International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1062

NOVEL MODEL FOR PREDICTING PRODUCTION-DECLINE: THEORETICAL DERIVATION AND CASE STUDIES

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ABSTRACT

There are implicit assumptions that should be considered for the commonly used production-decline models (Exponential, Harmonic and Hyperbolic decline models), such as relative stable well control conditions, leads to the difficulty on quantitative forecasting during some complicated situation happens. A new decline prediction model was proposed through theoretical derivation, and the decline rate was interpreted from three different parts (water cut rising, liquid productivity index changing , and pressure drop changing) for the first time. Furthermore, three calculation cases under different conditions (under constant liquid production rate, constant pressure drop and arbitrary conditions) were analyzed, and the different changing rules of deline rate were analyzed. Comparing to the actual dynamic data, the proposed model shows high accuracy, even if some complicated situation happens, however theprediction error of the common decline models could be large. So it makes great sense in improving the dynamic performance forecasting.

Keywords: Decline, Decline Rate, Water Cut Rising, Liquid Productivity Index Changing Rate, Producing Pressure Drop Changing Rate.

NONMENCLATURE

K	Permeability, mD
φ	Porosity,f
K_{rw}	Relative Permeability of Water phase, Dimentionless
K_{ro}	Relative Permeability of Oil phase, Dimentionless
S_{wd}	Movable Water Saturation at the Exit End,f
n_o	Oil Phase Index,f
n_w	Water Phase Index,f
S_{or}	Residual Oil Saturation,f
S_{wi}	Irreducible Water Saturation,f
$K_{rw}(S_{or})$	Relative Permeability of Water Phase Under Residual Oil Saturation, Dimentionless
$K_{ro}(S_{wi})$	Relative Permeability of Oil Phase under Irreducible Water Saturation, Dimentionless
μ_o	Viscosity of Oil Phase,mPa·s
μ_w	Viscosity of Water Phase,mPa·s
R_f	Recoverable Oil Recovery,f
Q_l	Liquid Production Rate, cm^3/s
Q_o	Oil Production Rate, cm^3/s
Q_w	Water Production Rate, cm^3/s
N_R	Moveable Oil Reserve, cm^3/s
f_w	Water Cut,f
S_{we}	Water Saturation at Exit End,f
ΔP	Pressure Drop,10^{-1}Mpa
t	Producction Time, s
D_t	Decline Rate, Dimentionless
D_i	Initial Decline Rate, Dimentionless
ω	Welge Equation Coeffient,f

1. INTRODUCTION

Decline rate prediction is undoubtedly the most commonly used for production profile forecasting in oil&gas development industry. Decline rate forecasting precision influences the project's economic benefit and investment decision [1-2]. In 1944, Arps [3] proposed the standard exponential, hyberbolic and harmonic decline models based on empirical observations of production decline under boundary-dominated flowing conditions. Afterward, type curve decline analysis approachs were proposed based on theoretical derivation which could be used to estimate formation parameters [4-6]. However, there are still some unresolved problems as follows: (1) Most of the decline rate forcasting methods were lack of theoretical basis; (2) The current commonly used prediction method remains to be further improved in order to deal with the difficulty in determining a proper decline pattern when different methods have approximate accuracy of fitting match with the actual dynamic data. (3) A method involving multiple factors is needed to be proposed for predicting the decline rate during the complicated conditions happen.

A new decline rate prediction model is proposed through theoretical derivation and it revealed that the decline rate was composed of from three different parts for the first time. The solution under constant fluid production rate, constant producing pressure drop, and arbitrary conditions were given, which was very useful for optimization of simulation measures and field development plan adjustment.

