

Thin Films, Oil Layers, and Three-Phase Flow in Porous Media¹

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ABSTRACT

This paper is concerned with two transport mechanisms governing three-phase displacement in porous networks. The first mechanism appears in three-phase mixtures near a tricritical point. In this case the system is in the complete wetting regime. The oil phase creates *thin* films situated between aqueous and gas phases through which it can be drained. The thermodynamical model involved in planning of oil recovery processes near a tricritical point is described. It consists of the model of van der Waals of a diffuse interface and that of Griffiths' of near-tricritical mixtures. The second transport mechanism involves *thick* oil layers sandwiched between water and gas in wedges of angular capillaries. Calculations using an idealized model of a capillary tubing with angular cross section show that for adequate combinations of pore geometry and fluid properties such layers are thermodynamically favorable even for three-phase systems in the partial wetting regime.

KEY WORDS: complete wetting; oil film; oil layer; oil reservoir; partial wetting; pore network; spreading coefficient.

1. INTRODUCTION

The oil phase in hydrocarbon reservoirs appears in two different connectivity regimes:

- the continuous regime in which oil spans large portions of the porous network extending over many pore diameters.
- the "blob regime" in which oil mainly exists as disconnected ganglia.

The continuous regime can be found in virgin reservoirs, i.e. before the start of oil production. On the other hand, as more and more of oil is produced and the reservoir pressure gradually decreases, the continuity of the oil phase breaks down.

The transition between the two regimes takes place after some amount of oil has been produced. Thus, the oil phase remaining in the reservoir consists of myriads of disconnected ganglia.

Consider now an isolated oil ganglion blocking a capillary of a nonuniform cross-section.

The ganglion is assumed to be under the influence of an external pressure gradient and the opposing force due to the capillary pressure. The balance of forces acting on the ganglion can be stated as follows:

$$P_2 = P_1 + \frac{2\sigma_{ow}}{R_2}, \quad (1)$$

$$P_3 = P_4 + \frac{2\sigma_{ow}}{R_1}, \quad (2)$$

where σ_{ow} is the oil-water interfacial tension. R_1 and R_2 are the downstream and upstream mean radii of curvature, respectively. P_1, P_2, P_3 , and P_4 are the pressures associated with the ganglion's rear and front oil-water interfaces (see Figure 1).

Combining eq.(1) and eq. (2) gives,

$$P_4 - P_1 = 2\sigma_{ow}\left(\frac{1}{R_2} - \frac{1}{R_1}\right). \quad (3)$$

The pressure drop in the aqueous phase is given by

$$P_1 - P_4 = \Delta\Psi_w \quad (4)$$

where $\Delta\Psi_w$ is the drop of pressure potential. Substituting for $P_1 - P_4$ in eq.(3) gives,

$$2\sigma_{ow}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \Delta\Psi_w. \quad (5)$$

The transport velocity of the aqueous phase can be estimated from the Hagen-Poiseuille equation:

$$v_w = -\frac{a^2}{8\mu}\left(\frac{\Delta\Psi_w}{l}\right) \quad (6)$$

where l is the approximate length of the pathway, a is its average radius, and μ is the viscosity of the aqueous phase.

Combining eqs. (4) and (6) gives the following expression:

$$2\sigma_{ow}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{8\mu_w v_w l}{a^2}. \quad (7)$$

Thus the length, l , of the ganglion is given by the following expression,

$$l = 2\sigma_{ow}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) / \left(\frac{8\mu_w v_w}{a^2}\right). \quad (8)$$

The approximate volume of the ganglion (neglecting its extreme ends) is as follows:

$$\Xi = \pi R_{av}^2 l = (0.25\pi R_2^2 a^2 \left(\frac{1}{R_1} - \frac{1}{R_2}\right)) / \left(\frac{\mu_w v_w}{\sigma_{ow}}\right). \quad (9)$$

The above expression can be stated in a more compact way by introducing a dimensionless group of parameters, N_c , defined as follows,

$$N_c = \frac{\mu v_w}{\sigma_{ow}}. \quad (10)$$

N_c is often referred to as the capillary number.

