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Research Article

A New Dynamic Model for Sealed Coring Saturation Correction in Hydrocarbon Reservoir

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It is one of the most intuitive methods to analyze the formation of oil and water saturation by sealed coring. But this method is affected by a variety of factors, such as pore volume change, fluid compression, and separation of dissolved gas. In view of the impact of such factors on sealed coring test saturation, there are four kinds of correlation methods currently, namely, comprehensive coefficient correction method, experiment correlation method, mathematical statistics method, and mathematical model correction method, with their own advantages and disadvantages. Based on the analysis of physical change during core lifting process, this paper proposes the mathematical model for dynamic correction of core saturation based on dissolved gas drive filtration theory, multiphase flow fractional flow theory, and corresponding work flow. This method comprehensively considers the impact of relative permeability of three-phase fluid flow, elastic compression nature of fluid and rock, fluid viscosity, volume factor, solution GOR, and other high-pressure PVTs, so it features a wider adaptability, and the accuracy of model correction results satisfies the project requirements. This method provides a reliable basis for the true oil-water saturation of actual reservoir and has an important theoretical and practical significance.

1. Introduction

The analysis of remaining oil saturation is the basis and foundation for water controlled reservoir potential evaluation and development plan adjustment.

There are numerous methods to calculate the remaining oil saturation of formation. The methods of indirect acquisition of the formation saturation, such as the logging interpretation method, have the problems of being affected by casing cement, casing collar, and other factors and having a lower resolution, and meanwhile they contain measurement errors and interpretation errors [1]. The method of direct acquisition of formation saturation is to obtain the formation rock by sealed coring and then obtain the remaining oil saturation [2] by test. Although this method requires a higher cost, the results obtained by such method are relatively accurate, intuitive, and reliable, so this method is utilized widely in China and provides reliable data of petrophysical properties [3, 4] for exploration and development and study and test of oilfield. But, the sealed coring method also has obvious systematic errors, and the actual formation fluid saturation [3] may be only obtained by saturation correction. Currently, there are four kinds of correction methods, namely, laboratory experiment correction method [5–9], correction coefficient method [10], mathematical statistics regression method [11, 12], and mathematical model correction method [13–17]. The indoor laboratory experiment method does not need to directly describe the complex processes of physical and chemical changes during the depressurization degassing process, with the results relatively accurate. But this method requires a heavy workload, the experiment results are only applicable to specific reservoirs, and the fitting results have no universality [5–9]. The mathematical statistics method is simple and easy to understand, but it considers neither the differences of core and fluid properties nor the state change in the coring process. The damage rates obtained from statistics are affected by different rock properties; the classification standards of sample points are not objective and contain larger errors; the correction coefficient method considers few factors and is quite simple, but it cannot obtain the accurate formation saturation results. In summary, the application of all the three methods is limited seriously. Only the mathematical model method has caused the extensive concern because it can describe the changes of core and fluids during the coring process by mathematical equations. The existing mathematical model correction methods [13–17] all consider the changes of rock pore volume and fluid volume and determine the changes of fluids in the coring process based on the fractional flow equation, but the established models have two problems: one is that the overall process coupling correction is not conducted for the changes of rock volume and changes of fluids; and the second is that the dissolution and separation of oil and gas are not considered in the overall coring process. In view of the above problems, this paper plans to establish a kind of method which considers both the rock deformation and separation of oil and gas in the overall process, so as to obtain a more accurate dynamic correction model for sealed coring saturation.

2. Existing Correction Methods for Sealed Coring Saturation

From the published literature, there are currently four kinds of correction methods about pressure impacting saturation, such as depressurization degassing.

(1) Comprehensive Coefficient Correction Method. Kairong and Wanshun [4] and Rahtmell et al. [5] propose the following correction method:

$$(S_o)_{\text{Reservoir}} = \frac{(S_o)_{\text{Core}} \cdot B_o \cdot E \cdot M}{(1-\nu)^2}, \tag{1}$$

of which parameter E is the comprehensive fluid contraction coefficient and refers to the *Parameter List* for the remaining parameters. The research of Kairong and Wanshun and Rahtmell et al. suggests that E is within 1.10~1.15, and the research of Kazemi [6] suggests that E is 1.062. It can be seen that this parameter has a wide value range, so this method is quite simple, but it cannot get accurate formation saturation results.

