

# Effect of Capillary, Viscous and Gravity Forces on Gas-Condensate Mobility

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## ABSTRACT

The dependence of gas and condensate relative permeabilities and of critical condensate saturation on the fluid properties (interfacial tensions, densities and wetting characteristics), on rock structure and operational parameters (velocity) is still poorly captured by the reservoir simulators. This paper proposes a model based on the dependence of relative permeability,  $K_r$ , and condensate mobility on two dimensionless numbers: the capillary

number (ratio of viscous to capillary forces) and the Bond number (ratio of gravity to capillary forces). The spreading characteristics of the condensate on the substrate (solid surface or water film) are also taken into account. The model is tested against experimental results reported in the literature. Good agreement is obtained, indicating that the model correctly captures most of the controlling parameters.

## INTRODUCTION

Describing flow processes that occur both far from and close to the wellbore region is a major issue in accurately predicting gas-condensate reservoir performance. When a gas-condensate reservoir is produced, the pressure drawdown leads to the buildup of a liquid bank that becomes progressively mobile. Once mobile, this oil bank flows towards the producing wells potentially causing impairment. The liquid accumulation that occurs in the vicinity of the production wells tends to lower the deliverability of the gas due to multiphase flow effects. In addition, the gas that is to be produced tends to become lighter due to condensation and therefore is less marketable.

Predicting gas-condensate reservoir performance requires an accurate modeling of the flow behavior coupled with a correct thermodynamic modeling of the various processes involved. Once the liquid segregates, the way in which the densities of the two phases start diverging and the gas/liquid interfacial tension builds up depends on the thermodynamic properties of the gas-condensate system. Hence, depending on how close to the critical point the sys-

tem will get when the pressure decreases and the phase envelope is reached, the liquid accumulation and production are ruled by the balance between three main mechanisms: gravity segregation, capillary holdup and viscous drag. In order to predict gas deliverability, two major features have to be studied: the dependence of  $K_r$  on the gas-condensate interfacial tension and on the flow conditions.

For a long time only the effect of interfacial tension on  $K_r$  has been studied, and  $K_r$  changes have been attributed to rapid interfacial tension changes near to critical point (Asar and Handy, 1988; Bardon and Longeron, 1980; and Haniff and Ali, 1990). More recently, the effect of flow velocity on  $K_r$  has been acknowledged (Henderson et al., 1993 and Henderson et al., 1995). The investigations have been oriented toward a dependence of  $K_r$  on the capillary number, a dimensionless number that includes both the interfacial tension and the velocity (Blom et al., 1997; Henderson et al., 1995; Kalaydjian et al., 1996; Schechter and Haynes, 1992).

Another parameter that has been extensively studied is the critical condensate saturation,  $S_{cc}$ . Determination of this value has been controversial. Values ranging between zero and 50% pore volume have been reported (Barnum et al.,

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1995 and Morel et al., 1992). This saturation is the minimum liquid saturation above which the condensate becomes mobile, corresponding to a non-zero condensate relative permeability. These low values of the condensate  $K_r$  control gas-condensate segregation and impact the phase distribution and the condensate ring buildup. To correctly predict gravity segregation for near-critical systems, it is necessary to compare viscous, capillary and gravity forces. To this end two relevant dimensionless numbers are used: the capillary number ( $Ca$ , ratio of the viscous to the capillary forces and predominant close to the well) and the Bond number ( $Bo$ , ratio of the gravity to the capillary forces and predominant far from the well). More specifically, three configurations can be identified: **1)** near-wellbore region: high velocity, high interfacial tension (high  $Ca$ , low  $Bo$ ); **2)** reservoir: low velocity, intermediate interfacial tension (low  $Ca$ , high  $Bo$ ); and **3)** near-critical reservoir: low velocity, low interfacial tension (high  $Ca$ , high  $Bo$ ).

The behavior of liquid condensate on the water/gas or solid/gas interface is a key factor. Complete wetting of the condensate on solid or water (spreading) would favor hydraulic continuity leading to low liquid saturations. There is evidence that for near-critical systems, the condensate phase perfectly wets either the rock or the water phase covering the pore surface (Ragil et al., 1998). However, as the pressure decreases towards the well, a wetting transition may occur that would render the condensate phase only partially wetting on water. This would favor its trapping by capillary forces.

