249, China