(2) Experiment Correlation Method. Shenglai et al. [7], Liang [8], and Liu [9] utilize the experiment method for correction of sealed coring saturation. The core of this method is to clean the core and inject a certain amount of simulated formation oil after ensuring that it is saturated with water and then simulate the drop of core barrel pressure to obtain the correlation formula of water saturation before core degassing and saturation after degassing:

$$(S_o)_{\text{Reservoir}} = A \cdot (S_o)_{\text{Core}} - B. \tag{2}$$

We can obtain coefficient A and coefficient B through regression; namely, we obtain the correction equation of water saturation of one reservoir. This method may not consider the complex processes of physical and chemical changes during the depressurization degassing process but has quite obvious disadvantages: ① experiment results are only applicable to specific reservoirs, and the fitting results have no universality; ② the simulated formation oil contains errors; ③ the experiment process contains errors.

(3) Mathematical Statistics Method. Egbogah and Amaefule [10] and Yijing et al. [11] consider that oil-water saturation losses of similar types of rocks should be basically the same, so the measured saturation of a large number of cores should satisfy the relation:

$$\frac{(S_o)_{\text{reservoir}}}{\eta_o} + \frac{(S_o)_{\text{core}}}{\eta_w} = 1, \tag{3}$$

of which η_o stands for the loss rate of crude oil saturation; η_w stands for the loss rate of formation water saturation; we can see that formula (3) is the equation of one line, so we can obtain the loss rate of crude oil saturation and that of formation water saturation as coefficients in this equation. Xin et al. [13] and Huiming et al. [14] further discover that different correction coefficients can be obtained for different types of rocks. This method is simple and easy to understand, but the loss rate is impacted by different rock properties, and the classification standards of sample points are not objective and contain larger errors.

(4) Static Zero-Dimensional Model Correction Method. Mathematical models proposed by Xin et al. [13], Huiming et al. [14], and Yuhuan [15] are basically consistent and all establish the zero-dimensional mathematical model based on fractional flow equation and mass conservation in the basic theory of "the oil-gas-water is allocated according to fractional flow rate in the total volume of discharged total volume," and consequently the derived correction equation for oil saturation is

$$(S_o)_{\text{Reservoir}} = S_{or} + \frac{1 - S_{wr} - S_{or}}{1 + (\mu_o/\mu_w)\, m e^{-n(S_o)_{\text{Reservoir}}}}. \tag{4}$$

There is an important assumed condition in these models; namely, it is considered that the fluid saturation in the core is completed instantaneously when the core is lifted to the ground, without considering that the precipitation and escape of dissolved gas in the lifting process are a changeable process and even without considering the fluid escapes from the core due to dissolved gas drive in the process.

3. Establishment of Dynamic Correction Model for Sealed Coring Saturation

3.1. Affecting Factors for Sealed Coring Saturation. A large number of study results show that the oil-water saturation measured by sealed coring are affected by the following 5 aspects [3–10]: ① rock pore volume change and fluid volume change; ② depressurization degassing of crude oil in core, and appearance of dissolved gas drive; ③ volatilization of oil and water in the transport process after the core is lifted to the ground; ④ mud invasion in drilling coring; ⑤ experiment error.

In the 5 factors, experiment errors are omnipresent, and the research of Xin et al. [13–15] suggests that the mud invasion and core transport process are not very important factors, so they are not key considerations in this paper. The combination of multiple researches indicates that the main affecting factors of core saturation of sealed coring are rock pore volume change, fluid volume change, and dissolved gas drive [1–10], so the correction of the three kinds of affecting factors is also the key problem focused by numerous researches.

3.2. Dynamic Variation of Oil-Water Saturation in Coring Process. The well bottom is generally in the HTHP state in sealed coring. When the core is lifted to the ground, the change range of temperature in the core barrel is small due to a short time, while the pressure change is quite obvious, so the pressure change is the main reason to cause fluid saturation change in the core.

In the lifting process, the pressure continues to decline, and the fluid saturation in the core also changes constantly, which is a dynamic continuous process. Based on the discrete principle, we can utilize a finite number of stepped processes to approximately represent one continuous physical process; namely, we can replace the continuous pressure change in the core lifting process with stepped pressure, and the fluid in the core can have the following changes for reduction of Δp each time:

① After pressure changes Δp, if the pressure in the core barrel is higher than the saturation pressure, only the core pore volume and liquid volume in the core change. Under the combined action of the two, the liquid in the core is squeezed out, causing the changes of fluid saturation in the core. When the pressure drop Δp is small, the oil-water volume squeezed out may be considered to be distributed according to the oil-water fractional flow [13–15].

② If the pressure in the core barrel is lower than the saturation pressure after the pressure changes Δp, the dissolved gas separation phenomenon appears. So, besides the expansion of liquids and reduction of pore volume, the dissolved gas also expands and the volume change range is wider, and consequently, the fluid volume squeezed out is larger, and the change range of fluid volume in the core is also wider.

With the continuous lifting of core barrel, the pressure in the barrel reduces further. The saturation change in the core barrel may repeat the above ① or ② process, and when the pressure is much lower than the saturation pressure, the gas precipitation amount increases and becomes continuous phase. So most of the gas escapes from the core and carries liquid flowing out of the core, showing obvious characteristics of dissolved gas drive.

