Influence of Oil and Gas State on Oil Movability and Sweet Spot Distribution in Tight Oil Reservoirs from the Perspective of Capillary Force*

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Abstract

The coexisting free gas, solution gas and oil in a tight oil reservoir, constrained by the capillary force of the micro-nano pore-throat system, is of crucial importance to the sweet spot of the tight oil reservoir. Equations of modified total capillary force for the liquid phase are proposed to indicate the tight oil mobility in situ, which are derived as follows. (1) New variables representing the free gas volume ratio in pore space, 'yi-free', and the solution gas volume ratio in the liquid phase, '$y_{i\text{-solution}}$', are proposed to modify the vapor pressure in the Kelvin capillary force equation, based on the Peng-Robinson and Van-Laar equations. (2) Relationships between the vapor-liquid state, phase flow state for production and gas-to-oil production ratio (GOR) are established based on the modified capillary force function curve, in correspondence with the production zones (i.e., the oil zone, wet gas zone and dry gas zone), according to the North American and Yanchang tight production data. The following conclusions can be drawn. (1) We proposed a modified total capillary force function to indicate the tight oil mobility in-situ, based on the EOS (Peng-Robinson Equation) and EOS+λ(Van-Laar Equation) methods, composed of the variables of free gas volume ratio in the reservoir, solution gas volume ratio in the liquid phase, and other geological parameters such as the formation pressure, temperature, wettability coefficient, rock particle diameter and pore diameter. (2) A relationship between the GOR, the gas and oil state and phase flow state for production was established, based on the modified capillary force function and the production data of Yanchang and North American tight oil fields. Five phase stages are identified according to the gas volume ratio (y_i) in situ, e.g., a pure liquid phase in a single oil flow for production, a mixed gas and oil state in a multiphase transient flow for production, a mixed gas and oil state in multiphase stable flow for production, a condensate gas state in a multiphase super-critical flow for production, and a dry gas state in a single gas flow for production. (3) Tight oils are more

mobile in three stages according to the capillary function curve in situ: around the critical point of $y_{i\text{-}critical(1)}$, which corresponds to a single oil flow for production and a tight oil sweet spot for the oil zone, such as Yanchang and Bakken tight oils; at the transition zone between oil and wet gas zones before $y_{i\text{-}critical(2)}$, which is in correspondence with a multiphase stable flow state and a sweet spot for the wet gas zone, such as the Eagle Ford tight oil; and between the $y_{i\text{-}critical(2)}$ and $y_{i\text{-}critical(3)}$ in a condensate gas state, which is in correspondence with a multiphase super-critical flow for production and a sweet spot at the transition zone between wet gas and dry gas zones.

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Influence of oil and gas state on oil movability and sweet spot distribution in tight oil reservoirs from the perspective of capillary force