Equation (9) can be reformulated as follows.

$$\Xi = \frac{0.25R_{av}^2 a^2}{N_c} \left(\frac{1}{R_1} - \frac{1}{R_2}\right). \quad (11)$$

The total amount of oil left in the interconnected network of capillaries can be obtained by replacing the quantities appearing in eq.(11) by their statistical averages. Consequently, eq.(11) can be rewritten as follows,

$$S_{or} = \frac{const.}{N_c}, \quad (12)$$

where S_{or} is the residual oil saturation representing the total volume of the oil phase left in the network after the loss of continuity.

Typical values of N_c at the end of a water injection are approximately $10^{-7} - 10^{-6}$. It is usually assumed that N_c must be increased to $10^{-4} - 10^{-2}$ in order to mobilize a significant amount of the residual oil. Such an increase of the capillary number can be achieved, for example, by injecting water into the formation. However, a significant increase of water velocity, v_w , is only possible to the extent one can increase the pressure gradient created by the injection pumps by the same order of magnitude. Similarly, one can increase the viscosity of water by injecting water-soluble polymers. However, such action will be hampered by its limited effect on the oil flow rate. This is the reason why the only way to achieve a significant increase in capillary number, N_c , in eq.(12) is to decrease the interfacial tension σ (cf. eq.(10)). The oil-water interfacial tension can be reduced, for example, by injecting a surfactant into the formation. This leads to creation of a three-phase fluid mixture in the subsurface characterized by the ultralow oil-water interfacial tension and modified wetting properties. Wetting properties of near-critical three-phase fluid mixtures relevant to enhanced oil recovery processes are described in the next section.

2. WETTING REGIMES IN OIL RESERVOIRS

Hydrocarbon reservoirs contain three coexisting phases: water, oil, and gas. Depending on the value of the initial spreading coefficient, S^i , oil can either spread as a thin wetting film or create a lense situated between the water and gas phases. The initial spreading coefficient S^i is defined by the following expression,

$$S^i = \sigma_{gw} - (\sigma_{ow} + \sigma_{go}), \quad (13)$$

where σ stands for the interfacial tension, the subscript g stands for gas, w represents water, and o indicates oil.

Figure 2 shows the forces acting at the three-phase contact line along which water, oil, and gas phases meet. The oil phase at the gas-water interface originates either from adsorption from the vapor phase or can be attributed to spreading. The

equilibration of the three coexisting phases leads to a notion of the equilibrium spreading coefficient,

$$S^{eq} = \sigma_{gw}^e - (\sigma_{ow}^e + \sigma_{go}^e), \quad (14)$$

The equilibrium spreading coefficient, S^{eq} , is either negative or equal to zero. More specifically, when $S^{eq} = 0$, the oil phase completely wets the gas-water interface. On the other hand, for $S^{eq} < 0$, it only partially wets the gas-water interface. It should be noted that the equilibrium spreading coefficient S^{eq} can never be positive. If, momentarily, the gas-water interface would immediately coat itself with a layer of the aqueous phase, replacing the supposedly higher free energy per unit area of the direct gas-water contact, σ_{gw} , by the supposedly lower sum of the free energies per unit area of gas-oil and oil-water contacts, $\sigma_{go} + \sigma_{ow}$, thereby lowering the free energy of the system [1].

The message contained in the above statement is that the spreading coefficient may change as the thermodynamic state of the system varies. Over a certain range of a chemical potential (or another thermodynamical field) the spreading coefficient may be negative. Otherwise, it is equal to zero (see Figure 3a). The transition between the two regimes occurring at $\mu = \mu^*$ is the wetting transition predicted theoretically by Cahn [1]. In particular, presence of a wetting transition can be deduced theoretically in three-phase mixtures close to a tricritical point. The deduction procedure is based on van der Waals-Cahn-Hilliard theory of near-critical interfaces briefly described in the next section.