2. METHODS

2.1 Further theoretical analysis of the decline rate

The theoretical analysis of the decline rate:

$$D_t = -\frac{1}{Q_o}\frac{dQ_o}{dt} = -\frac{d(Q_l - Q_w)}{Q_o dt} = -\frac{d(1-f_w)Q_l}{Q_o dt} + \frac{dQ_l}{Q_l dt} \tag{1}$$

The theoretical prediction model of the decline rate is thus obtained

$$D_t = \frac{Q_l}{N_R}\frac{df_w}{dR_f} - \frac{d(\frac{K_{ro}}{\mu_o} + \frac{K_{rw}}{\mu_w})}{(\frac{K_{ro}}{\mu_o} + \frac{K_{rw}}{\mu_w})dS_{we}} \cdot \frac{dS_{we}}{dt} - \frac{d\Delta P}{\Delta P dt} \tag{2}$$

In which[7],

$$\frac{df_w}{dR_f} = \frac{Mw^{n_o-n_w}(R_f+w-1)^{n_w-1}(1-R_f)^{n_o-1}[n_w(1-R_f)+n_o(R_f+w-1)]}{[Mw^{n_o-n_w}(R_f+w-1)^{n_w}+(1-R_f)^{n_o}]^2} \tag{3}$$

While $M = \frac{\mu_o B_o K_{rw}(S_{or})}{\mu_w B_w K_{ro}(S_{wi})}$

$$\frac{dS_{we}}{dt} = [(1-S_{wf}-S_{or})^{1-n_o} + \frac{n_o-1}{\omega}K_{ro}(S_{wc})\frac{\alpha B_o}{V_p}t]^{\frac{1}{1-n_o}-1}\frac{\alpha K_{ro}(S_{wc})B_o}{\omega V_p} \tag{4}$$

As suggested in Equation (2), the decline rate is composed of three different parts: the water cut rising rate $\frac{Q_l}{N_R}\frac{df_w}{dR_f}$, dimensionless fluid productivity index changing rate $\frac{d(\frac{K_{ro}}{\mu_o} + \frac{K_{rw}}{\mu_w})}{(\frac{K_{ro}}{\mu_o} + \frac{K_{rw}}{\mu_w})dS_{we}} \cdot \frac{dS_{we}}{dt}$, and producing pressure drop changing rate $\frac{d\Delta P}{\Delta P dt}$.

It could be found that numerous factors affect the decline rate such as physical properties, relative permeability, oil-water viscosity ratio, liquid production, pressure drop, well space, and skin factor.

2.2 Theoretical model of the decline rate

Three different conditions were furtherly analyzed, under constant liquid production rate, constant pressure drop, and arbitrary conditions.

(1) Decline rate changing rules under constant liquid production rate

In the case of constant liquid production rate

$$\frac{dQ_l}{dt} = 0 \tag{5}$$

The equation for the decline rate could be obtained

$$D_t = \frac{Q_l}{N_R}\frac{df_w}{dR_f} \tag{6}$$

So

$$D_t = \frac{Q_l}{N_R}\frac{Mw^{n_o-n_w}(R_f+w-1)^{n_w-1}(1-R_f)^{n_o-1}[n_w(1-R_f)+n_o(R_f+w-1)]}{[Mw^{n_o-n_w}(R_f+w-1)^{n_w}+(1-R_f)^{n_o}]^2} \tag{7}$$

In which

$$R_f = 1 - \frac{\omega}{[1+0.006738\exp(\frac{3.5n_w+6.5n_o}{n_w+n_o})(\frac{1}{M}\frac{f_w}{1-f_w})^{\frac{1.3n_w+0.7n_o}{n_w(n_w+n_o)}}]^{\frac{n_w}{n_o}}} \tag{8}$$

(2) Decline rate changing rules under constant pressure drop

The equation of the decline rate under constant pressure drop is as follows:

$$\frac{D_t}{D_i} = (1-R_f)^{n_o-1} \tag{9}$$

So

$$\frac{D_t}{D_i} = \frac{\omega^{n_o-1}}{[1+0.006738\exp(\frac{3.5n_w+6.5n_o}{n_w+n_o})(\frac{1}{M}\frac{f_w}{1-f_w})^{\frac{1.3n_w+0.7n_o}{n_w(n_w+n_o)}}]^{\frac{n_w}{n_o}(n_o-1}} \tag{10}$$

(3) Decline rate changing rules under arbitrary conditions

The calculation steps are shown in Fig. 1, which required iterative calculation as numerous factors such as the water cut rising and pressure drop changing are considered simutaneously.