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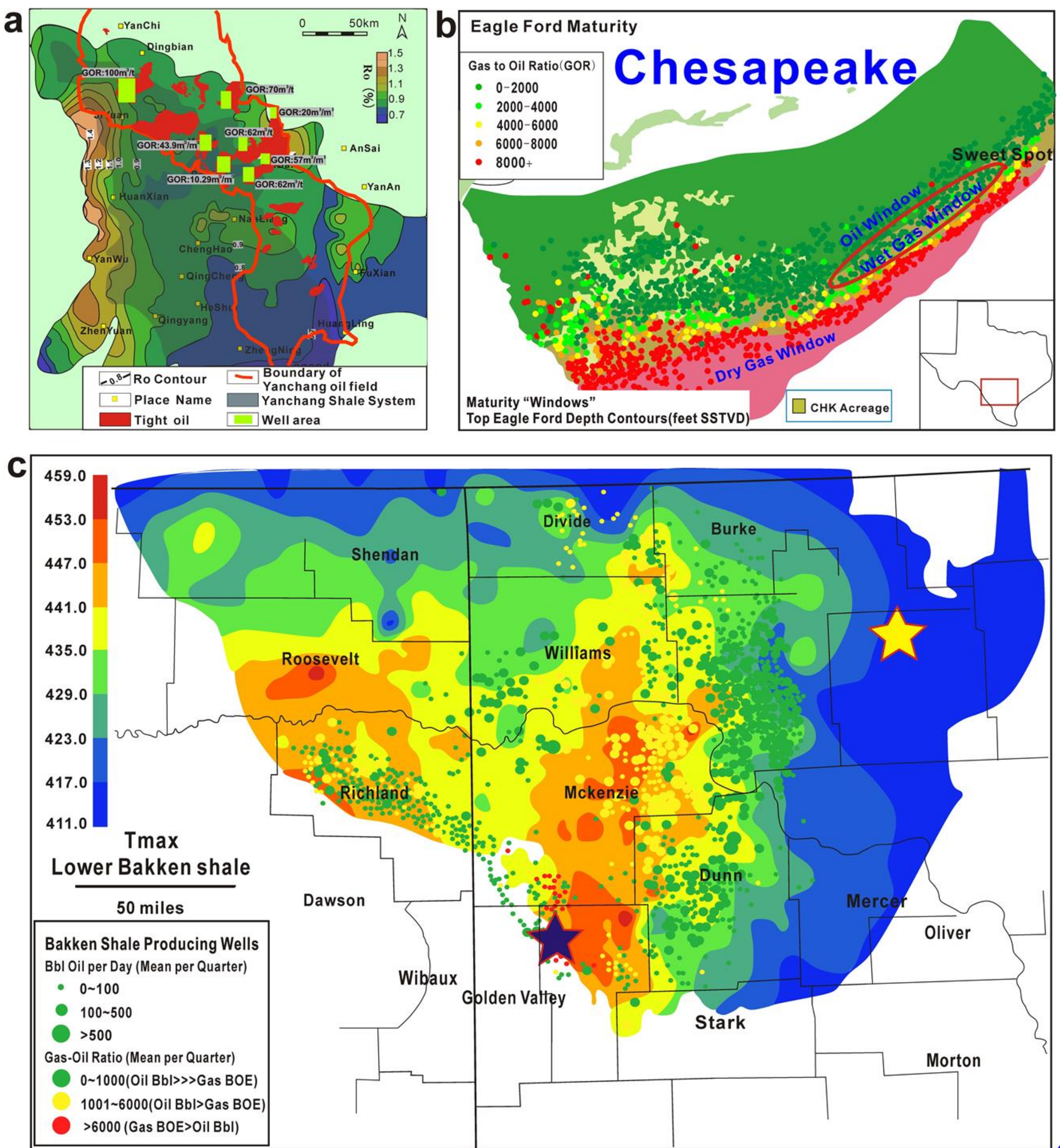
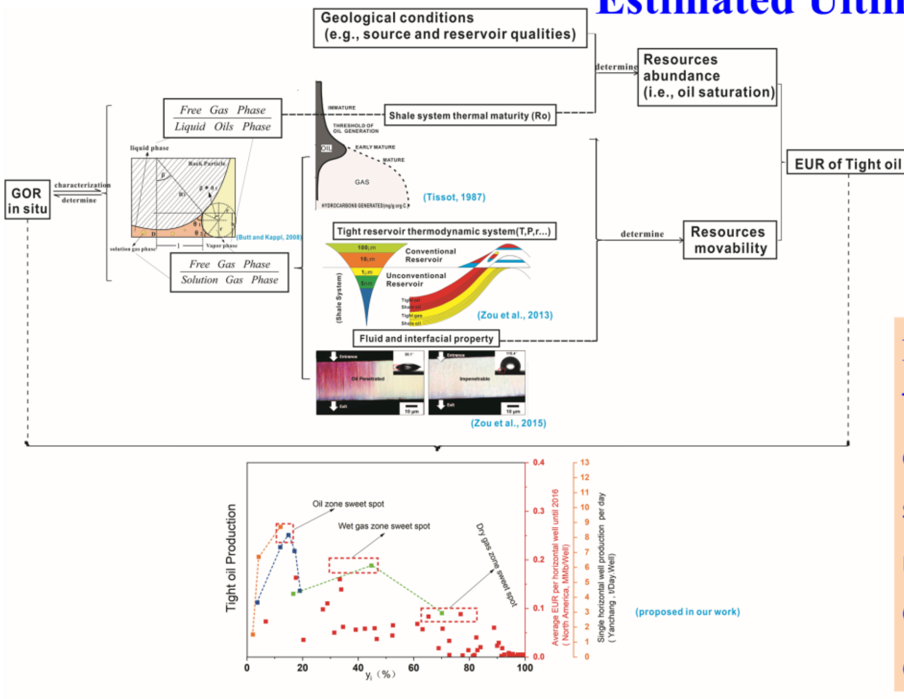
1.Background



2. Introduction

The relationship between the Gas-Oil-Ratio (GOR) and Estimated Ultimate Recovery (EUR) data

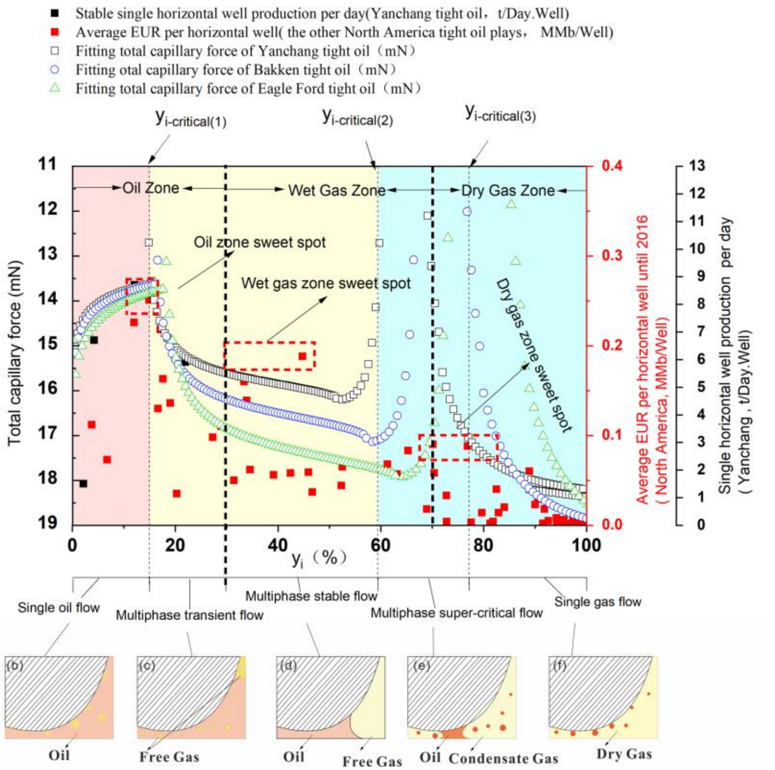


- The geological conditions
- The shale system thermal maturity （Ro)
- The tight reservoir thermodynamic system
- The fluid interfacial property

Issues:

The coexisting free gas, solution gas and oil in a tight oil reservoir, constrained by the capillary force of the micro-nano pore-throat system, is of crucial importance to the sweet spot of the tight oil reservoir. However, there is still no system numerical model for the GOR system considering those controlling factors related to the EUR data.