The objective of this paper is to present a model for gas-condensate  $K_r$  as a function of the capillary number and to demonstrate that apparently contradictory laboratory results on the dependence on interfacial tension and flow rate, separately considered, can be reconciled. This is achieved, within the framework of the Darcy description of multiphase flow in porous media (relatively far from the well so that inertial effects are not an issue), by introducing a unique dependence of  $K_r$  on the capillary number. Also, modeling of the combined effect of gravity and capillary forces on the critical condensate saturation is introduced. The model takes into account the spreading characteristics of the condensate on the substrate (solid surface or water film).

### RELATIVE PERMEABILITY AND CAPILLARY NUMBER

As seen in the previous section, the interfacial tension alone cannot adequately parameterize the relative permeabilities. The displacement of several phases in a porous medium is governed by two different forces: viscous and capillary (in the absence of gravity). Capillary pressure is

assumed to represent the effect of capillary forces, while viscous forces intervene in the Darcy equations and are represented by the  $K_r$ . Phase distribution and displacement within the porous medium depend on a complex combination of those two forces.  $K_r$  was found to depend on interfacial tension (Asar and Handy, 1988; Bardon and Longeron, 1980 and Haniff and Ali, 1990), a typical capillary parameter, and on the flow velocity. When the interfacial tension vanishes, the capillary resistance to flow decreases. Therefore, the curvature of the  $K_r$  curves, which expresses for a given fluid the capillary effect induced by the presence of another fluid, decreases as well.  $K_r$  curves become straight lines either when miscibility is approached or when flow rate is increased enough to make capillary forces negligible. Therefore, it is anticipated that  $K_r$  curves depend on the capillary number,  $Ca$ , a dimensionless number defined as the ratio of the viscous to the capillary forces:

$$Ca = \frac{\mu v}{\sigma}. \quad (1)$$

Dullien (1992) proposed another capillary number that includes the characteristics of the porous medium in addition to those of the fluids

$$CA = 4 \frac{Ca \cdot l}{R}, \quad (2)$$

where  $l$  is the core length and  $R$  is a typical size of a pore radius. It is chosen to be equal to the pore size corresponding to the entry pressure deduced from the mercury intrusion curve; that is  $R = 2 \cdot \sigma \cdot \cos(\theta) / P^*$ , with  $P^*$  being the pressure at which the mercury starts invading the porous medium. When this capillary number is equal to unity, viscous forces balance capillary forces. When  $CA \geq 1$ , viscous forces are dominant.

It is worth checking this assumption by comparison with Bardon and Longeron's data (1980). These authors report a significant change in  $K_r$  for an interfacial tension smaller than 0.04 mN/m. The tests were carried out in a 40-cm long Fontainebleau sandstone with 82-mD permeability and approximately 10% porosity. The velocity was about 20 cm/h. According to the authors, the shape of the  $K_r$  curves did change for a capillary number equal to  $0.4 \cdot 10^{-4}$  (standard formulation). To calculate the value of the capillary number  $CA$ , it is necessary to know the pore size corresponding to the entry pore pressure. This pore size can be calculated using the rough estimate  $\sqrt{(8k/\phi)}$ , which gives an average value of about 2 microns and thus a pore radius corresponding to the entry pressure of about  $10 \mu\text{m}$ . This gives  $CA = 6.4$ . This value of  $CA$ , greater than unity, is thus con-

sistent with dominant viscous forces that tend to decrease the curvature of  $K_r$  curves.

