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Study on Impact of Compositional Gradient on Volatile Oil Reservoir Development

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Abstract

The existing of compositional gradient in volatile oil reservoir makes the reservoir special. It will have great significance in calculating reserves, determining reasonable development mode and improving volatile oil recovery, if the composition profile and vertical distribution characteristic of the underground fluid are considered, when developing volatile oil reservoir. Based on the theory of compositional gradient[1], the paper analyzed the compositional gradient in various kinds of reservoir, researched the impact of compositional gradient on reserves estimation in volatile oil reservoir, and then evaluated the final recovery efficiency of different development modes (depletion, water-flood, gas injection) with the method of compositional numerical simulation. Results show that: If the reservoir fluid contains more light components, the compositional gradient phenomenon will be more obvious; by choosing fluid samples at the middle of the reservoir to calculate reserves of the volatile oil reservoir, accurate value will be obtained; when developing volatile oil reservoirs, the compositional gradient phenomenon affects greater on recovery efficiency of gas injection development than that of depletion and water-flood development. The achievements provide theoretical guidance and basis for volatile oil reservoir development.

Key words: Volatile oil reservoir; Compositional gradient; Compositional simulation; Development mode; Phase behavior

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INTRODUCTION

Temperature and pressure usually change with depth in reservoirs, compositional gradient phenomenon exists in volatile oil reservoirs since its fluids are closed to the critical point. Under the influence of compositional gradient, the density, viscosity, initial dissolved gas/oil ratio and formation oil volume factor of the reservoir oil change continuously from top to bottom of the structure whereas there are great differences of the variation between the saturated and unsaturated reservoir. With an accurate EOS, Sage and Lacey (1938) researched compositional gradient and concluded that compositions changed with depth in reservoirs[2]. In the late 19th, Gibbs proposed a theoretical model of evaluating compositional gradient with constant temperature which indicated that the influence of gravitational field will be obvious when the hydrocarbon fluid is closed to the critical point. In 1994, Curtis H. Whitson researched the variation characteristics of the compositional gradient to the depth on different types of reservoir, results showed that: variation of the saturation pressure caused by compositional gradient from black oil to near-critical oil aggravated continuously; compositional gradient phenomenon became weaker and variation of compositional gradient was opposite to that of saturated degree in high unsaturated reservoirs [3]. In 1997, Padua pointed out that the negative effect on compositional gradient caused by the changing of reservoir temperature should be noticed when compositional gradient exists in deep water reservoirs[4].

After 1999, studies of compositional gradient abroad mostly focused on its impacts on oilfield development. E. Syahrial (1999) first revealed the distribution of light and medium hydrocarbon components in the inner formation of volatile oil reservoir concerning the compositional gradient, the decrease with depth of light components leads to the alternation of miscible displacement mechanism and the final miscible effects would be entirely different[5]. In 2001, Juan M. Jaramillo presented that the accuracy of reserve estimation will be lowered while neglecting compositional gradient in near-critical reservoir[6]. By simulation, S. Luo and M. A. Barrufet (2004) studied compositional gradient in near-critical reservoir development, their study shows that compositional gradient has significant impacts on the in-place hydrocarbon estimation and fluid properties prediction, they also presented that optimistic or pessimistic estimation depends upon the reference depth for sample fluid taken in the calculation[7]. In 2006, Zhao Wenzhi pointed out that variation of compositional gradient between saturated and unsaturated reservoir differed much, which had great influence on reserve's estimation[8]. In 2010, by making environments on the Tubei reservoir fluid samples, Li Juhua estimated the oil in place by means of compositional gradient simulation, the reserves considering compositional gradient was 5.38% higher than the former calculation[9].

This paper analyzes the variation of compositional gradient in different kinds of reservoir (near-critical oil, volatile oil, light oil and black oil), researches the variation of saturation pressure and components of samples under different depth and evaluates their impacts on reserve estimation. Oil and gas in place under different reference depths in the reservoir are calculated and conceptual models are built to progress numerical simulation research aiming at comparing different development modes, then the impacts of the compositional gradient on the development of volatile oil reservoir is studied further.