4. Simulation Results



5. Conclusions

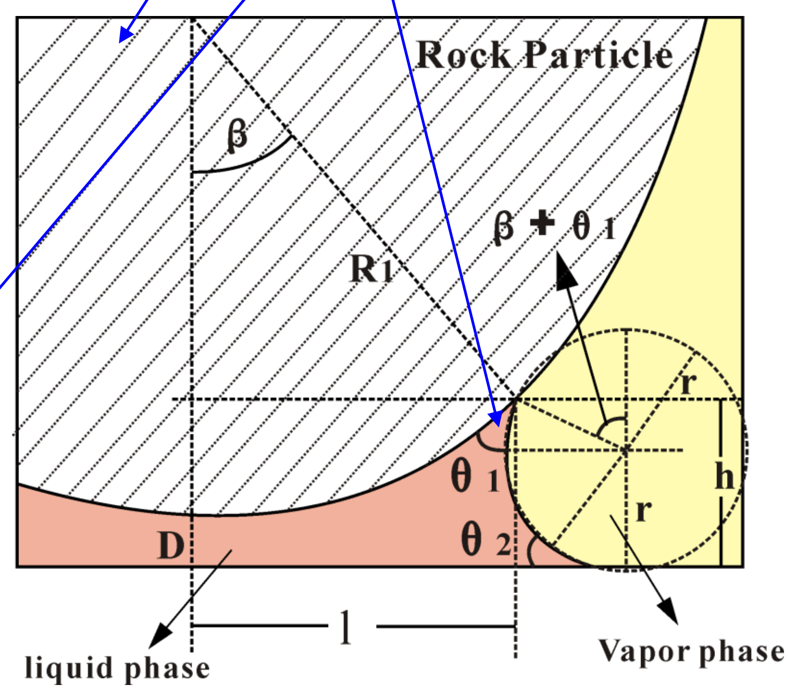
- We proposed a modified total capillary force function to indicate the tight oil mobility in-situ, based on the EOS (Peng-Robinson Equation) and EOS+λ(Van-Laar Equation) methods, composed of the variables of free gas volume ratio in the reservoir, solution gas volume ratio in the liquid phase, and other geological parameters such as the formation pressure, temperature, wettability coefficient, rock particle diameter and pore diameter.
- A relationship between the GOR, the gas & oil state and phase flow state for production was established, based on the modified capillary force function and the production data of Yanchang and North American tight oil fields. Five phase stages are identified according to the gas volume ratio (y_i) in situ: (1) an increasing movability curve with the y_i at the first stage, which indicates a pure liquid phase and a single oil flow for production; (2). an unstable movability curve at the second stage, which indicates the free gas begins to accumulate and flow, i.e., the multiphase transient flow for production; (3) a stable mobility curve at the third stage, which indicates a multiphase stable flow for production; (4) an unstable mobility curve at the fourth stage, which indicates a condensate gas state and a multiphase super-critical flow for production; (5) a decreasing mobility curve at the fifth stage, which indicates a dry gas state, and a single gas flow for production.
- Tight oils are more mobile in three stages according to the capillary function curve in situ: around the critical point of $y_{i\text{-critical}(1)}$, which corresponds to a single oil flow for production and a tight oil sweet spot for the oil zone, such as Yanchang and Bakken tight oils; at the transition zone between oil and wet gas zones before $y_{i\text{-critical}(2)}$, which is in correspondence with a multiphase stable flow state and a sweet spot for the wet gas zone, such as the Eagle Ford tight oil; and between the $y_{i\text{-critical}(2)}$ and $y_{i\text{-critical}(3)}$ in a condensate gas state, which is in correspondence with a multiphase super-critical flow for production and a sweet spot at the transition zone between wet gas and dry gas zones.

◆ The total capillary force (F) indicates the a mesoscopic binding force in an abbreviated equation, relating to the solid interfacial cohesion (‘γ’) in our research, and the capillary pressure difference between gas and oil phase

$$F = 2\pi\gamma R_1 \left(2c \pm \frac{D In(\hat{P} / P^{o})}{\lambda_k}\right)$$

◆ 2 π γR1, indicates a property of the rock particle, where γ indicates the cohesion between solid surface to the oil liquid.

◆ c indicates a property of the property of the liquid phase. It is a geometrical parameter indicating the meniscus once gas accumulate to a certain amount. It is also settled as a constant to depict the nature property of liquid phase.



◆ This is our modified item in equation, indicating the gas-liquid equilibrium state.

◆ In other words, this item is used to indicate the gas-oil interaction when the gas-to-oil ratio is changed.

◆ Also, this is the most important factor when we take GOR into consideration for the tight oil and gas resources exploration.