3. VAN DER WAALS THEORY OF INTERFACES

This section describes van der Waals theory of an interface separating two coexisting phases in its modern version applicable to a large family of multicomponent systems whose behavior can be described in terms of a suitable order parameter. Before we state a formal definition of the order parameter, we make a distinction between two types of intensive thermodynamic variables: fields and densities [2]. By fields we understand those variables, that have the same values in the coexisting phases (e.g., pressure, temperature, chemical potential, etc.). On the other hand, the variables which have different values in each coexisting phase (e.g., mole fraction, composition, etc.) are referred to as densities.

The order parameter can be thought of as some linear combination of density variables characterizing the system under consideration. It is usually interpreted as a numerical measure of the "amount of order" that exists in the neighborhood of the thermodynamical state characterizing the system under consideration.

Consider first a multicomponent mixture consisting of two coexisting phases (e.g., two liquid phases or a liquid phase in equilibrium with its vapor). The order parameter is denoted by X . X_α and X_β stand for the values of X in the bulk α and β phases, respectively. When the coexisting α and β phases correspond to a one-component liquid and its vapor, X can be interpreted as equal to $\rho - \rho_c$ where ρ is the specific density of the liquid and ρ_c is its value at the critical point. In the region of two-phase coexistence, the order parameter takes the value X_α in the α phase and X_β in the β phase.

Let's denote the interfacial free energy density of a two-phase system by $f(X)$. It is well known that $f(X)$ is a continuous function in X with a characteristic "hump" corresponding to the two-phase region $\rho_\alpha - \rho_c = X_\alpha \prec X_\beta = \rho_\beta - \rho_c$ [3]. The fundamental assumption of van der Waals theory is that the interfacial free energy is a sum of two components. The first component is the function $-V(X)$ defined as the difference between $f(X)$ and the straight line. The second component is an expression proportional to the square of the composition gradient i.e.,

$$\Psi(z) = -V(X(z)) + \frac{1}{2}m\left(\frac{dX}{dz}\right)^2, \quad (15)$$

where z is a distance in a direction perpendicular to the plane of the interface and m is a positive constant.

The total free interfacial energy per unit area is defined as follows.

$$\sigma = \int_{-\infty}^{\infty} \left\{ -V(X(z)) + \frac{1}{2}m\left(\frac{dX}{dz}\right)^2 \right\}. \quad (16)$$

It should be noted that

$$\lim_{z \rightarrow -\infty} X = X_\alpha \quad (17)$$

and

$$\lim_{z \rightarrow \infty} X = X_\beta. \quad (18)$$

The equilibrium density profile is the function $X(z)$ that minimizes σ in eq.(16).

The equilibrium density profile can also be obtained in a different way utilizing an analogy between the above mentioned minimization problem and the particle moving in a one-dimensional space subject to potential $V(X)$ [1]. In the particle analogy, the $X(z)$ that minimizes σ is the position coordinate of the particle

moving between X_α and X_β (Hamilton's principle). Thus the equilibrium density profile can be obtained from the Euler-Lagrange equation (L is the Lagrangian of the system).

$$\frac{\partial L}{\partial X} = \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{X}} \right), \quad (19)$$

or, equivalently

$$m \left(\frac{d^2 X}{dz^2} \right) = - \frac{\partial V}{\partial X}. \quad (20)$$

Thus eq.(16) can be restated as follows,

$$\sigma = \int_{-\infty}^{\infty} (-V + K) dz = \int_{X_\alpha}^{X_\beta} \sqrt{-2mV(X)} dX \quad (21)$$

where $K = \frac{1}{2}m \left(\frac{dX}{dz} \right)^2$ is the kinetic energy of the particle and σ corresponds to the action defined as the integral of momentum over coordinate.

