上市储量评估中水驱曲线分年产量计算新方法

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摘　要:水驱曲线法是上市储量评估中已开发时间较长的水驱油田比较重要的一种动态评估方法。为了准确快速地获取上市储量评估中水驱曲线的分年产量,避免曲线相交法求解分年产量需要迭代计算带来的麻烦,在研究了水油比与累积产水的线性关系基础上,提出了一种水油比递推计算分年产量的方法。实例计算表明,该方法可以考虑未来开井数即未来产液量的变化;与曲线相交法迭代计算相比计算结果的累计误差在 0.6 % 以内,满足上市储量评估中水驱曲线法分年产量预测的精度要求,提高了上市储量评估中水驱曲线法获取分年产量的工作效率。

关键词:水驱曲线;上市储量;水油比与累积产水关系;递推公式;分年产量
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New Method of Annual Oil Production Calculation by Water Drive Curve in Listed Reserves Evaluation

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Abstract: The water drive curve is an important dynamic evaluation method for long-developed waterflood oil fields in listed reserves evaluation. In order to accurately and quickly obtain the annual oil production by water drive curve method in listed reserves evaluation, and avoid iterative calculation to solve the annual oil production by the curve intersection method, the linear relationship between WOR and cumulative water production is studied and proved. A recursion formula of WOR for calculating the annual oil production is proposed. The calculation results show that this method can take into account the variation of the number of wells to be opened in the future, i. e., the future total production variation, and the cumulative error of the calculated results is within 0.6 % compared with the iterative calculation by the curve intersection method. It can meet the precision requirement of the water drive curve method in listed reserves evaluation, and improves the efficiency of obtaining the annual oil production by the water drive curve method in listed reserves evaluation.

Keywords: Water drive curve; Listed reserves; WOR vs cumulative water production; Recursion formula; Annual oil production

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0 前言

上市储量评估中对已开发较长时间的油田一般采用动态法进行评估，常用方法为递减法和水驱曲线法[1-5]。国内关于上市储量的研究主要集中在评估的概念、方法原则、影响因素以及推广应用等方面[6-20]。喻秋兰等人针对上市储量所用的水驱曲线提出了单井液量平均化、考虑井数变化、考虑液量风险以及后期强制递减四点改进，这四点改进使得水驱曲线法在储量评估中较之递减法具有更多的灵活性[6]。刘宗宾等人详细说明了水驱曲线法在上市储量中的评估原理，评估要点，并列举了实例进行了说明，但是文中提出的“曲线相交法”求解分年产量并未具体说明过程[8]。而在实际计算分年产量时往往需要采用数值迭代求解[10]。为了避免分年产量预测时数值迭代带来的编程麻烦，提高上市储量中利用水驱曲线法评估剩余技术可采的效率，提出了水油比与累积产水的线性关系式，可用于分年产量的快速计算。

1 水油比与累积产水关系

渤海油田上市储量评估中，对于已开发的水驱油田采用水驱曲线法进行储量评估时一般采用水油比与累积产油的半对数坐标系下的直线关系[6-8]：

$$\ln WOR = a + b \cdot N_p \tag{1}$$

对式(1)关于时间求导并整理有：

$$\frac{dWOR}{dt} = b \cdot Q_w \tag{2}$$

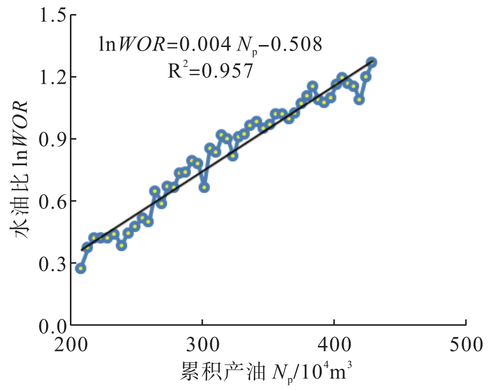
对式(2)积分得：

$$WOR = c + b \cdot W_p \tag{3}$$

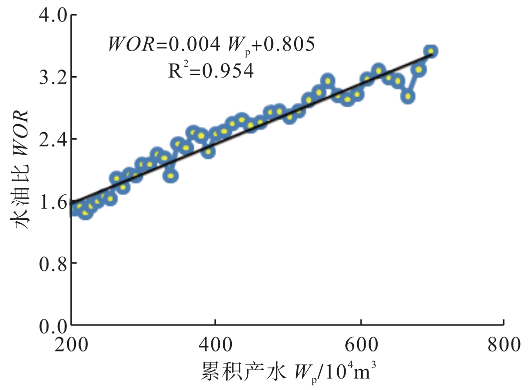
式中：WOR 为水油比，a、b、c 为水驱曲线常数；Q_w 为年产水，$10^4\ m^3/a$；N_p 为累积产油，$10^4\ m^3$；W_p 为累积产水，$10^4\ m^3$。