1) The function of reserve recovery degree, water cut, and oil productivity index could be calculated base on relative permeability curves;

2) The correlation between water cut and recovery degree should be corrected through dynamic production data fitting.

3) The multiplying factor of producing pressure drop could be obtained through liquid prediction and pressure drop analysis (The multiplying factor should be correlated with the pressure drop changing with liquid prodution changing).

4) The change rules of the decline rate reflects water cut rising, pressure drop changing , and the recovery degree changing could be obtained through iterative calculation.

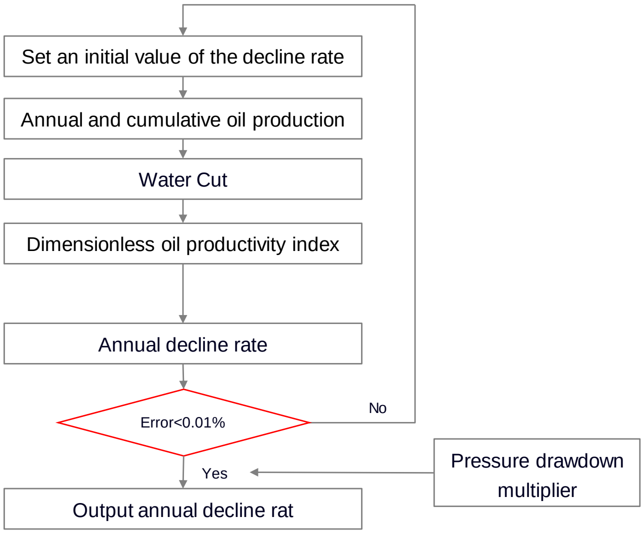

Fig.1 Flow chart of iterative calculation of the decline rate under complicated conditions

3. RESULTS AND DISSCUSSION

Different changing rules of the decline rate under different conditions will be performed as follows. According to Eq.(2) and Eq.(3), the decline rate was influenced by numerous factors. The basic parameters were presented in Tab.1.

Tab 1 Basic values of influencing factors

n_w, f	n_o ,f	S_{wi}, f	S_{or}, f	K_{rw} (S_{or}),f	μ_o/ μ_w,f	Q_l ,bbl/d	N_R, MMbbls
1.4	2.3	0.30	0.21	0.34	3.75	1200	6

3.1 Decline rate changing rules under constant liquid production rate

The oil-water viscosity ratio was chosen for the decline rate changing rules presented because the changing rules keeps consistent under constant liquid production rate with different influence factors changing. The decline rate changing rules under different oil-water viscosity ratio are shown in Fig 2.

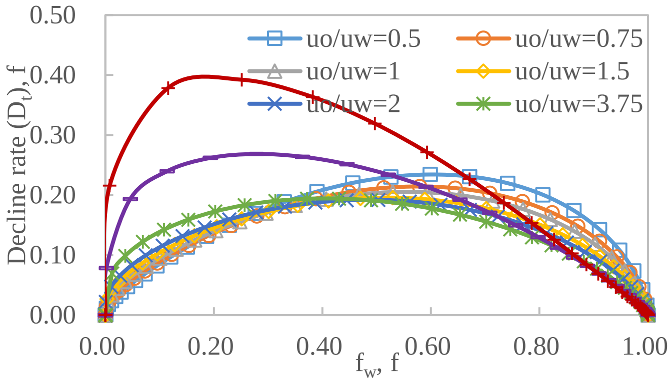

Fig.2 Decline rate with water cut at different oil -water viscosity ratio

Under constant liquid production, the decline rate increases at first and then decreases. When the crude oil phase viscosity is smaller than the water phase viscosity, the peak value of the decline rate gradually decreases as the oil-water viscosity ratio increases; when the oil phase viscosity is larger than the water phase viscosity, the peak value of the decline rate gradually increases with the increase of oil-water viscosity ratio.