The above equation will be used in the calculations of the equilibrium spreading coefficient in a multicomponent mixture exhibiting tricritical behavior. The necessary framework for such calculations is the Van der Waals-Landau-Griffiths model of three-phase equilibria near a tricritical point. This model is briefly described in the next section.

4. GRIFFITHS MODEL

The main assumptions of the Griffiths model of a tricritical behavior are as follows [2]:

1. The free energy density is an analytic function of the fields and densities.
2. In a sufficiently small neighborhood of a tricritical point, the free energy density can be expanded in a power series of the one-dimensional order parameter Ψ ,

$$F(\Psi) = a_1 \Psi + a_2 \Psi^2 + a_3 \Psi^3 + a_4 \Psi^4 + \Psi^6. \quad (22)$$

The a_i are model fields that are related to the physical fields f_k (such as e.g., temperature and pressure) by the linear relations,

$$a_i = \sum_{k=1}^4 \alpha_{ik} (f_k - f_{kt}). \quad (23)$$

The coefficients α_{ik} are initially unknown and appear as a matrix of constant coefficients. f_{kt} are the values of f_k at the tricritical point.

The absence of the term a_5 is due to the fact that it can always be eliminated by replacing Ψ by $\Psi + \Psi_0$ in choosing Ψ_0 appropriately. Furthermore, the coefficient a_6 must be positive (for thermodynamic stability) and can be set equal to unity.

In his model Griffiths uses a free energy defined by the following relation

$$\Omega = \Omega_r + \Omega_s, \quad (24)$$

where the regular part, Ω_r , is an analytic function of the fields and the singular part, Ω_s , is given by the following equation,

$$\Omega_s = \min_{\Psi} F(a_1, a_2, a_3, a_4; \Psi). \quad (25)$$

The order parameter Ψ takes different values in the coexisting phases. More precisely, these values appear at the absolute minima (with respect to Ψ) of F (cf. eq.(22)) for a fixed value of $a = (a_1^*, a_2^*, a_3^*, a_4^*, \Psi)$. If these minima occur for several values of Ψ then each of these values can be ascribed to a distinct phase and $\{a_j^*\}$ belong to an appropriate coexistence manifold in the field space diagram.

Griffiths [2] has shown that for the class of mixtures exhibiting tricritical behavior one can associate the temperature with the field a_4 , i.e. $a_4 \sim (T - T_t)/T_t$ where T_t is temperature corresponding to the tricritical point. Consequently, by keeping a_4 fixed one obtains an isothermal section of the phase diagram. An example of such a section is shown in Figure 4. Three-phase region is spanned by an infinite series of triangles. The points in the interior of each triangle represent the overall compositions of the three-phase mixtures. The compositions of the three phases lie at the triangles' vertices. As the tricritical point is approached, a_4 traverses a range of negative values toward $a_4 = 0$. This approach is not arbitrary: it is controlled by three different exponents describing the geometry of the three-phase region near the tricritical point. More specifically, thickness of the stack of triangles shrinks as $|a_4|^{3/2}$; the altitude of each triangle vanishes as $|a_4|$; and the length of the three-phase region (measured as the length of the longest side of the triangle) varies as $|a_4|^{1/2}$. As shown in Figure 5, near the tricritical point the three points representing the coexisting phases become asymptotically collinear. Consequently, there is always a phase, which in all its properties, is intermediate between the two other phases.

Prediction of multiphase behavior of a concrete mixture requires knowledge of the relation between the model variables and their experimental counterparts [4]. However such knowledge is not necessary if one is only interested in qualitative

properties of the phase behavior. In this case one can disregard the regular part of the free energy, Ω_r , because it does not affect the nature of the phase diagram. By a "phase diagram" we mean here the set of points at which two, or more phases, coexist. Thus a phase diagram is essentially a "map" of the singular part of the free energy, Ω_s

The minimization of the total thermodynamical potential, Ω , with respect to Ψ results in a cubic equation [1,2],

$$\Psi^3 + \frac{1}{2}a_4\Psi + \frac{1}{2}a_3 = 0, \quad (26)$$

with three real roots Ψ_α , Ψ_β , and Ψ_γ provided that $a_4 < 0$ and $|a_3| \leq 4(-a_4/6)^{3/2}$.