3.3. Theoretical Basis and Computation Process for Dynamic Correction Model

3.3.1. Theoretical Basis for Dynamic Model. The process of oil-gas two-phase fluid flow or oil-gas-water three-phase fluid flow is unstable, but every instant in the overall process can be approximately regarded as a stable state. In this way, the unstable state of the overall process can be treated as the superposition of countless stable states, and this method is called stable state successive displacement method [15]. When the value taken for time interval or pressure is very small, the results obtained by this method basically comply with the actual situation.

3.3.2. Dynamic Correction Equation for Two-Phase Fluid. When the pressure declines Δp, if the dissolved gas is not separated, the total fluids ΔN_e squeezed out due to expansion of liquids and rock pore volume compression cause is

$$\Delta N_e = V_b \cdot \left[C_f + \phi\left(C_w \cdot S_w + C_o \cdot S_o\right)\right] \cdot \Delta p. \tag{5}$$

According to the material balance principle, *residual crude oil amount after core depressurization = crude oil amount before depressurization − crude oil amount squeezed out*, and it is considered that the oil-water amount squeezed out is distributed according to the fractional flow equation, so we can get

$$\frac{S_{o-\Delta p}}{B_{o-\Delta p}}\phi V_b = \frac{S_o}{B_o}\phi V_b - \Delta N_e \cdot f_o. \tag{6}$$

Simplify and substitute (5) into the above equation:

$$\frac{S_{o-\Delta p}}{B_{o-\Delta p}} = \frac{S_o}{B_o} - \frac{1}{B_{o-\Delta p/2}}\left[\frac{C_f}{\phi} + \left(C_w \cdot S_w + C_o \cdot S_o\right)\right] \cdot \Delta p \cdot \left(1 - f_w\right), \tag{7}$$

Of which, f_w stands for water cut, and according to fractional flow equation:

$$f_w = \frac{1}{1 + \left(K_{ro}/\mu_o\right)\left(\mu_w/K_{rw}\right)} \tag{8}$$

of which K_{ro} and K_{rw} are a function of saturation, and the corresponding saturation should be the average saturation $\overline{S}_w = (S_w + S_{w-\Delta p})/2$ before and after depressurization. Considering there are only oil-water two phases, $\overline{S}_w + \overline{S}_o = 1$.

Thus, (7) is an implicit function equation of saturation $S_{w-\Delta p}$, and we can obtain $S_{w-\Delta p}$ with the iteration method.

3.3.3. Correction Equation for Three-Phase Flow Saturation. When the pressure declines Δp, if the dissolved gas is separated, the total fluids ΔN_e squeezed out due to expansion of liquids and rock pore volume compression cause is

$$\Delta N_e = V_b \cdot \left[C_f + \phi\left(C_w \cdot S_w + C_o \cdot S_o + C_g \cdot S_g\right)\right] \cdot \Delta p. \tag{9}$$

When depressurization Δp is very small, the seepage in the core can be approximately considered as steady seepage, so the oil-gas-water three phases squeezed out of the core may be approximately distributed according to fractional flows f_o, f_w, and f_g.

According to the material balance principle, *residual oil amount after core depressurization = oil amount before core depressurization − discharged oil amount*.

$$\frac{S_{o-\Delta p}}{B_{o-\Delta p}} = \frac{S_o}{B_o} - \frac{1}{B_{o-\Delta p/2}}\left[\frac{C_f}{\phi} + \left(C_w \cdot S_w + C_o \cdot S_o + C_g \cdot S_g\right)\right] \cdot \Delta p \cdot f_o. \quad (10)$$

In a similar way, we can get the correction equation of water saturation:

$$\frac{S_{w-\Delta p}}{B_{w-\Delta p}} = \frac{S_w}{B_w} - \frac{1}{B_{w-\Delta p/2}}\left[\frac{C_f}{\phi} + \left(C_w \cdot S_w + C_o \cdot S_o + C_g \cdot S_g\right)\right] \cdot \Delta p \cdot f_w. \quad (11)$$

According to the material balance principle, *free gas quantity after depressurization = free gas quantity before depressurization + dissolved gas amount before depressurization − dissolved gas amount after depressurization − discharged gas amount*, so we can get the correction equation for gas saturation:

$$\frac{S_{g-\Delta p}}{B_{g-\Delta p}} = \frac{S_g}{B_g} + \frac{S_o}{B_o} \cdot R_s(p) - \frac{S_{o-\Delta p}}{B_{o-\Delta p}} \cdot R_s(p-\Delta p) - \frac{\left[C_f/\phi + \left(C_w \cdot \bar{S}_w + C_o \cdot \bar{S}_o + C_g \cdot \bar{S}_g\right)\right] \cdot \Delta p \cdot f_g}{B_{g-\Delta p/2}}. \quad (12)$$