3.2 Decline rate changing rule under constant pressure drop

The decline rate changing rules under constant pressure drop with different oil-water viscosity ratio are shown in Fig 3.

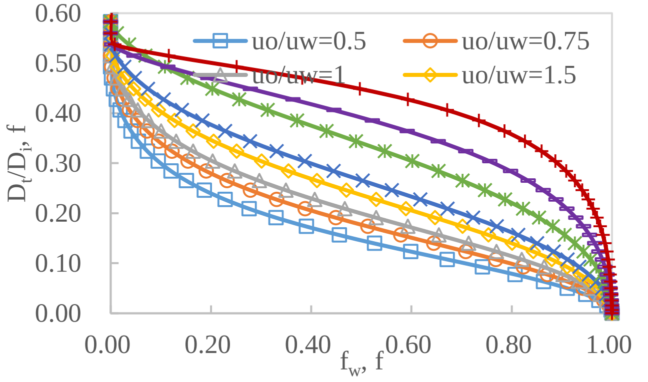

Fig.3 Ratio of current decline rate to initial decline rate with water cut under different oil-water viscosity ratio

The decline rate always decreases as the water-cut rises under a constant pressure drop; the larger the oil-water viscosity ratio is, the larger the decline rate under the same water-cut. In general, the decline rate of the heavy oil is higher than that of the light oil. Besides that, as the oil-water viscosity ratio increases, the downtrend of the decline rate changes from a U shape curve to a reversed U shape curve.

3.3 Decline rate changing law under complicated conditions

The calculation method was verified through actual dynamic data from X carbonate reservoir in Middle East, with about 60 to 70 times aquifer volume.

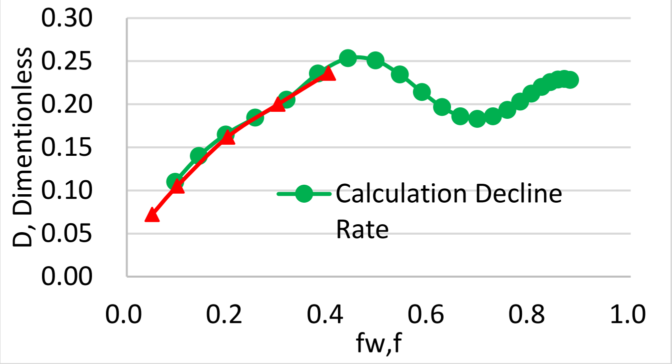

Fig.4 Decline rate for typical complicated carbonatite reservoirs in the Middle East

The theoretical prediction model for the decline rate under complicated conditions is used for prediction. Water cut would reach 40% and the decline rate 24% in 2017, showing high accuracy comparison with the actua decline rate of 23.6% (Seeing Fig.4). The forecasting result shows another decline rate peak because of the pressure drop devrasing with the formation pressure decreasing as the target oilfield depends on natural energy development.

4. CONCLUSIONS

(1) The theoretical prediction models for the decline rate were proposed with clear interpretation from three different parts for the first time: water cut rising, liquid productivity index changing, and pressure drop differential changing.

(2) Under constant liquid production rate, the decline rate increases at first and then decreases. Under constant pressure drop, the decline rate tends to decrease contineously. Under complicated conditions, the decline rate changing results from numerous influencing factors which vary in different stages; the changing rules differs as different combinations of factors taking charge, and sometimes two or more peaks would occur.

(3) The theoretical models provided the theoretical basis for dynamic performance prediction, which was lacked for the commonly used models. The new proposed method could also be used in different working systems, stages and complicated conditions with high prediction accuracy.

ACKNOWLEDGEMENT

This study was supported by China National Science and Technology Major Project [Grant 2017ZX05032-004] and Innovation Fund of China National Offshore Oil Corporation [CNOOC-KY-KJCX-CRI-2017-01].

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