The solution of eq.(26) can be written in a unified way as follows,

$$\Psi_\delta = A \cos \varphi_\delta, \quad (27)$$

where

$$\varphi_\delta = \begin{cases} 120 + \theta & \text{if } \delta = \alpha \\ 120 - \theta & \text{if } \delta = \beta \\ \theta & \text{if } \delta = \gamma \end{cases} \quad (28)$$

It should be noted that θ lies in the interval $0 < \theta < 60^\circ$, $A = (-\frac{2a_4}{a_3})^{1/2}$, and $a_4 < 0$.

The fields a_i can reformulated as follows [4],

$$a_1 = \frac{3}{8}A^5 \cos \theta, \quad (29)$$

$$a_2 = \frac{9}{16}A^4, \quad (30)$$

$$a_3 = -\frac{1}{2}A^3 \cos 3\theta. \quad (31)$$

According to the van der Waals theory of interfaces, the interfacial tension between phases α and β is given by the expression,

$$\sigma = m_1 \int_{\psi_\alpha}^{\psi_\beta} \sqrt{-V(\Psi)} d\Psi, \quad (32)$$

where m_1 is a smoothly varying function of fields.

Following Griffiths [2,5,6] the excess free energy density is given by,

$$\sigma_{\alpha\beta} = \sigma_0(\Psi_\beta - \Psi_\alpha)^3(3\Psi_\gamma) \quad (\sigma_0 = \text{const.}), \quad (33)$$

$$\sigma_{\beta\gamma} = \sigma_0(\Psi_\gamma - \Psi_\beta)^3(3\Psi_\alpha). \quad (34)$$

Summarizing, the calculation of interfacial tensions in the three-phase region are performed according to the following algorithm:

1. Specify the overall composition $\rho = (\rho_\alpha, \rho_\beta, \rho_\gamma)$ and fix $a_4 < 0$.
2. Select $a_3(\rho)$ such that $|a_3| \leq 4(-\frac{a_4}{6})^{\frac{3}{2}}$ and find θ (cf. eq. (31)).
3. Calculate $\Psi_\alpha, \Psi_\beta,$ and Ψ_γ from eq. (27).
4. Find $\sigma_{\alpha\beta}, \sigma_{\beta\gamma}$ from eq. (33) and eq. (34).

The equilibrium spreading coefficient S^{eq} (cf. eq.(14) and, consequently, the type of wetting regime, can be now readily determined. The interfacial tension plots corresponding to the path 2 in the composition space which enters the three-phase region through a tieline where two phases are in equilibrium (cf. Figure 4) and leaves it through a similar tieline is shown in Figure 6.

5. OIL LAYERS IN THE PORE SPACE

This section is concerned with a simple model describing behavior of three phases in a wedge appearing in pore space [7,8]. The oil-water contact angle is assumed to be smaller than the gas-oil contact angle i.e, $\theta_{ow} < \theta_{go}$ (see Figure 7a). In addition, only the radii of the curvature, r_{ow} and r_{go} , of the oil-water, and gas-oil interfaces in the plane of the edge are assumed to be finite. Consequently, the oil-water- and gas-oil capillary pressures are given by $P_{cow} = \sigma_{ow}/r_{ow}$ and $P_{cgo} = \sigma_{go}/r_{go}$, respectively. The oil layer ceases to be stable as soon as the oil-water-solid contact line coincides with the gas-oil-solid contact line (see Figure 7b). In this case, the distance AB shown in Figure 7b for an interface of radius r and contact angle θ is given by the following expression,

$$AB = r \frac{\cos(\theta + \beta)}{\sin \beta}, \quad (35)$$

where β is half angle of the wedge and $\theta + \beta < \pi/2$.