◆ The disjoining pressure of water-oil-solid pore system in this figure is similar to the total capillary force in our work(proposed by Butt) and is used to indicate a mesoscopic binding force in an abbreviated equation, relating to the solid interfacial cohesion ('γ') in our research, and the capillary pressure difference between water and oil phase

α： oil liquid, γ:water, β: solid surface

Capillary pressure difference between α and γ, where P α and P γ indicate the binding force of the solid surface to the oil and water phase separately.

Equals the solid interfacial cohesion 'γ' in our work

imbibition

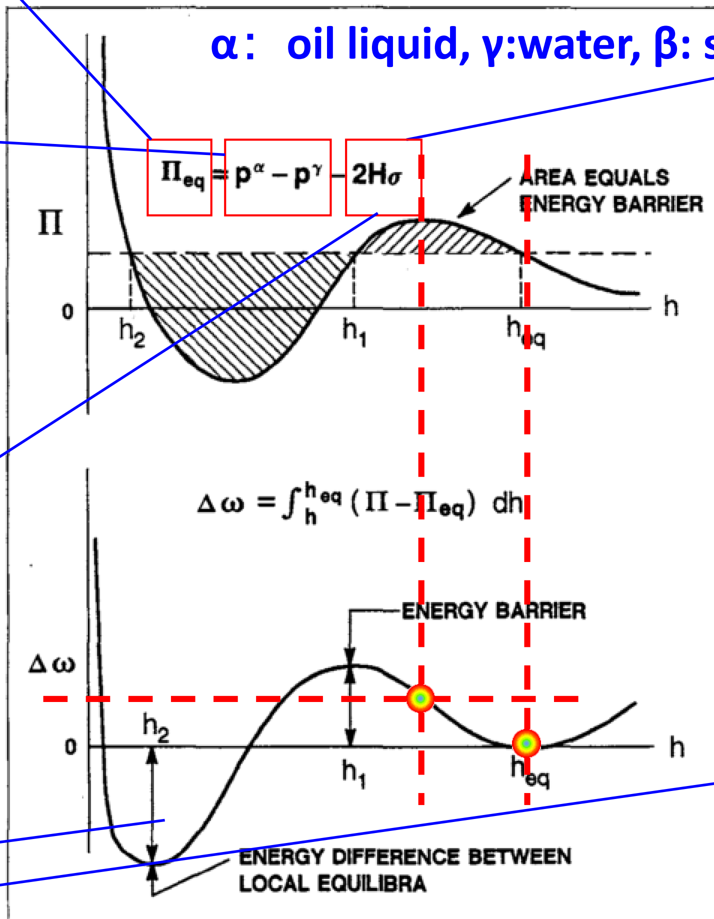


Fig. 2—Isotherms of disjoining pressure and specific interaction potential.

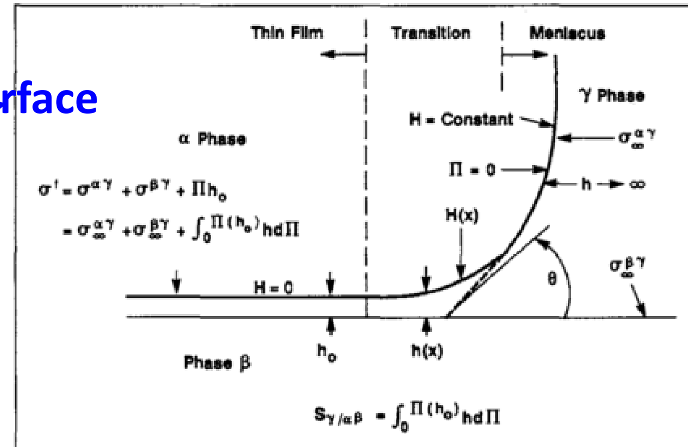


Fig. 1—Contact region between two fluids and a solid. T, μ_c, and Φ_g are constant.

◆Imbibition , i.e., the water imbibition process floods the oil automatically in a water wet reservoir, acts when the specific interaction potential is negative. Basically, it is still determined by the capillary pressure difference between water and oil phase, i.e., the difference of binding force of the solid surface to the water or oil phase.

◆equals to the ‘γ’ in our equation: $F = 2\pi\gamma R_1(2c \pm \frac{DIn(\hat{P}/P^o)}{\lambda_k})$

$$\gamma_{12} = \gamma_1 + \gamma_2 - W_{12} = \frac{1}{12\pi}\left[\frac{A_{11}}{d_{11}^2} + \frac{A_{22}}{d_{22}^2} - \frac{A_{12}}{d_{12}^2}\right]$$

◆ **γ1 indicates the molecular force of phase 1 on the interface where 1 indicates the oil component.**

◆ **γ2 indicates the molecular force of phase 2 on the interface where 2 indicates rock particle component.**