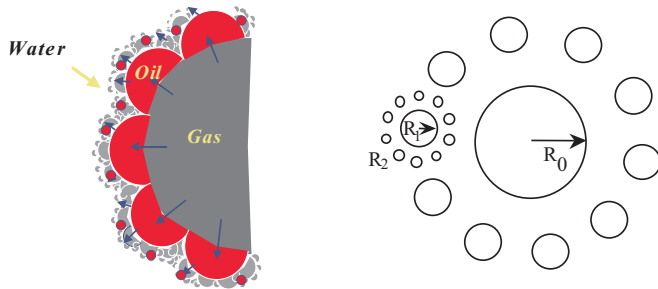
Another example is that found in Henderson et al. (1995). Gas capillary numbers ranging between  $0.18\text{E-}5$  and  $0.14\text{E-}4$  were reported. The experiments were performed on a core 61 cm long, of 92-mD permeability, 19.8% porosity and an irreducible water saturation of 0.264. This gives  $CA > 1$  ( $1.96 < CA < 7.86$ ), and explains why the authors found an effect of the flow rate, and thus of the capillary number on the relative permeabilities since all the tests were performed in the domain of dominant viscous forces.

Another example is the work presented by Asar and Handy (1988). They performed experiments in a Berea sandstone sample one ft long, with 20% porosity and 193-mD permeability. Four interfacial tension values ranging from 0.03 to 0.82 mN/m were tested. Even though only the range of the applied pressure drops is given, and calculation of the exact  $CA$  for each experiment is not possible, it is seen that  $CA$  ranges between 0.5 and  $\sim 80$ . This explains why, for the highest interfacial tension ( $\sigma = 0.82\text{mN/m}$ ), capillary effects are dominant and the measured  $K_r$  curves approach those obtained for conventional gas-oil flood, while for  $\sigma = 0.03\text{mN/m}$ , viscous effects are dominant and  $K_r$  curves approach straight lines.

### MODELING OF THE RELATIVE PERMEABILITY ( $K_r$ ) AND THE CRITICAL CONDENSATE SATURATION ( $S_{cc}$ )

#### Porous medium model

It is well known that the transport properties in a porous medium depend strongly on pore structure geometry. Several papers proved that sedimentary rocks are one of the most extensive natural fractal systems (Katz and Thompson, 1985 and Radlinski et al., 1999). They demonstrated that the pore volume and the pore-rock interface is fractal



**FIG. 1** The fractal pore model and the phase distribution within it.

over length scales that may range from the nanometer to a few microns and have the same surface fractal dimension  $D_s$ .  $D_s$  takes values between 2 and 3, in which 2 characterizes smooth clay-free rocks, while values close to 3 are characteristic of strongly clayey sandstones. This fractal dimension can be easily determined from the capillary pressure curve at low wetting phase saturation (Davis, 1989) or using sophisticated measurement methods as the X-ray or neutron scattering techniques (Bale and Schmidt, 1984), improving the measurement accuracy considerably.

The modeling approach proposed here has been inspired by the de Gennes (1985) paper on the partial filling of a fractal structure by a wetting fluid (Lenormand, 1990). The internal surface of a pore is assumed to be a fractal surface; consequently, a perfectly wetting phase remains always continuous. The isotropic fractal surface is modeled as a bundle of parallel capillary tubes with a fractal cross section. The cross section of each tube is constructed by an iterative process, by dividing the half perimeter of a circle in  $\eta$  parts and replacing each part by half a circle (Figure 1). At each step  $k$  of the process,  $N_k$  new grooves are created with radius  $R_k$  and total cross-sectional area  $A_k$ ; these characteristics are given as a function of the initial tube radius  $R_0$  by the following relationships :

$$R_k = R_0 (\pi / \eta)^k \quad (3)$$

$$N_k = \eta^k \quad (4)$$

$$A_k = \frac{1}{2} \pi R_0^2 (\pi / \eta)^k. \quad (5)$$

It can be easily shown that the perimeter of a section is given by

$$L / L_0 = (R / R_0)^{(1-D_L)}, \quad (6)$$

where  $L_0$  is the perimeter of the main tube and  $D_L$  is the linear fractal dimension associated with the perimeter (linear fractal dimension,  $D_L = D_s - 1$ ) given by

$$D_L = \frac{\ln \eta}{\ln \eta / \pi}. \quad (7)$$

#### Capillary pressure and Relative permeability

At equilibrium, all tubes with size smaller or equal to  $R_k$ , where  $R_k$  is given by Laplace's law:  $P_c = 2\sigma/R_k$  are occupied by the wetting fluid, and larger tubes by the non-wetting one. Thus, the wetting fluid saturation is given as the surface of the tubes occupied by the wetting phase to the total cross section,