In the above three correction equations, the expressions for the fractional flows f_o, f_w, and f_g for the oil, water, and gas are, respectively,

$$f_o = \frac{K_{ro}/\mu_o}{K_{ro}/\mu_o + K_{rw}/\mu_w + K_{rg}/\mu_g},$$
$$f_w = \frac{K_{rw}/\mu_w}{K_{ro}/\mu_o + K_{rw}/\mu_w + K_{rg}/\mu_g}, \quad (13)$$
$$f_g = \frac{K_{rg}/\mu_g}{K_{ro}/\mu_o + K_{rw}/\mu_w + K_{rg}/\mu_g}.$$

3.3.4. Calculation Flow of Dynamic Model. According to the process analysis of oil-water saturation changes in the core lifting process, we can utilize the flow as shown in Figure 1 to fit the saturation of core test:

① Set initial reservoir saturation as $(S_o)_{\text{reservoir}}$ and $(S_w)_{\text{reservoir}}$, and the reservoir formation pressure of water injection development is generally higher than the saturation pressure, so $(S_g)_{\text{reservoir}} = 0$.

② Depressurize Δp, judge whether the pressure in core barrel is lower than the bubble point pressure, and if it is higher than the bubble point pressure, it is only required to correct the changes of core saturation according to oil-water two-phase flow; if the pressure in core barrel is lower than the bubble point pressure, the fluid in the core is degassed, dissolved gas drive appears, and it is required to correct the change of core saturation by three-phase flow.

③ Calculate the core saturation after depressurization Δp, and if the pressure in core barrel is still higher than the atmospheric pressure or the given reference pressure to ground, continue to depressurize. Replace the initial saturation with the calculated core saturation, and repeat ② process until the pressure in core barrel reduces to the given reference pressure.

④ When judging the reference pressure to ground, compare the core saturation obtained by calculation with the experiment test saturation. If error requirements are satisfied, it indicates that the saturation initially set by us is the reservoir saturation; if error requirements are not satisfied, we can reset an initiation saturation, and then repeat ①~④ processes until the core saturation obtained by calculation is close to the experiment test saturation.

4. Application Effect and Assessment of Dynamic Correction Model

4.1. Reservoir Introduction. Take one oilfield block in the Western China as an example, with the burial depth of about 2,280 m, oil layer thickness of about 20 m, initial formation pressure of 25.7 MPa, saturation pressure of 12.4 MPa, difference between reservoir pressure and saturation pressure of 13.3 MPa, and the initial oil saturation of about 40%; central reservoir temperature of 62°C, and geothermal gradient of 49.8 m/°C. The reservoir is mainly composed of fine sandstone, siltstone, and medium sandstone, with conglomerate and pebbled sandstone at the bottom. The porosity is 14.9~12.5%, with the average value of 13.9%; the permeability is $60\sim27.2\times10^{-3}\,\mu\text{m}^2$, with the average value of $45\times10^{-3}\,\mu\text{m}^2$, and the effective permeability is $26\times10^{-3}\,\mu\text{m}^2$. One sealed coring well (Well D400217) is drilled in the reservoir to determine the reservoir saturation distribution, with the logging information as shown in Figure 2.

4.2. Correlation Parameters for Coring Saturation Correction. After the saturation is measured by sealed coring, correction is made according to the dynamic model established in this paper. During the correction process, the required correlation parameters are formation water volume factor B_w, 1.020; formation water viscosity, 0.304 mPa·S. The high-pressure physical properties of formation oil and gas are as shown in Figure 3, including crude oil viscosity, gas viscosity, oil volume factor, gas volume factor, and solution gas-oil ratio; the fluid relative permeability data are as shown in Figure 4