A ratio of interfacial curvatures associated with oil-water and gas-oil interfaces is defined as follows,

$$R = \frac{r_{ow}}{r_{go}} = \frac{P_{cgo} \sigma_{ow}}{P_{cow} \sigma_{go}}. \quad (36)$$

If $r_{go} \gg r_{ow}$, then the oil layer becomes very thick. As $R \rightarrow 0$, only oil remains in the wedge. The coincidence of the oil-water-solid and gas-oil-solid contact lines occurs at the critical ratio R_c of interfacial curvatures R_c ,

$$R_c = \frac{\cos(\theta_{go} + \beta)}{\cos(\theta_{ow} + \beta)}. \quad (37)$$

Thus, a stable oil layer separating gas and water is possible only when $R < R_c$. For $R > R_c$, the oil layer is absent and there is a gas-water interface in the wedge.

Assuming that a molecular film of water covers the porewalls and that the system is water-wet (i.e., $\theta_{ow} = \theta_{gw} = 0$), the balance of forces at the gas-oil-solid contact line gives the following relationship,

$$\sigma_{gw} = \sigma_{go} \cos \theta_{go} + \sigma_{ow}. \quad (38)$$

Eq.(38) can be restated as follows,

$$\cos \theta_{go} = 1 + \frac{S^{eq}}{\sigma_{go}}. \quad (39)$$

Using the above relationship, the critical ratio R_c defined by eq.(37) is given by the following expression,

$$R_c = 1 + \frac{S^{eq}}{\sigma_{go}} - \left(-\frac{S^{eq}}{\sigma_{go}}\right)^{\frac{1}{2}} \left(2 + \frac{S^{eq}}{\sigma_{go}}\right)^{\frac{1}{2}} \tan \beta. \quad (40)$$

Figure 3b explains behavior of oil layers present in a wedge as the spreading coefficient decreases from zero to a negative value. It turns out that the critical ratio R_c decreases as the spreading coefficient S^{eq} decreases. This explains why in strongly water-wet systems oil layers may be present for $S^{eq} < 0$, and absent for $S^{eq} = 0$.

6. FINAL REMARKS

The simultaneous equilibrium of three phases has been described in two cases: (a) the complete wetting regime near a tricritical point and (b) in a capillary tubing of polygonal cross-section. In the former case the macroscopic condition that must be imposed on the three coexisting phases is absence of a line of three-phase contact or, equivalently, that the equilibrium spreading coefficient $S^{eq} = 0$. In the case where three-phases are situated in the edge of a polygonal tubing, it is possible to link the capillary pressures associated with the water-gas, oil-gas, and oil-water interfaces with their interfacial curvatures using Laplace equation of capillarity. Consequently, unlike the former case, the oil layers in wedges of capillary tubings can be found even when $S^{eq} < 0$. However, as the spreading coefficient decreases, the the critical ratio R^c also decreases and oil layers become less likely to exist.

REFERENCES

1. J.S. Rowlinson and B. Widom, *Molecular Theory of Capillarity* (Oxford University Press, 1982).
2. Griffiths R.B., Thermodynamical model for ternary and quaternary fluid mixtures. *J. Chem. Phys.* **60**:195 (1974).
3. Tisza L., *Generalized Thermodynamics* (The MIT Press, 1966).
4. M. Kaufman and R.B. Griffiths, Thermodynamic model for tricritical mixtures with application to ammonium sulfate + ethanol + benzene. *J. Chem. Phys.* **76**:1508 (1982).
5. B.Widom , Noncritical interface near a critical endpoint, *J. Chem. Physics*, **67**:872 (1977).
6. D.J. Klinger, M.J. Fisher, and B. Widom, Surface tension variation in multiphase fluid systems, *J. Phys. Chem.*, **87**:2841 (1983).
7. D.H. Fenwick and M. Blunt, Three-dimensional modeling of three phase imbibition and drainage, *Advances in Water Resources*, **21**:121 (1998).
8. M. Dong, F.L. Dullien, and I. Chatzis, Imbibition of oil in film form over water present in edges of capillaries with an angular cross section, *J. Colloid and Interface Science*, **172**:21 (1995).