1. THEORETICAL BASES OF COMPOSITIONAL GRADIENT

The compositional gradient phenomenon usually exists in thick oil/gas reservoirs, reservoirs with obvious structural relief or structural difference, saturated or slightly unsaturated reservoirs, volatile oil or near-critical reservoirs and thick heavy oil reservoirs. Expression of the thermal work of multicomponent system in gravitational field including not only the expanding or shrinking power that the system acts on the environment but also the displacement power occurred for the movement of different amount of substance (d_m) on the vertical direction (h). Therefore, Gibbs free energy under a gravitational field can be written by expression of Firoozabadi[13]:

$$\mathrm{d}G = -S\mathrm{d}T + V\mathrm{d}P + mg\mathrm{d}h + \sum_{i=1}^{Nc}(\mu + M\omega_i hg)\mathrm{d}n_i\ . \qquad (1)$$

Where G is Gibbs free energy, S is entropy energy, T is temperature, P is pressure, m is mass, g is gravity constant, h is depth, N_c is total component number, μ_i is chemical potential of component i, $M\omega_i$ is molecular weight, n_i is mole of component i.

The pressure and depth (z) are related by hydrostatic equation:

$$V\mathrm{d}p+mg\mathrm{d}h = 0, \qquad (2)$$

$$\text{Or } \mathrm{d}P = -\rho g\mathrm{d}h. \qquad (3)$$

For an isothermal system,

$$\mathrm{d}T = 0. \qquad (4)$$

So the equation can be converted to

$$(\mu_i+M\omega_i hg)_T = 0 \quad i = 1,\cdots N_C\cdots \qquad (5)$$

Gibbs depositional equation can be obtained from this formula:

$$(\mathrm{d}\mu_i+M\omega_i hg)_T = 0 \quad i = 1,\cdots N_C\cdots \qquad (6)$$

Expressing the chemical potential using fugacity formula[14] and at the meantime evaluating the integral from zero reference depth to h, then obtaining:

$$f_i = f^0{}_i\exp[-M\omega_i gh/RT] \quad i = 1,\cdots N_C\cdots \qquad (7)$$

f_i = fugacity of component i(psia); $f^0{}_i$ = reference fugacity of component i (psia).

Equations 1-7 provide the fugacity coefficient of component i under certain phase, such as state of pressure and component under benchmark (depth), then the fugacity coefficient is the function of vertical position. Therefore, a complete set of equations can be solved to confirm component and pressure changing with depths.

2. VARIATION ANALYSIS OF COMPOSITIONAL GRADIENT IN DIFFERENT TYPES OF RESERVOIR

Based on the theory above, compositional gradient phenomenon of typical black oil, light oil, volatile oil and near-critical fluid are calculated by phase behavior calculation. Data of the volatile oil is got from a certain typical volatile oil reservoir in West Africa and others from Whitson. Gas/oil contact is the position where the saturation pressure equals to the reservoir pressure at certain depth and pressure at that point is set to P_{GOC}.

Taking a certain deep-water reservoir in West Africa as an example a typical volatile oil reservoir which has a thick layer (850 m), this paper built a reservoir fluid model choosing volatile oil samples under depth of 3148m, mixed the components by means of Whitson(molar fraction and molecule constitution of the pseudo-components) and got 8 pseudo-components shown in Table 1, the phase characteristics of the pseudo-fluid fit its equation of state (EOS).

Table 1
Pseudo-Components of Typical Volatile Oil Samples (Depth 3,148 m, Formation Pressure 33.09 MPa)

Pseudo-components	GN1	GN2	GN3	GN4	GN5	GN6	GN7	GN8
Composition	$N_2\sim C_1$	$CO_2\sim C_2$	$C_3\sim C_4$	$C_5\sim C_8$	$C_9\sim C_{13}$	$C_{14}\sim C_{19}$	CN1	CN2
Molar fraction %	59.446	7.868	7.459	12.218	2.995	0.763	0.763	0.563

Fitting results are shown in Figure 1, as can be seen that molar fraction of light components decrease with the depth increasing and molar fraction of heavy components increases with the increasing burial depth of the reservoir. Besides, molar fraction of light and heavy components changing with depth calculated by compositional gradient model fit well with the measured samples, correction of the EOS is done.