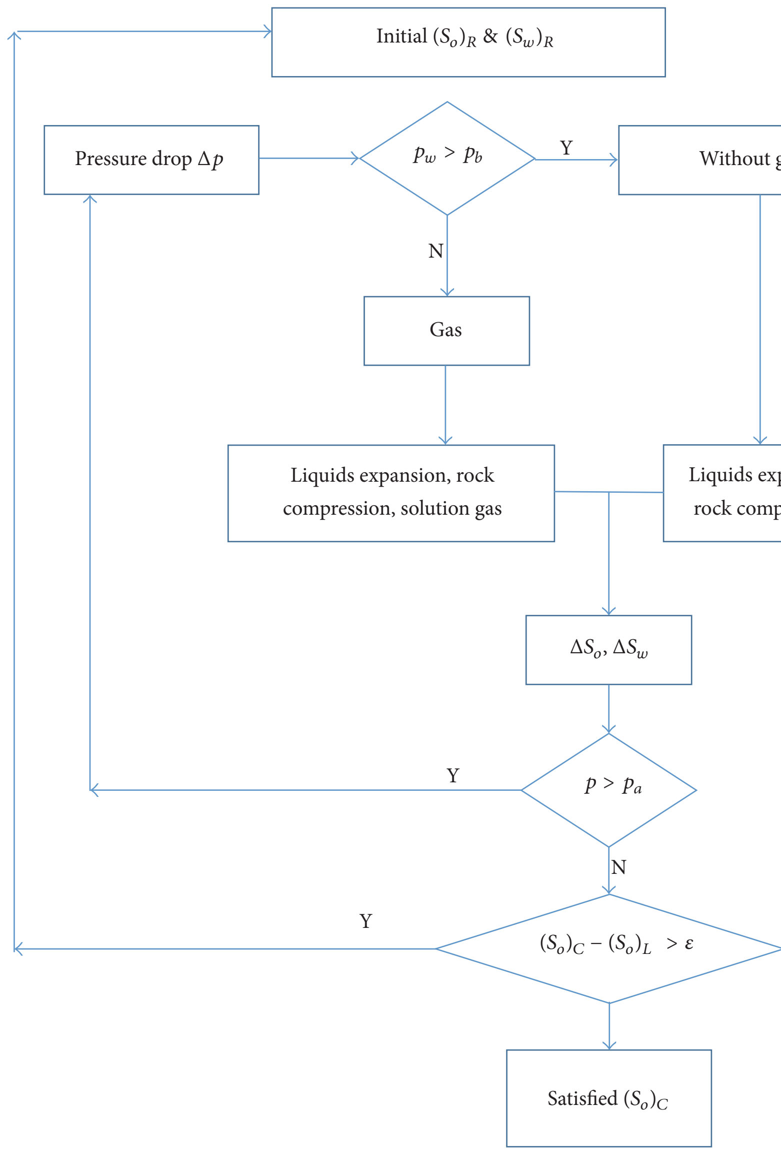

FIGURE 1: Flowchart of performance matching reservoir saturation.

which shows the crude oil and water two-phase relative permeability curve and Figure 5 which shows gas and fluid two-phase relative permeability curve, and the three-phase relative permeability data are obtained by Stone I model calculation [18].

$$k_{ro} = \frac{k_{row}(S_w) \cdot k_{rog}(S_g) \cdot (S_o - S_{om}) \cdot (1 - S_{wc} - S_{om})}{k_{rocw} \cdot (1 - S_w - S_{om}) \cdot (1 - S_{wc} - S_{om} - S_g)}. \quad (14)$$

4.3. Comparative Analysis of Correction Result and Logging Interpretation Saturation. The logging interpretation saturation of Well D400217 originates from practice and is the fluid saturation value which is obtained by acquiring relevant saturation calculation parameters based on core data, then calibrating four-characteristic parameters of core according to logging evaluation method, and then making calculation by saturation formula. For the comparison with the dynamic method provided in this paper, the results are as shown in Figure 2 and Table 1. As can be seen from Table 1, the sealed coring saturation after correction is relatively close to logging interpretation saturation compared with the result corrected by static zero-dimensional model [13], which shows that the dynamic correction method provided in this paper has a certain reliability.

4.4. Assessment of Dynamic Saturation Correction Model. Seen from the calculation results (Table 1), the results obtained by dynamic model established in this paper are closer to the logging interpretation saturation compared with the results obtained by other methods. Seen from the establishment process of dynamic model, the model in this paper has made progress in two aspects compared with other