$$S_w = \frac{\sum_k A_k}{\sum_0 A_k} = \left( \frac{R_k}{R_0} \right)^{(2-D_L)} \quad (8)$$

and the correlation between capillary pressure and wetting-phase saturation is given by

$$P_c = \frac{2\sigma}{R_0} S_w^{1/(D_L-2)} \quad (9)$$

To simplify calculation of  $K_r$ , the grooves are replaced by capillary tubes of the same diameter and parallel to the direction of flow. To calculate  $K_r$ , Poiseuille's law is applied in each capillary of the bundle. If the flow rate in a single tube of radius  $R_k$  is given by

$$Q_k = -\frac{\pi R_k^4}{8\mu} \nabla P, \quad (10)$$

then the  $K_r$  of the wetting phase, which occupies the smallest tubes, is calculated as

$$K_{rw} = \frac{\sum_k Q_k N_k}{\sum_0 Q_k N_k} = S_w^{(DL-4)/(DL-2)}. \quad (11)$$

We have assumed that the wetting fluid flows down to zero saturation and that there is no irreducible or immobile wetting-phase saturation. However, irreducible phase saturation can be easily introduced in the calculations as presented elsewhere (Vizika, 1993). This model, when applied to film flow and low wetting-phase saturations, allows estimation of  $K_r$  curves for a range of saturation values where reliable experimental results are hard to obtain (Kalaydjian et al., 1997 and Moulu et al., 1997).

### Modeling of gas-condensate relative permeability as a function of $CA$

#### Threshold condensate saturation

Here we use the model described above to calculate gas-condensate  $K_r$  and the impact of capillary number on it. There exists experimental evidence that near the critical point the condensate is the wetting phase that spreads spontaneously on the solid surface (Williams and Dawe, 1989). During a depletion, and as the pressure goes down, the condensate saturation builds up. As the wetting phase progresses, the condensate occupies first the surface roughness and the smallest pores. If  $CA$  is low ( $0 < CA < 1$ ), capillary forces will be dominant for the whole range of condensate

saturations. If  $CA$  increases ( $CA \sim 1$ ), viscous forces start being important, and for high  $CA$  ( $CA > 1$ ), they become dominant.

For a given macroscopic capillary number, different flow regimes may exist inside the porous medium at the pore level. In the bundle of capillaries for example, all tubes are subject to the same pressure gradient. Locally, however, different flow velocities develop depending on the tube radius. These different velocities lead to different local capillary numbers, meaning that flow may be capillary-dominated in the smallest pores, while simultaneously viscous-dominated in the rest. That means that for a given macroscopic or bulk capillary number,  $CA_0$ , we can define a threshold condensate saturation,  $S_{tc}$ , below which flow is capillary-dominated and above which viscous forces predominate. Suppose that in the bundle of capillaries model,  $S_{tc}$  occupies the smallest pores from  $R_\infty$  to  $R_k$ . The capillary number in the tubes  $k$  is  $CA_k$ . From the definition of  $CA$  (equation (2)) it is seen that

$$\frac{CA_k}{CA_0} = \frac{R_k}{R_0}, \quad (12)$$

which can be combined with equation (8) to express in a different way the wetting fluid saturation

$$S_c = \left( \frac{CA_k}{CA_0} \right)^{(2-D_L)}. \quad (13)$$

It is now obvious that the threshold condensate saturation is the one for which  $CA_k = 1$ .

$$S_{tc} = (CA_0)^{(D_L-2)}. \quad (14)$$

For a given pore structure (given  $D_L$ ), this expression permits calculation of the part of the wetting fluid flowing by capillary-dominated flow as a function of the macroscopic capillary number. Figure 2 shows the dependence of  $S_{tc}$  on  $CA$  for different fractal dimensions. It is seen that the higher the capillary number, the lower the threshold condensate saturation. It is also seen that, for a given  $CA$ ,  $S_{tc}$  increases with  $D_L$ . This means that, for the same macroscopic flow conditions, the more fractal the pore structure, the higher the wetting-phase saturation (condensate) subject to a capillary flow regime. In other words, in a clayey sandstone (high  $D_L$ ), the wetting phase maintains a low mobility up to rather high saturations, even at high capillary numbers where viscous forces would be expected to predominate.