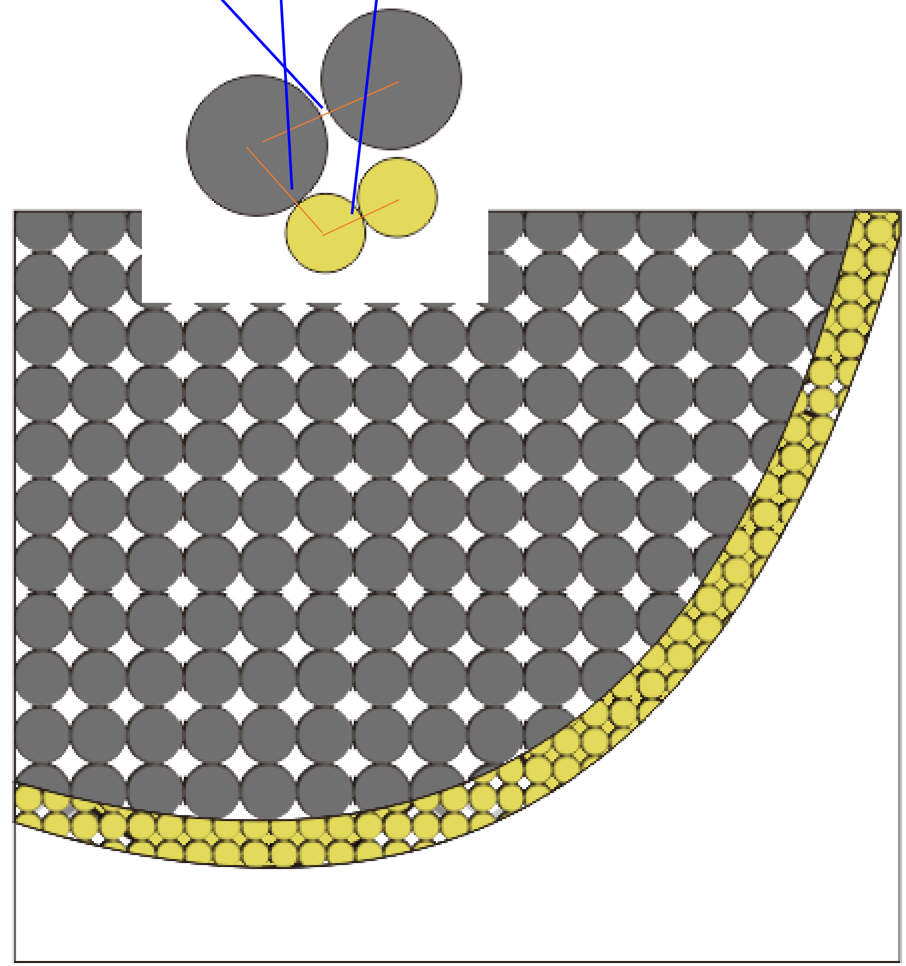
◆ **γ12 indicates the molecular force between phase 1 and 2, equals to the ‘γ’ in our equation.**

◆ **A is the Hamaker constant determined by the material properties.**

◆ **d11 indicates the molecular distance of phase 1;**

◆ **d22 indicates the molecular distance of phase 2;**

◆ **d12 indicates the molecular distance between phase 1 and 2**



◆**Basically, the interface molecular force (γ12) is a dispersion force interacted between the rock grain and the oil phase. It is treated to be a constant parameter representing the material properties of solid and liquid modlecular.**

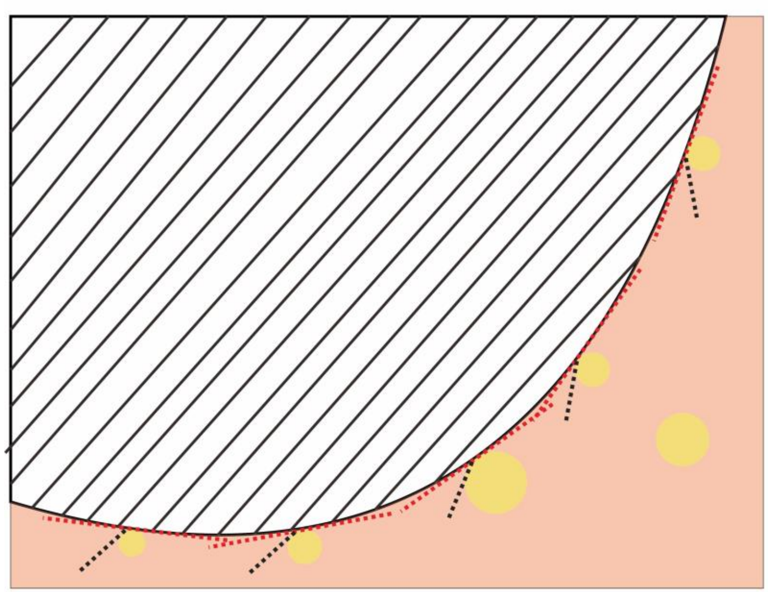
◆No matter the single phase flow or the multiple phase flow, it is all in a vapor-liquid equilibrium system, i.e., a system composed of vapor, solution liquid and solutions, which is depicted using a variable of the molar ratio of oil-gas composite.