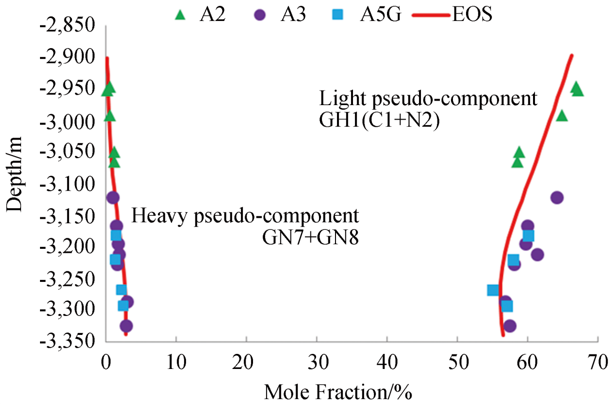

Figure 1
Plot of Light Pseudo-Component GN1(C1+N2) and Heavy Pseudo-Component GN7+GN8 Versus Depth

The results indicate that the compositional gradient phenomenon generally exists in all kinds of reservoir with showing same characteristics: Saturation pressure firstly rises and then decreases with the increasing depth, maximum critical point variable exists near the gas/oil contact.

With the increasing content of light component, compositional gradient phenomenon turns more obvious and saturation pressure gradient increases gradually. Moreover, system gradient of the dew point pressure is higher than that of the bubble point pressure in all reservoirs. As shown in Figure 2, saturation pressure of the black oil reservoir changes the least with depth changing, then the light oil reservoir, whose saturation pressure at the top and bottom and the maximum critical point pressure P_{GOC} are more or less the same. The black oil and the light oil reservoir can be taken as constant composition distribution and fluid properties changing with depth can be ignored when carrying out numerical simulation calculation. But in volatile oil and near-critical reservoir, compositional gradient phenomenon is extremely obvious, meanwhile, the saturation pressure at the top and bottom and the maximum critical saturation pressure P_{GOC} differs greatly. Actually, the saturation pressure gradient of the whole oilfield in the near-critical reservoir reaches 0.025 MPa/m.

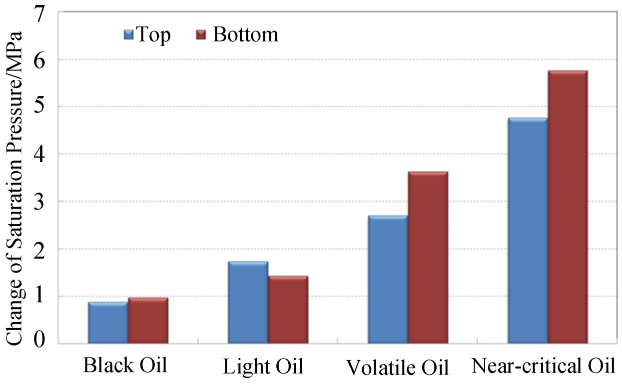

Figure 2
Saturation Pressure Variation Amplitude in Different Types of Reservoirs

3. EFFECT OF COMPOSITIONAL GRADIENT ON RESERVES ESTIMATION

Ignoring compositional gradient in near-critical reservoir will result in lower accuracy of reserves estimation. When converted to surface, volume of hydrocarbon underground changes cause fluid properties change vertically with the depth varying in volatile oil reservoir. Fluid properties of this kind of reservoir are closed to the critical point, so hydrocarbon mixture has a more complicated phase behavior than that in the dry gas and black oil reservoirs. Therefore, when estimating the in place hydrocarbon in thick reservoirs, it is extremely important to consider the compositional gradient in reservoirs whose fluid components distribution differs obviously. Initial hydrocarbon in place calculated is different if setting reference datum with oil samples of different depth.