#### Condensate relative permeability

The wetting fluid  $K_r$  is given by equation (11) up to  $S_{tc}$ .



The fluid above the threshold saturation,  $S_{tc}$ , flows in the larger tubes by viscous-dominated flow. The respective relative permeability for  $S_c > S_{tc}$  is taken proportional to the flowing saturation (straight lines). In calculating wetting fluid relative permeability with the bundle of tubes model, the assumption is made that flow occurs independently in each tube. This is particularly relevant at rather low liquid saturations.

A sample calculation of the condensate (wetting phase)  $K_r$  and its evolution with  $CA$  is given in Figure 3. A  $D_L = 1.4$  has been used in these calculations. This value is representative of a weakly clayey sandstone. The  $K_{rc}$  curves for three different capillary numbers ( $CA = 3, 10$  and  $100$ ) are presented in this figure. For comparison purposes, the curve for purely capillary-dominated displacement is also given. It is seen that as viscous forces become important (increasing  $CA$ ), the part of the fluid flowing under capillary-dominated flow is reduced, and  $K_r$  increases considerably.

#### Gas relative permeability

Gas as the non-wetting phase occupies the bulk of the pores. To calculate its relative permeability, it is assumed that, if the condensate occupies all tubes with radius smaller than  $R_k$ , gas flows as though it was in a single pore with radius  $R_g = R_0 + R_1 + \dots + R_k$  (Moulu et al., 1997). Thus for low condensate saturations ( $S_c < S_{tc}$ ),  $K_{rg}$  is given by

$$K_{rg} = K_{rg\max} \left(1 - S_c^{1/(2-D_L)}\right)^4. \quad (15)$$

$K_{rg\max}$  is the maximum value of the gas  $K_r$  in presence of the other phase. For lower  $S_g$ , ( $S_c > S_{tc}$ ), gas circulates in the

biggest pores with a  $K_{rg}$  proportional to the flowing gas saturation,

$$K_{rg} = \frac{S_g}{1 - S_{tc}} K_{rg}(S_{tc}). \quad (16)$$

It is seen that, in addition to  $K_{rc}$ ,  $K_{rg}$  depends on the porous medium (through  $D_L$ ) and on the capillary number (through the dependence on  $S_{tc}$ ).

A sample calculation of the gas (non-wetting phase) relative permeability and its evolution with  $CA$  is given in Figure 4. As for  $K_{rc}$  (Figure 3), a linear fractal dimension of 1.4 has been used in these calculations. The  $K_{rg}$  curves for three different capillary numbers ( $CA = 3, 10$  and  $100$ ) are plotted. Also the curve for purely capillary-dominated displacement is given for comparison. As viscous forces increase (increasing  $CA$ ), the  $S_{tc}$  decreases and the saturation range where gas permeability is proportional to  $S_g$  increases.

#### Comparison with experiments

The proposed model is now tested against experimental measurements of near-critical fluid  $K_r$  as reported in the literature.  $K_r$  curves at near-critical conditions have been reported by Schechter and Haynes (1992). The experiments (injections at an average flow rate of  $0.098 \text{ cm}^3/\text{s}$ , for three interfacial tensions:  $0.1, 0.006$  and  $0.002 \text{ mN/m}$ ) were performed in a Clashach sandstone of  $30 \text{ cm}$  in length, with a permeability of  $200 \text{ mD}$  and a porosity of  $18\%$ . These data allow calculation of the  $CA$  numbers from the  $Ca$  values given by the authors: for  $Ca \times 10^{-4}, 4 \times 10^{-3}$  and  $10^{-2}$  we

