Application of water drive characteristic curve in oil field development planning index prediction

Baolai Liu
Geological Brigade of the Second Oil Production Plant of Daqing Oilfield Co., Ltd., 163000, China
Liu_Baolai@petrochina.com.cn

Abstract. In the prediction of water drive development index in oilfield development planning, we often use constant liquid method to calculate production, injection-production balance prediction, water drive characteristic curve and exponential decline. At different development stages, various forecasting methods are constantly improving. However, after oilfield development enters the declining stage, many forecasting methods are no longer suitable for the current development index prediction. However, there is a certain correlation among all kinds of forecasting methods. To a certain extent, it can make up for their own shortcomings to predict various development indicators through the joint solution of parameters among different forecasting methods, which has good practicability in the prediction of development indicators in oilfield development planning.

Keywords: Oilfield development planning; Declining stage; Prediction of water drive index.

1. The raising of questions
How to make a reasonable oilfield planning scheme through oilfield development index prediction has always been a key research issue in the petroleum industry. In this paper, the water cut, cumulative oil production, annual oil production and other development indexes of water drive development oilfield at different development time after entering the decline period are predicted by the exponential decline prediction model and the water drive curve joint solution method, so as to guide the preparation of oilfield development planning.

2. Research on methods
The commonly called C-type water drive characteristic curve, also known as Sipachev curve, was first proposed by literature [1], and theoretically deduced by literature [2]. It can predict cumulative water production and cumulative oil production, as well as the relationship between cumulative liquid-oil ratio and cumulative liquid production. It is a widely used development index prediction method at present, and its main relational expression is:

$$\frac{L_p}{N_p} = a + bL_p$$  \hspace{1cm} (1)
In which: $L_p$ —— Accumulated fluid production, $10^4$t;

$N_p$ —— Accumulated oil production, $10^4$t;

The relationship between predicted water cut and cumulative oil production by C-type water drive characteristic curve is as follows:

$$f_w = 1 - \frac{(1 - bN_p)^2}{a} \quad (2)$$

In which: $a$ —— Intercept of straight line of characteristic curve of type c water drive;

$b$ —— Slope of straight line of characteristic curve of type c water drive:

Exponential decline prediction model has the function of predicting oil production, cumulative oil production and recoverable reserves. The relationship between oil production and time after decline in this model is as follows:

$$Q_i = Q_{io} e^{-iD} \quad (3)$$

In which: $Q_i$ —— Decreasing the initial oil production, $10^4$t/a;

$Q_i$ —— Oil production at time $t$ after decreasing, $10^4$t/a;

$iD$ —— Initial decline rate;

The logarithm of both sides is simplified as follows:

$$D_i = \frac{\lg Q_i - \lg Q_{io}}{t \lg e} \quad (4)$$

The relationship between cumulative oil production and time is as follows:

$$N_{pi} = N_{pi} + \frac{Q_i}{D_i} [1 - \exp(-iD_i t)] \quad (5)$$

In which: $N_{pi}$ —— Decreasing the initial cumulative oil production, $10^4$t;

$N_{pi}$ —— Cumulative oil production at time $t$ after decline, $10^4$t;

When $t \to \infty$, the recoverable reserves of the oilfield are obtained:

$$N_r = N_{pi} + \frac{Q_i}{D_i} \quad (6)$$

Substitute formula (5) into formula (2) to obtain the water content prediction relation of the combined method:

$$f_w = \frac{1 - b \left[ N_{pi} + \frac{Q_i}{D_i} (1 - \exp(-iD_i t)) \right]}{a} \quad (7)$$

After the predicted oil production, cumulative oil production and water cut are obtained by formulas (3), (5) and (7), the water production, liquid production, cumulative water production and cumulative liquid production of the oilfield can be predicted by the following formula:

$$Q_w = Q_o \frac{f_w}{1 - f_w} \quad (8)$$

$$Q_i = Q_o \frac{1}{1 - f_w} \quad (9)$$

$$W_p = \sum Q_w \quad (10)$$

$$L_p = \sum Q_i \quad (11)$$

3. Parameter solving

According to the actual production data of the oilfield, firstly, the annual oil production of the oilfield changes with time in the semi-logarithmic coordinate system, and the initial oil production $Q_i$ in the decline period is determined, and then the decline rate $D_i$ is obtained by formula (4).
Because the exponential decline model predicts the development index after the initial point of decline, it also predicts the development index after the initial point of decline in this joint solution model. When calculating $a$ and $b$ parameters of C-type water drive characteristic curve, we will linearly regress the accumulated liquid-oil ratio $L_p/N_p$ of development data in exponential decline stage and its corresponding accumulated liquid production $L_p$ according to the relationship of formula (1), and determine the $a$ and $b$ values of C-type water drive characteristic curve.

Substituting the obtained $D_i$, $a$ and $b$ values into equations (3), (5), (6), (7), (8), (9), (10) and (11), the recoverable reserves and oil production, water production, liquid production and cumulative oil production in each stage can be obtained.