同理，通过式(3)可以推导出式(1)的表达式，即式(1)和式(3)在数学上具有等价关系。由(1)、(3)可知，若累积产油与水油比在半对数坐标中符合直线关系，则水油比与累积产水在直角坐标系中也符合直线关系，且两者直线的斜率相等。

为了验证以上结论，以渤海 Q 油田北区 2014 至 2017 年的生产实际数据为例，分别拟合半对数坐标下的水油比与累积产油以及直角坐标下的水油比与累积产水，见图 1。从拟合结果可以看出两者结果的直线拟合程度都在 95 % 以上，且拟合的斜率均为 0.004，通过实例验证了式(3)的正确性。



a) 累积产油与水油比关系曲线



b) 累积产水与水油比关系曲线

图 1 渤海 Q 油田北区拟合结果对比

2 产量计算方法推导

对于刘宗宾等人提出的曲线相交法预测水驱曲线的分年产量，在实际求解过程中存在的主要难点是计算分年产量时需要先假设预测年的产量初值，对每一个预测年都采用迭代法进行数值求解。为了提高计算水驱曲线分年产量的效率，避免数值迭代计算带来的编程麻烦，在产量预测时利用水油比与累积产水的直线关系可以进行产油量的递推计算。

假设第 t 年年末累积产水为 W_{pt}，第 $t+1$ 年年末累积产水为 W_{pt+1}，第 $t+1$ 年的年产水为 Q_{wt+1}，则 $Q_{wt+1} = W_{pt+1} - W_{pt}$；根据式(3)有：

$$WOR_t = c + b \cdot W_{pt} \tag{4}$$

$$WOR_{t+1} = c + b \cdot W_{pt+1} \tag{5}$$

式(4)、(5)相减可以得到水油比与年产水的关系式：

$$WOR_{t+1} - WOR_t = bQ_{wt+1} \tag{6}$$

根据年产水与年产液的关系有：

$$Q_w = \frac{WOR}{1 + WOR} Q_l \tag{7}$$

联立式(6)、(7)可以得到水油比与阶段产液的关系式：

$$WOR_{t+1} - WOR_t = b \frac{WOR_{t+1}}{1 + WOR_{t+1}} Q_{lt+1} \tag{8}$$

求解方程(8)可以得到水油比的计算式：

$$WOR_{t+1} = \frac{(WOR_t - 1 + bQ_{lt+1}) + \sqrt{(WOR_t - 1 + bQ_{lt+1})^2 + 4\,WOR_t}}{2} \tag{9}$$

式中：WOR_t 为第 t 年的水油比；WOR_{t+1} 为第 $t+1$ 年的水油比；Q_l 为年产液，$10^4\ m^3/a$；Q_{lt+1} 为第 $t+1$ 年的年产液，$10^4\ m^3/a$。

对于油田未来产液 Q_{lt+1} 的预测一般采用评估基准日之前 1 a 内的单井平均产液 L_{well} 乘以未来油田每一年的开井数 n_{t+1} 获取[6]，即 $Q_{lt+1}=n_{t+1}\cdot L_{well}$。根据式(9)可以预测基准年之后每一年的水油比，再根据式(10)就可以计算上市储量水驱曲线的分年产量。

$$Q_{ot+1}=\frac{Q_{lt+1}}{1+WOR_{t+1}} \tag{10}$$

3　实例应用

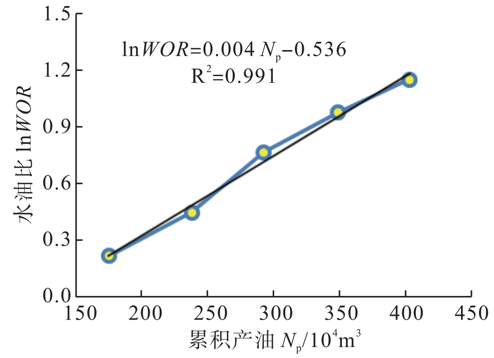
渤海 Q 油田北区目前有生产井 48 口，该井区 2012 至 2017 年的生产数据见表 1。上市储量水驱曲线法在产量预测时一般采用分月数据进行合理水驱直线段选取。由于分月数据量过于庞大，在本实例计算过程中采用分年数据进行水驱直线段的拟合分析。考虑 2012 年含水率小于 50 %，因此剔除该年的数据。采用 2013 至 2017 年数据点进行直线回归分析，得到了水油比与累积产油、水油比与累积产水的拟合，见图 2。从拟合结果可以看出两者斜率均为 0.004，因此可以进行产量的分年预测。