Reserves obtained by fitting sample mentioned above presents its actual value, oil and gas in place under different reference depths are separately calculated by the compositional gradient model.

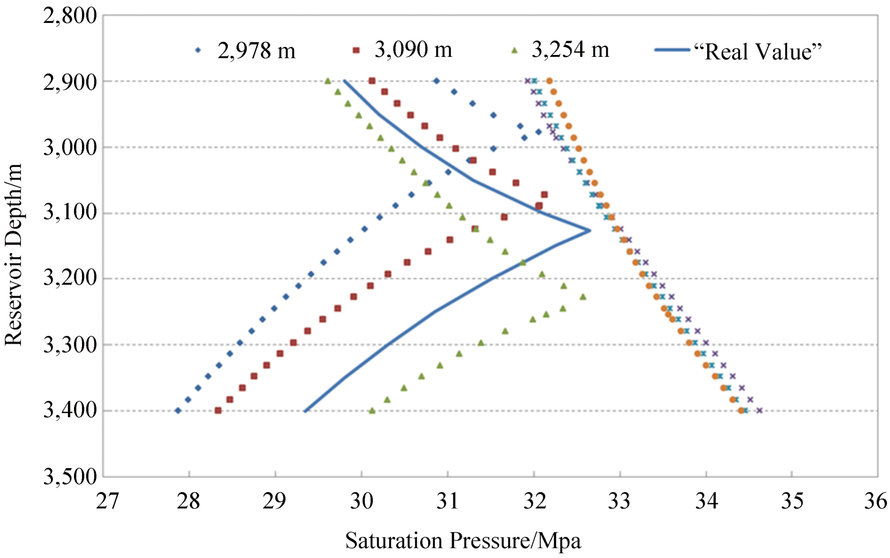

Figure 3
Curves of Different Samples Saturation Pressure Changing With Depths

As shown in Figure 3, critical saturation pressure points gradually move down while depths of the collected samples increase, bubble point pressure of the samples under the middle depth (3,090 m) fits the "real value" well and the bubble point pressures estimated drop 1-1.5 MPa on the average, meanwhile, forecast of saturation pressure and component distribution of the samples at the top and bottom are not ideal. Oil in place under different sample depths neglecting and concerning compositional gradient are each calculated and the results are shown in Tables 2. Fluid sample in the middle of the reservoir at the reference depth of 3,148 m is used as the reference point and calculated oil and gas reverses of samples at this depth is set as the "real reserves" in numerical simulation.

Table 2
Comparison of Oil/Gas Reserves by Using Reference Sample at Different Depth

	3,148 m		Top	Middle	Bottom
	Without CG	With CG		With CG	
Oil in place /(surface)	26,253,245	36,668,492	38,266,951	36,939,623	35,584,442
Gas in place/(surface)	1.63×10^{10}	1.34×10^{10}	1.11×10^{10}	1.31×10^{10}	1.48×10^{10}

Calculating results indicate that oil and gas in place will probably be overestimated or underestimated while neglecting the compositional gradient. Oil in place will be overestimated when the reference depth located at the top of the reservoir, while the gas calculated in place is small. In contrast, oil in place will be underestimated when the reference depth located at the bottom of the reservoir, while the gas calculated in place is large. But for sample in the middle of the reservoir, the results are closed to the "real value" due to the neutralization of the increment of calculated oil reserves on the top and the decrement of calculated gas reserves at the bottom. Comparison of the relative error of oil& gas surface reserves is shown in Figure 4. Results show that the error is the smallest when the samples are selected from the middle of the reservoir. Therefore, it is better to choose samples in the middle of the reservoir to build fluid model in oil and gas in place estimation or in compositional numerical simulation in the volatile reservoir.