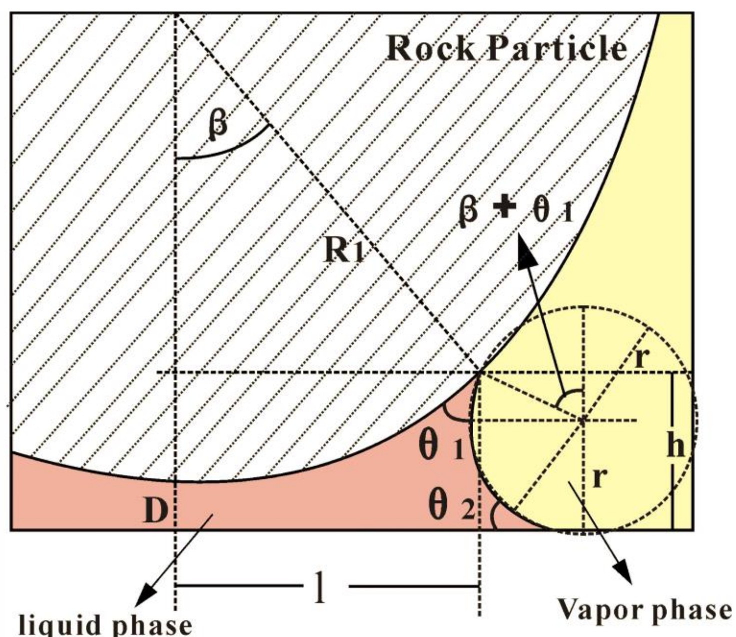
◆Total capillary force always acts as a binding force for the whole tight reservoir pore system, except the two ending points.

◆Solution gas and some free gas exist in the single phase flow stage. However， the small amount free gas will not begin to flow before the a critical point.

◆As long as there is free gas, the total capillary forece in our equation will be rational. In addition that a ‘c’ and ‘γ’ are all settled as constants parameters in our fitting research.

◆A constant value of a ‘c’ and ‘γ’ indicates the dispersion force of the grains and the contact relation between all stayed in the same angle .





The Peng-Robinson Equation

The details of the development of the Pe... tion are given in the original paper (1). Th... summarized here for convenience.

The equation has the form:

$$P = \frac{RT}{v - b} - \frac{a(T)}{v(v + b) + b(v - b)}$$

In this equation:

$$b = 0.07780 \frac{RT_c}{P_c}$$

$$a(T) = a(T_c) \cdot \alpha(T_R, \omega)$$

$$a(T_c) = 0.45724 \frac{R^2 T_c^2}{P_c}$$

$$Z_c = 0.307$$

$$\alpha^{1/2}(T_R, \omega) = 1 + \kappa(1 - T_R^{1/2})$$

$$\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2$$

$$\ln \hat{\varphi}_i = \frac{1}{RT}\int_0^p \left(\bar{V}_i - \frac{RT}{p}\right) dp$$

$$\ln \hat{\varphi}_i = \frac{1}{RT}\int^{V_t} \left[\frac{RT}{V_t} - \left(\frac{\partial p}{\partial n_i}\right)_{T,V_t,\{n\}_{\neq i}}\right] dV_t - \ln Z$$

◆This is not a modified P-R EOS equation, but a fugacity coefficient formula based on the P-R EOS. In other words, it is just the P-R EOS method to calculate Φ, but not a modified one.

$$\ln \hat{\varphi}_i = \frac{b_i}{b}(Z-1) - \ln\frac{p(V-b)}{RT} + \frac{a}{bRT}\left(\frac{b_i}{b} - \frac{2}{a}\sum_{j=1}^{N} y_j a_{ij}\right)\ln\left(1 + \frac{b}{V}\right)$$

$$\ln \hat{\varphi}_i = \frac{b_i}{b}(Z-1) - \ln\frac{p(V-b)}{RT} + \frac{a}{2\sqrt{2}bRT}\left(\frac{b_i}{b} - \frac{2}{a}\sum_{j=1}^{N} y_j a_{ij}\right) \times \ln\left(\frac{V + (\sqrt{2}+1)b}{V - (\sqrt{2}-1)b}\right)$$

◆ This is derived combined with the above euqations

$$\ln \hat{\varphi}_i = \frac{pb_i}{RT} - \ln\frac{p(V-b)}{RT} + \frac{1}{RT}\sum^{5} \frac{E_k(T)_i}{(V-b)^{k-1}}$$

◆ Assumption: the tight reservoir is semi-closed system for mixed phases.

其中，$E_2(T)_i = 2\sum_{j=1}^{N} y_j F_2(T)_{ij}$ 和 $E_k(T)_i = \frac{kF_k(T)}{k-1}\left(\frac{F_k(T)_i}{F_k(T)}\right)^{1/k}$

$(k = 3,4,5)$

$$f_i = P\hat{y}_{i-solution}\hat{\phi}_i$$

◆ Assumption: the gas-liquid equilibrium is a homogeneous mixed phase system., i.e., the system pressure is divided by the component content.

◆ We use this to modify the total capillary force

$$= P\tau y_{i-solution}\left[e^{\frac{b_i}{b}(Z-1)} - In^{\frac{P(\hat{V}^l - b)}{RT}} + \frac{a}{2\sqrt{2}bRT}\cdot\left(\frac{b_i}{b} - \frac{2}{a}\sum_i^N y_{i-solution}a_{ij}\right)\cdot In\left(\frac{\hat{V}^l + (\sqrt{2}+1)b}{\hat{V}^l + (\sqrt{2}+1)b}\right)\right]$$