CAPTIONS

Figure 1: Entrapped oil ganglion blocking a capillary.

Figure 2: (a) Oil phase spread on water in the presence of their common vapor prior to equilibration. The initial spreading coefficient $S^i < 0$. (b) The configuration of three equilibrated phases in the complete wetting regime ($S^{eq} = 0$). (c) The configuration of three equilibrated phases when $S^{eq} < 0$.

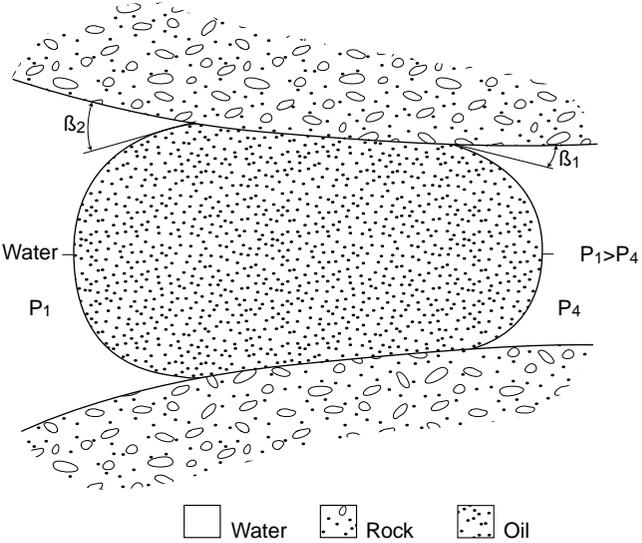
Figure 3: (a) Variation of the equilibrium spreading coefficient S^{eq} as a thermodynamic field μ changes. At $\mu = \mu^*$ there is a transition between the complete and partial wetting regimes [1]. (b) Variation of the equilibrium spreading coefficient S^{eq} in a square-sectional tubing as the critical ratio of capillary pressures R_c decreases.

Figure 4: Three-phase region in an isothermal composition space. It is a three-dimensional volume spanned by an infinite series of triangles (three of which are shown in the Figure). The points in the interior of each triangle represent the overall compositions of mixtures whose phase compositions lie at the triangles' vertices. The lines $K_{1,2}$ and $K_{2,3}$ are critical phases in equilibrium with a noncritical phase (C and A). Also shown are paths 1 and 2 along which the interfacial tension is often experimentally investigated.

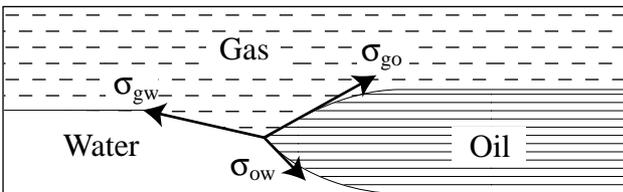
Figure 5: Schematical representation of the three-phase region as a tricritical point is approached (after [1]).

Figure 6: Interfacial tension determined using the Landau-Griffiths model. vs. distance in the isothermal density space corresponding to path 2 shown in Figure 4.

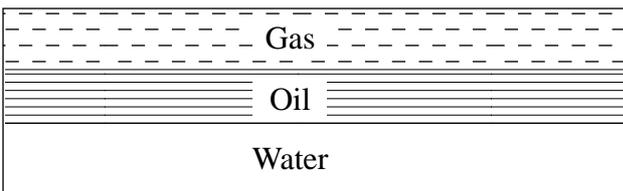
Figure 7: (a) Configuration of oil, water, and gas in an angular corner with half angle β : the oil layer is stable (b) Configuration of the three-phases where the gas-oil and oil-water interfaces touch at point B : the oil layer is unstable (modified after [7]).



(a)



(b)



(c)