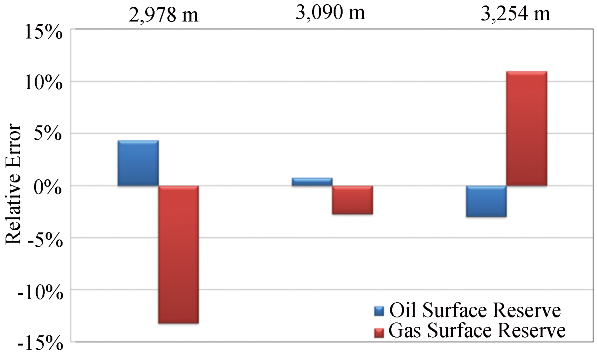

Figure 4
Calculated Relative Error of Oil/Gas Surface Volume

4. EFFECT OF COMPOSITIONAL GRADIENT ON DEVELOPMENT MODE

In conjunction with the researching conclusions of compositional gradient, numerical stimulation of different development modes (depletion, water injection, gas injection) is conducted by building conceptual models, the middle of reservoir is set as the reference depth and the produced gas is used as the injecting gas, basic parameters are shown in Figure 5.

Table 3
Basic Parameter of Simulation

Parameters	Number
Grid system	162×160×12
Reservoir depth	2,968 m - 3,789 m
Average permeability	1,000 md
Average porosity	0.2
WOC	3,338 m
Reference depth	3,148 m
Reference depth pressure	33 MPa
Rock compressibility	5E-5/MPa^{-1}

Results show that, by choosing the middle of the reservoir as the reference depth, the ultimate recovery of depletion and water injection is similar in both neglecting and concerning the compositional gradient, since the impact of top and bottom of reservoir neutralize each other in process of concerning the compositional gradient, and actually, influence of compositional gradient on development weakens. But numerical simulation of gas injecting shows that the influence of compositional gradient on gas injecting ultimate recovery is extraordinary obvious, the recovery concerning the compositional gradient is 10% higher than ignoring it.

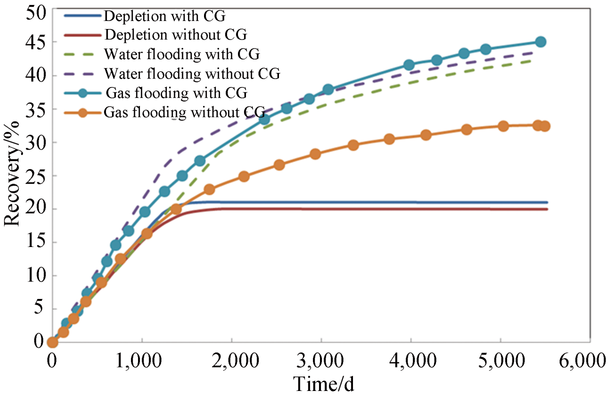

Figure 5
Recovery of Different Development Modes in Volatile Oil Reservoir

There are two main reasons causing the great changes of the recovery in process of gas injecting: The injecting gas brings new components into the reservoir which change the entire structure of components of the reservoir fluids. The compositional gradient phenomenon causes confrontation in composition distribution under varying depth, besides, the miscible mechanism and miscible condition of the injecting gas under varying depth change greatly.

CONCLUSION

(a) The composition distribution of the black oil and light oil reservoir can be taken as constant; the change of liquid properties with depth can be neglected in process of numerical simulation calculation. The compositional gradient phenomenon is obvious in volatile oil and near-critical reservoir, saturation pressures both on the top and at the bottom differ greatly with the maximum critical saturation pressure.

(b) It is extremely important to consider the compositional gradient in estimating reserves of the hydrocarbon fluids when this phenomenon is remarkable, in estimating oil and gas in place of the sample reservoir, the error is smallest by applying samples that closed to the middle of the reservoir.

(c) Characteristic analysis of the volatile oil reservoir fluids indicate that the injecting gas will affect the saturation pressure, density and volume factor of the crude oil if the reservoir is developed by gas injection.

(d) Ultimate recovery of depleted and water injected development mode are closed both in concerning and neglecting the compositional gradient, meanwhile, impacts of the compositional gradient on ultimate recovery of gas injection is extremely obvious.

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