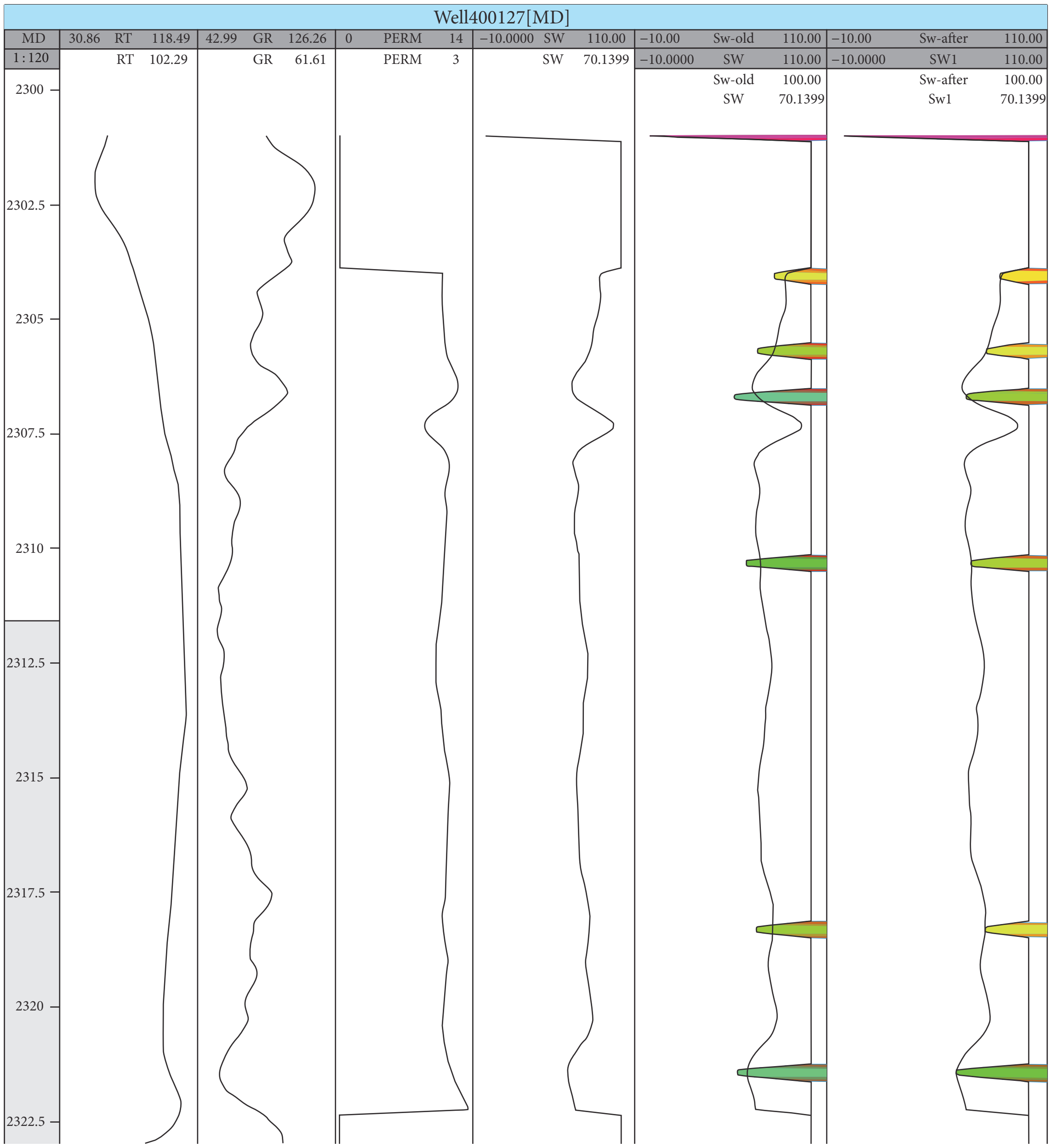

Figure 2: Comparison between ground water saturation and water saturation corrected by dynamic model in Well D400217. The logging information is shown at the first to forth columns as "RT," "GR," "PERM," and "SW" in this figure. RT means resistivity log. GR means gamma ray. PERM means permeability. And SW means water saturation. And the corrected water saturation is also listed in this figure at the last two columns.

Table 1: Saturation test of Well D400217.

Core depth meter	Logging interpretation saturation %	Saturation before correction %	Saturation corrected by dynamic model %	Saturation corrected by static model %
2304.000	85.14	77.20	84.94	87.22
2305.625	77.72	67.10	76.83	78.86
2306.625	64.50	52.30	64.25	65.52
2310.250	68.85	60.40	68.12	69.12
2318.250	76.19	66.20	75.73	77.32
2321.375	60.63	54.30	60.52	61.54