Binary components system

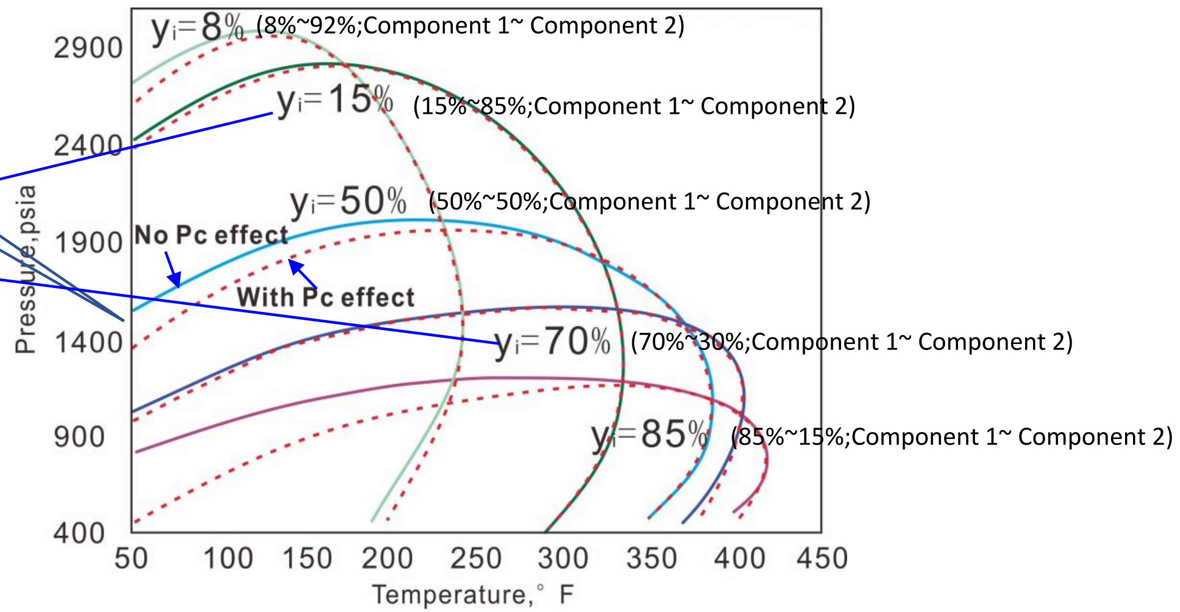
Light hydrocarbon component

Heavy hydrocarbon component

Component	Mole fraction	Critical pressure (MPa)	Critical temperature (K)	Critical volume $(m^3/gmol) \times 10^3$	Molecular weight (g/gmol)	Acentric factor	Parachor coefficient
Component	0.2063	4.4903	412.46	0.2039	44.79	0.1481	150.47
Component 2	940	1.9907	673.76	0.7648	220.34	0.5671	570.11

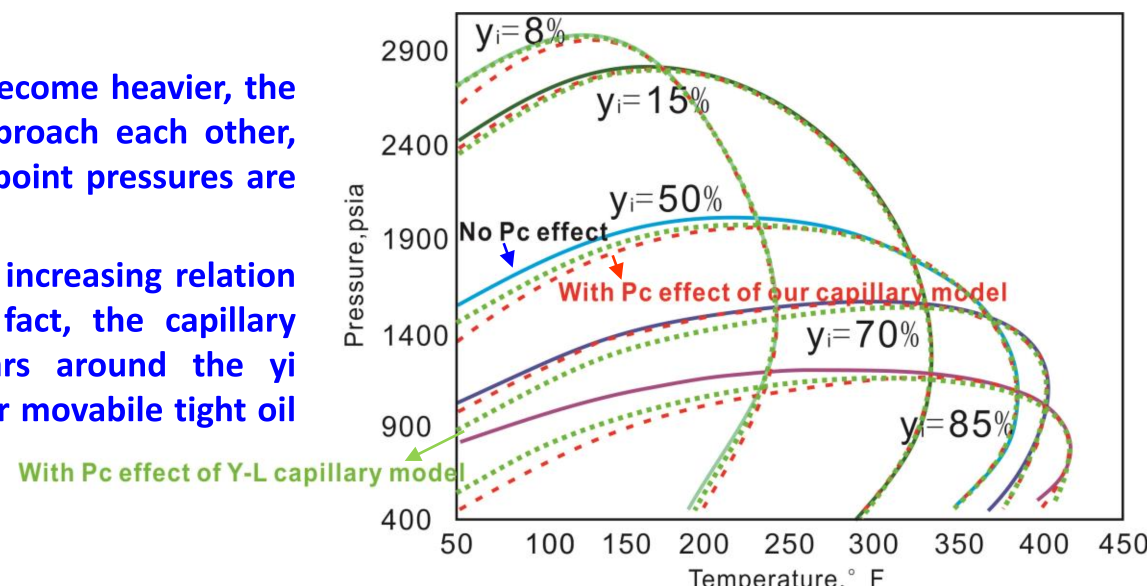
capillary Condensation (Pc effect)