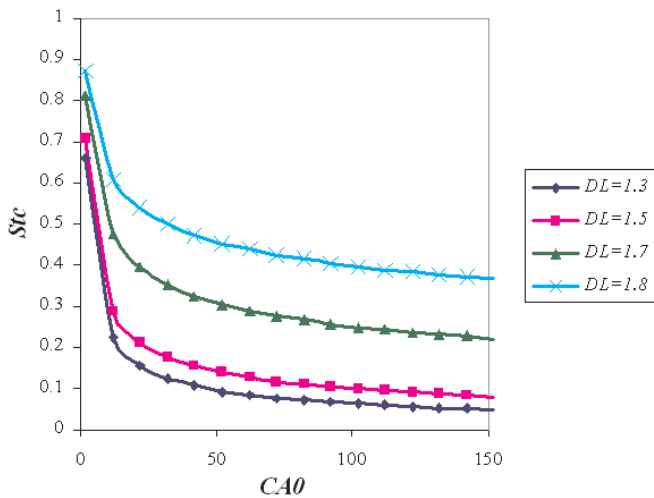


FIG. 2 Threshold condensate saturation as a function of the macroscopic capillary number for various fractal dimensions.

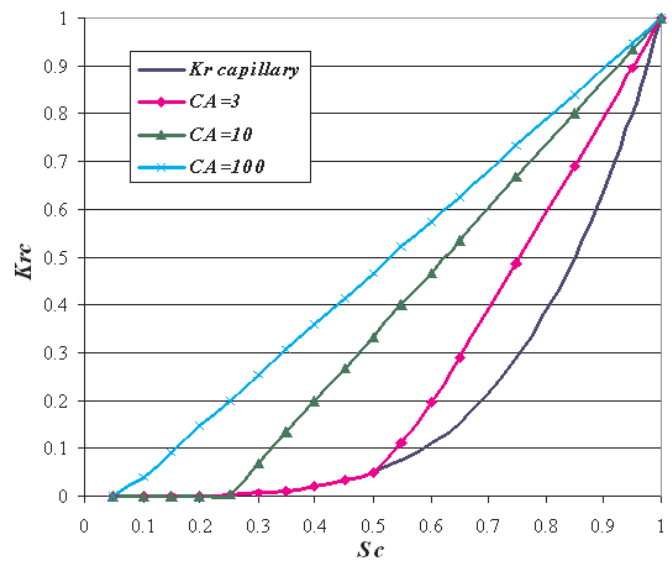


FIG. 3 Effect of capillary number on the condensate relative permeability ( $D_L = 1.4$ ).

get the respective  $CA$  values 12, 133 and 400. Then  $S_{lc}$ ,  $K_{rc}$  and  $K_{rg}$  have been calculated with the model by taking  $D_L$  equal to 1.65. This value, representative of a clayey sandstone (Katz and Thompson, 1985), has been measured in a Clashach sample of comparable permeability to that used in Schechter and Haynes' experiments. A comparison between Schechter's measurements and the present model's predictions are given in Figures 5 and 6. For this example, a good agreement between experiment and calculations is obtained. The model successfully predicts gas-condensate  $K_r$  as a function of the macroscopic capillary number. It also successfully predicts the threshold saturation  $S_{lc}$ , below which the reduction of condensate mobility becomes significant. It is worth noting that there is no adjustable parameter in the model. The only parameter that has been assigned an arbitrary value (not reported in Schechter and Haynes, 1992) is the fractal dimension  $D_L$ .

Bardon and Longeron (1980) have also reported  $K_r$  measurements at different and very low interfacial tensions. For flow rates 0.011, 0.01 and 0.012 cm<sup>3</sup>/s and interfacial tensions 0.065, 0.038 and 0.0014 mN/m respectively, the  $Ca$  numbers calculated by the authors were:  $0.19 \times 10^{-4}$ ,  $0.38 \times 10^{-4}$  and  $0.11 \times 10^{-2}$ . The  $CA$  numbers calculated as indicated above are 2.5, 6 and 168. Comparison between the experiments and the calculations is given in Figures 7 and 8 for the condensate and the gas  $K_r$ , respectively. The fractal dimension has been taken equal to 1.3. This value is representative of a very weakly clayey sandstone as was the one used in the experiments (Fontainebleau sandstone). A satis-

factory agreement is observed considering the uncertainties in the experimental  $K_r$  data that have been obtained by numerical fitting of displacement and production data.