表 1　渤海 Q 油田北区生产历史数据

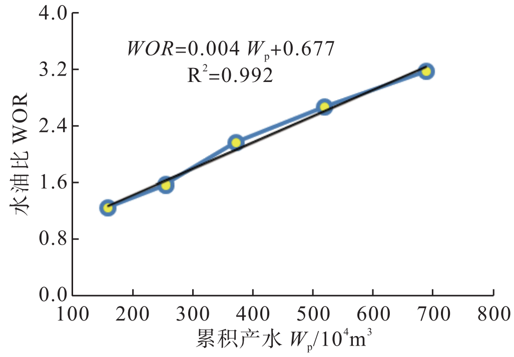
年份	年产油 / $10^4\ m^3$	年产水 / $10^4\ m^3$	累积产油 / $10^4\ m^3$	累积产水 / $10^4\ m^3$	含水率 / (%)
2012	104.71	70.61	104.71	70.61	40.3
2013	70.69	87.15	175.40	157.76	55.2
2014	62.32	96.70	237.72	254.46	60.8
2015	54.57	116.62	292.29	371.08	68.1
2016	55.98	147.78	348.27	518.86	72.5
2017	53.73	168.81	402.00	687.67	75.9

预测的基准年为 2017 年，根据表 1 计算基准年的年产液为 $222.54\times10^4\ m^3$，平均单井年产液为 $4.64\times10^4\ m^3$，基准年的水油比为 3.142。考虑开井数不变以及 2022 年以后每年开井数减少 1 口这两种方式，利用式(9)、(10)计算得到 2018 至 2050 年两种方式的分年产量，见图 3。与刘宗宾等人提出的曲线相交法编程求解结果对比如下。

考虑开井数不变，通过曲线相交法求解的剩余技术可采储量为 $543.60\times10^4\ m^3$，利用递推计算方法计算的剩余技术可采储量为 $540.76\times10^4\ m^3$，相对误差为 0.52 %；考虑 2022 年后每年开井数减少 1 口，通过曲线相交法求解的剩余技术可采储量为 $477.68\times10^4\ m^3$，利用递推计算方法计算的剩余技术可采储量为 $475.11\times10^4\ m^3$，相对误差为 0.54 %。由图 3 两种方法分年产量计算结果对比可知，不管是考虑开井数不变还是 2022 年后每年开井数减少 1 口，两种方法计算的结果基本重合。从以上分析可知：不管是否考虑未来开井数即未来产液量的变化，本文提出的递推计算方法精度够高，满足上市评估中产量预测的要求。



a) 累积产油与水油比关系曲线



b) 累积产水与水油比关系曲线

图 2　渤海 Q 油田北区水驱曲线拟合

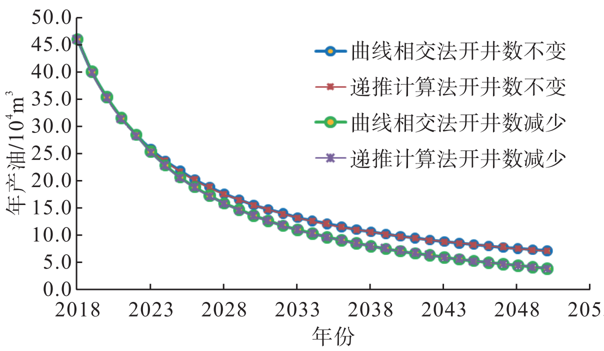


图 3　两种方法分年产量计算结果对比

4　结论和认识

1）推导了水油比与累积产水的线性关系式；得出了“累积产油与水油比在半对数坐标中符合直线关系”与“水油比与累积产水在直角坐标系中符合直线关系”两者等价的结论，并通过实际生产数据进行了验证。

2）在水油比与累积产水的线性关系基础上进一步推导了水油比递推计算公式，利用公式可以简便快速地求解分年产量，提高上市储量水驱曲线法分年产量预测的工作效率。

3)通过实例分析,验证了在开井数不变以及开井数变化两种情况下,递推计算方法与前人提出的曲线相交法计算的分年产量相比具有相当高的计算精度,满足上市储量评估中产量预测的要求。

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