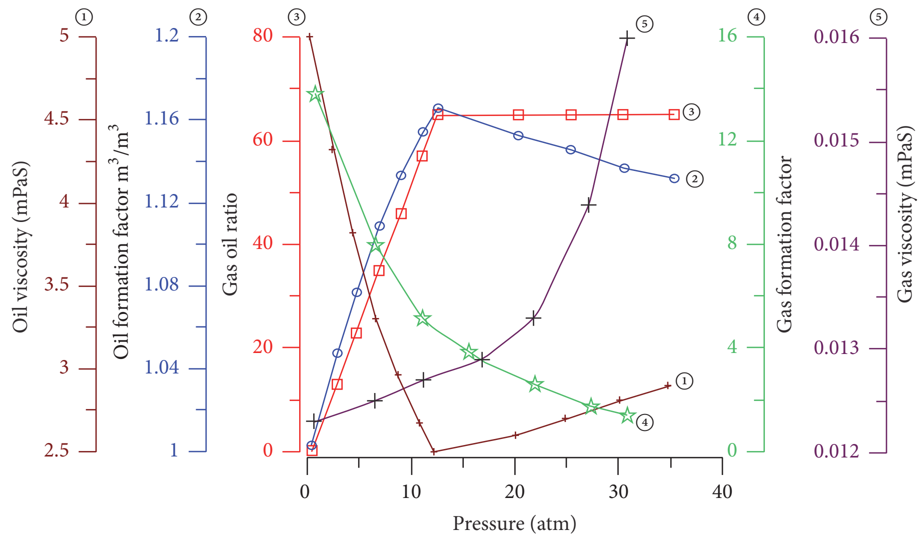

FIGURE 3: Reservoir block PVT data curve. *Note*. Curve ① is the crude oil viscosity curve, curve ② is the oil volume factor curve; curve ③ is solution gas-oil ratio curve; curve ④ is gas formation volume factor curve; curve ⑤ is gas viscosity curve.

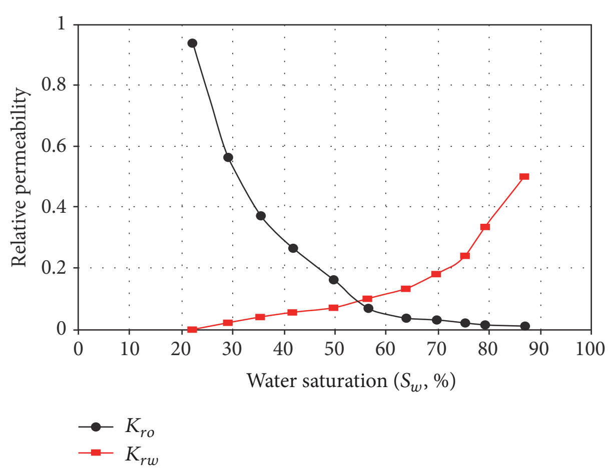

FIGURE 4: Relative permeability curve between crude oil and water.

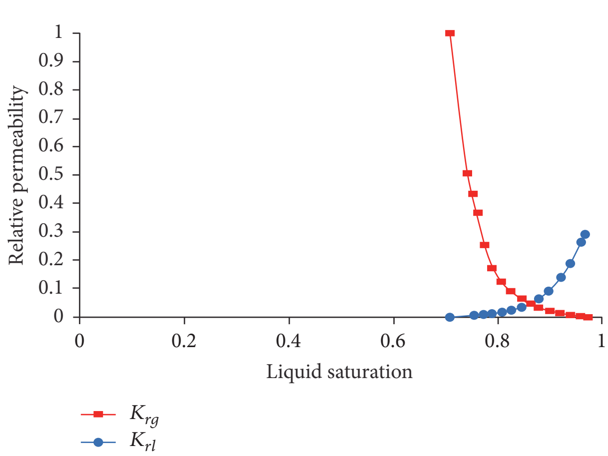

FIGURE 5: Relative permeability curve between natural gas and liquid.

study results [10–12, 14]: the first is that the dynamic change process of pressure is considered in the coring process, which is more suitable with the actual situation of saturation change; the second is that the pore volume change and fluid volume change are considered simultaneously, which is more suitable with phase change law of core in the coring process.

5. Conclusions

(1) In the sealed coring process, the fluid saturation change in the core is a dynamic process, and the pore and oil-water volume, crude oil degassing, and so on continuously change with the pressure change.

(2) Based on the steady state successive displacement principle and multiphase flow fractional flow theory, and the analysis of dynamic variation characteristics of core saturation, this paper establishes the mathematical model for dynamic correction of oil-water saturation and proposes the process flow of saturation correction. This method not only considers the dynamic change process of pressure but also calculates the state change processes of pore volume and fluid volume simultaneously, which makes the dynamic model more suitable with the phase change law of core in the coring process compared with other methods.

(3) With the basic data and logging information of coring well in one oilfield, this method has higher reasonableness and accuracy and is more suitable for saturation correction of sealed coring well compared with the logging interpretation saturation and zero-dimensional model method calculation, so this method has the value for generalization.