4. Example application analysis
The development layers of a primary infill network in an oilfield were put into production one after another in 1997. Take the logarithm of water drive oil production in each year during the development process, and draw it in the coordinate system with time as abscissa to get Figure 1. It can be seen from Figure 1 that since 1999, the output has been declining, and the declining speed has shown a linear trend, so it can be considered that the water drive output of this development series changes according to the law of exponential decline. $Q_i=30.35\times10^4t$, $t=13a$, $Q_i=8.1139\times10^4t$, $N_{i0}=52.25\times10^4t$, $N_{i1}=228.19\times10^4t$ corresponding to this. Bring the above data into formula (4) to get $D_i=0.10147a-1$, and linearly regress the cumulative liquid-oil ratio $L_p/N_p$ of development data after 1999 and its corresponding cumulative liquid production $L_p$ according to the relationship of formula (1), and determine the characteristic curve of type C water drive, $a=1.7711$, $b=0.28\times10^{-2}$.

Figure 1. Semi-logarithmic graph of annual oil production

Figure 2. Regression curve of C type water drive characteristics
Substitute \( D_i \) and \( N_{pi} \) values into formula (6) to get:

\[
N_a = 52.25 + \frac{30.35}{0.10147} = 531.35 \times 10^4 (t)
\]

The values of \( D_i \), \( a \) and \( b \) are brought into formulas (3), (5) and (7), respectively, to obtain the relevant formulas for predicting the theoretical annual oil production, cumulative oil production and water cut after the decline of water drive production since 1998.

\[
Q_o = Q_t = 30.35 e^{-0.10147 t}
\]

\[
N_p = \frac{30.35}{0.10147} \left[ 1 - \exp(-0.10147t) \right] + 52.25
\]

\[
f_w = 1 - \left[ 1 - 0.28 \times 10^{-2} \left( \frac{52.25 + \frac{30.35}{0.10147} \left[ 1 - \exp(-0.10147t) \right]}{1.7711} \right) \right]^2
\]

Given different development time \( t \), the theoretical annual oil production, cumulative oil production and water cut of a certain oilfield after the development layer system of primary infill well pattern enters the decline stage are predicted by the formulas (12), (13) and (14) (see Table 1). Drawing (Figure 3, Figure 4 and Figure 5) shows that the predicted annual oil production, cumulative oil production and water cut are in good agreement with the actual data.

**Table 1.** Comparison of actual and predicted data of development layer of primary infill well pattern in an oilfield

| Year/a | t/a | \( Q_o /10^4 \text{t.a}^{-1} \) | \( Q_t /10^4 \text{t} \) | \( N_p /10^4 \text{t} \) | \( f_w /\% \) |
|--------|-----|-----------------|-----------------|-----------------|--------|
| 1997   | 0.16| 0.16            | 27.60           | 62.71           | 62.40  |
| 1998   | 21.73| 21.9            | 35.90           | 77.61           | 75.52  |
| 1999   | 30.35| 52.3            | 50.15           | 82.57           | 83.10  |
| 2000   | 1   | 25.26           | 77.5            | 62.71           | 62.40  |
| 2001   | 2   | 21.78           | 99.3            | 67.81           | 69.30  |
| 2002   | 3   | 16.82           | 116.1           | 76.10           | 75.52  |
| 2003   | 4   | 14.80           | 130.9           | 78.68           | 79.09  |
| 2004   | 5   | 13.50           | 144.4           | 81.13           | 81.83  |
| 2005   | 6   | 13.18           | 157.6           | 82.57           | 83.10  |
| 2006   | 7   | 11.92           | 169.5           | 83.35           | 84.30  |
| 2007   | 8   | 10.94           | 180.4           | 85.28           | 85.47  |
| 2008   | 9   | 10.41           | 190.8           | 86.58           | 87.15  |
| 2009   | 10  | 10.55           | 201.4           | 87.24           | 88.53  |
| 2010   | 11  | 9.76            | 212.2           | 87.48           | 89.67  |
| 2011   | 12  | 8.93            | 220.1           | 87.43           | 90.60  |
| 2012   | 13  | 8.11            | 228.2           | 88.73           | 91.36  |
| 2013   | 14  | 7.33            | 245.8           | 91.99           |        |
| 2014   | 15  | 6.62            | 252.2           | 92.56           |        |
| 2015   | 16  | 5.99            | 258.2           | 92.99           |        |
| 2016   | 17  | 5.41            | 263.7           | 93.38           |        |
| 2017   | 18  | 4.89            | 268.8           | 93.87           |        |
| 2018   | 19  | 4.41            | 273.6           | 94.24           |        |
| 2019   | 20  | 3.99            | 278.1           | 94.57           |        |
| 2020   | 21  | 3.60            | 278.1           | 94.81           |        |
5. Some understandings
(1) In this paper, by analyzing and processing the oil production of water drive in the development series of a primary infill well pattern in an oilfield, it is determined that the water drive decline law of the development series basically accords with exponential decline.
(2) Through the method of joint solution of exponential decline prediction model and C-type water drive characteristic curve, after oilfield development enters the decline stage, the development indexes in different periods are predicted, and the two models are complementary.

(3) There is a certain deviation between the theoretical prediction value and the actual value, and the coincidence degree is high after considering the necessary production factors, which has high practical value in the process of oilfield development planning.

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