Critical Points

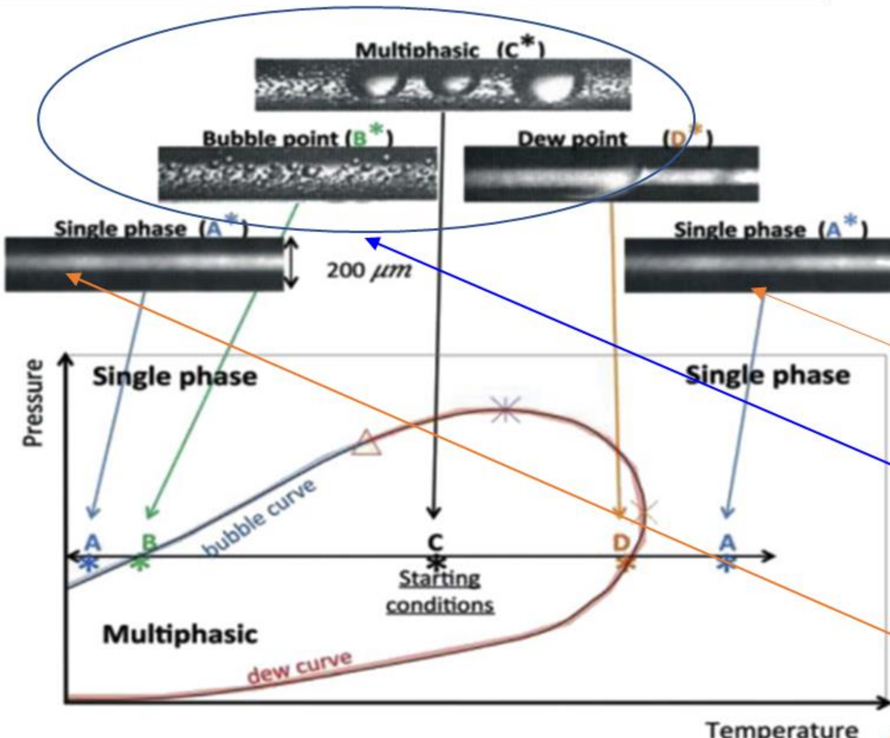


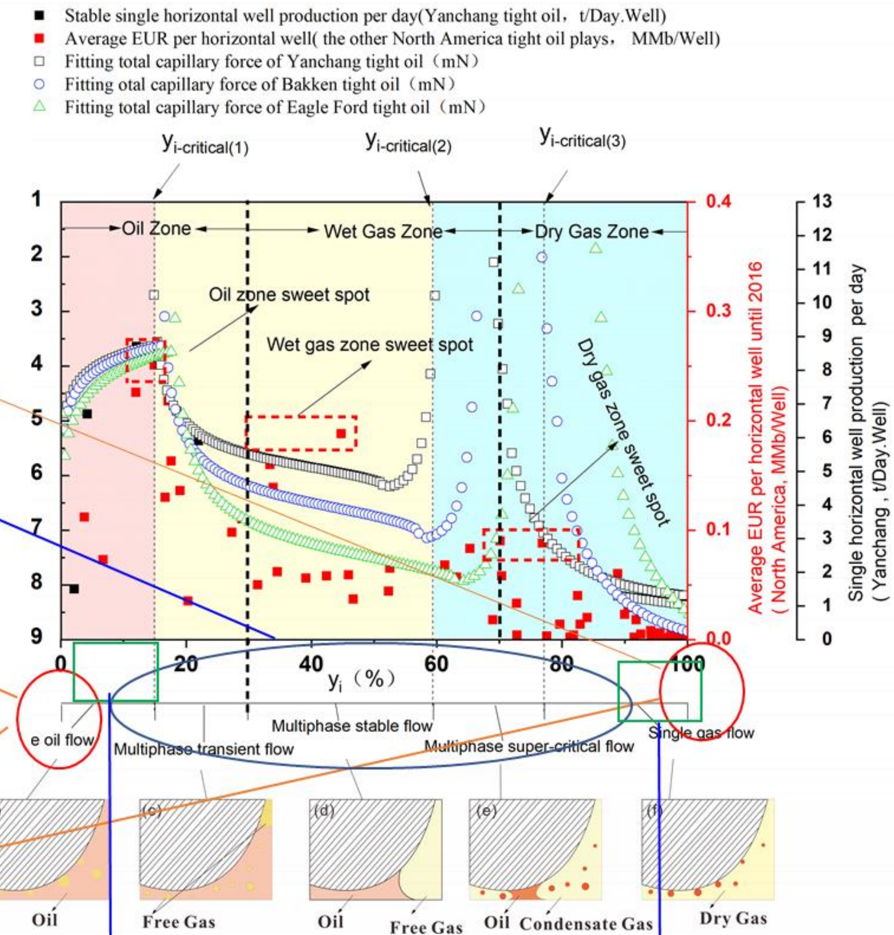
◆**For the Y-L capillary model, as the fluids become heavier, the critical temperature and criconden-therm approach each other, decreasing the size of the region where dew-point pressures are increased by capillary pressure.**

◆**For our capillary model, it is not an simple increasing relation between the P-V-T and gas-to-oil ratio. In fact, the capillary condensation phenomenon nearly disappears around the yi values of 15% and 70%, responding to a higher movabile tight oil resources in situ.**



◆Except the two endpoints in red circles, all the flow state are in a gas-oil(vapor, liquid, solution gas） equilibrium





◆ The single flow (oil/gas) dose not mean the pure phase, except the two endpoints in red circles. Basically, when the vapor or liquid phased is determined by the P-T conditions in-situ, based on a given the component (i.e, the gas to oil ratio) . From the perspective of thermodynamic system in tight reservoir, it is very hard to reach the pure phase as the endpoints in our fitting result. In addition, the total capillary force in these two endpoints decrease rapidly, indicating a reducing binding effect for the tight oil movability in-situ.

◆ The total capillary force of the single flows (i.e., single oil and gas flows) is calculated on the Van-Laar solution equation, which is rational for a single flow state solution system, considering the vapor-liquid equilibrium in a undersaturation or a supersaturation states