Parameter Description

S_o, S_w, S_g: Oil saturation, water saturation, and gas saturation, f

B_o: Oil volume factor, m^3/m^3
E: (In the literature) comprehensive fluid compressibility
M: (In the literature) correction coefficient of mobility
V: Heterogeneous coefficient
A, B: Regression coefficients, dimensionless
η_o: Loss rate for crude oil saturation
η_w: Loss rate of formation water saturation
m, n: Regression coefficient in semilogarithmic diagram for K_{ro}~S_o curve
V_b: Rock appearance volume, m^3
Φ: Porosity, f
C_f: Rock bulk compressibility coefficient, 1/MPa
C_w: Formation water bulk compressibility, 1/MPa
C_o: Formation crude bulk compressibility, 1/MPa
f_o, f_w, f_g: Oil cut, water cut, and gas cut
$B_{o-\Delta p}, B_{w-\Delta p}, B_{g-\Delta p}$: Volume factor of oil, water, and gas under pressure $p - \Delta p$ when the pressure declines Δp
$B_{o-\Delta p/2}, B_{w-\Delta p/2}, B_{g-\Delta p/2}$: Volume factor of oil, water, and gas under pressure when the pressure declines Δp
R_s: Formation crude solution gas-oil ratio, m^3/m^3
μ_o, μ_w, μ_g: Viscosities of oil, water, and gas, mPa·S
K_{ro}, K_{rw}, K_{rg}: Relative permeabilities of oil, water, and gas, f
S_{wc}, S_{or}: Confined water saturation and residual oil saturation, f.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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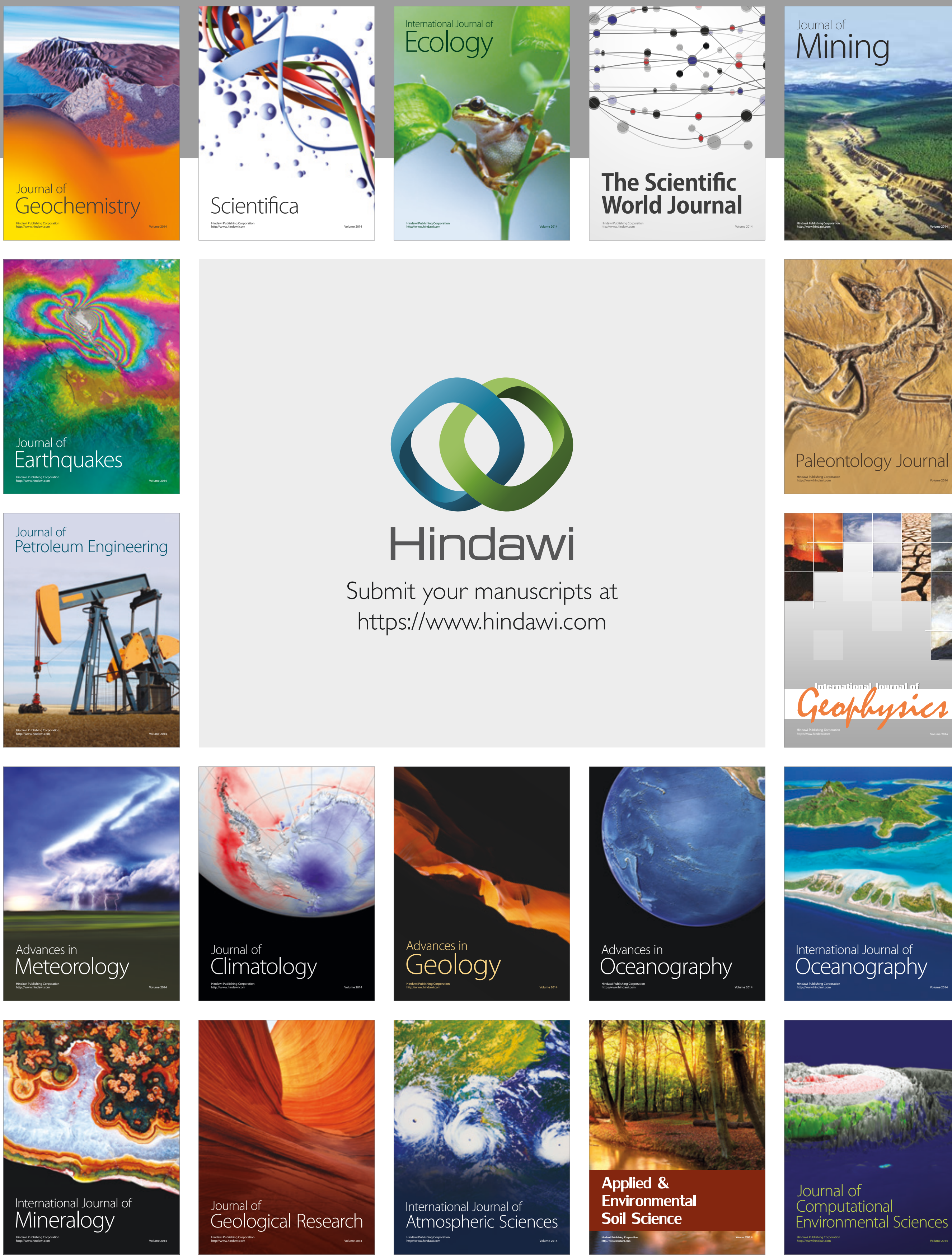
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