### Gravity segregation and critical condensate saturation, $S_{cc}$

The same model for the porous medium can be used to calculate the critical condensate saturation for mobility as a function of the spreading and interfacial properties of the fluid system, and the characteristics of the pore structure. We need first to introduce the Bond number, which is defined as the ratio of the gravity to capillary forces, in a way equivalent to that proposed by Schechter et al. (1994) (e.g., defined at the macroscopic scale).

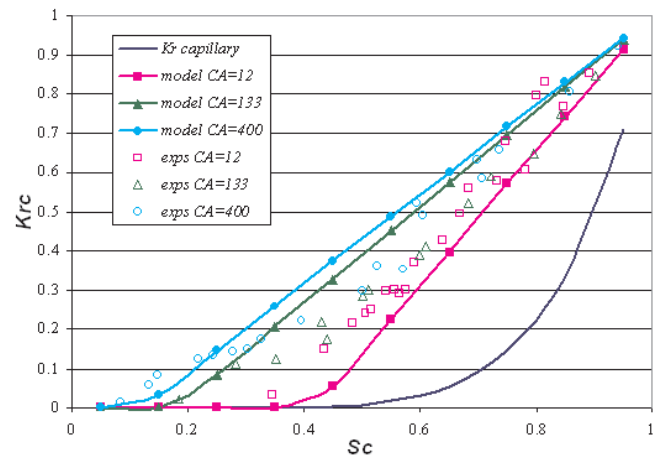


FIG. 5  $K_{rc}$ : Comparison between the model and Schechter and Haynes' experimental results.

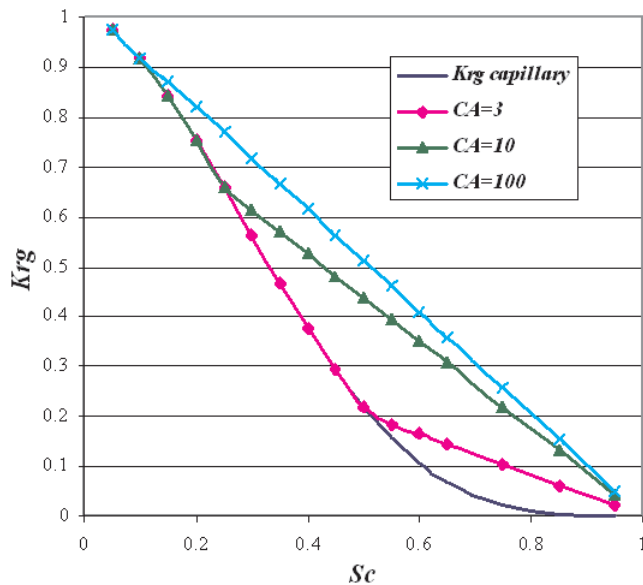


FIG. 4 Effect of capillary number on the gas relative permeability ( $D_L = 1.4$ ).

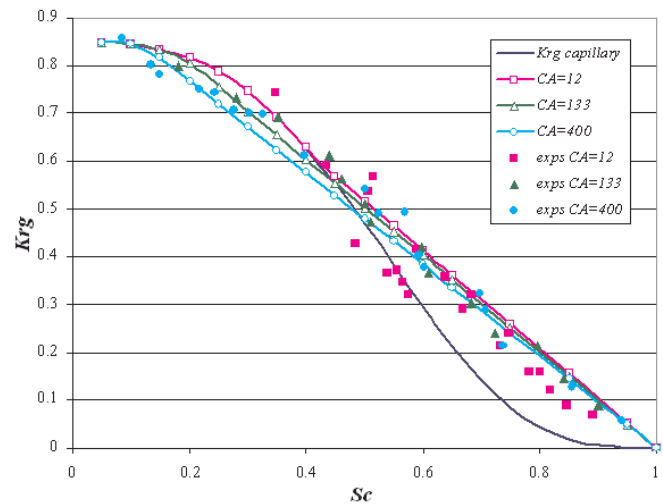


FIG. 6  $K_{rg}$ : Comparison between the model and Schechter and Haynes' experimental results.

$$Bo = \frac{\Delta \rho g R l}{\sigma} \quad (17)$$

It is considered here that  $S_{cc}$  is the minimum saturation at which the condensate is continuous and that the conditions are such that gravity forces, favoring segregation, are dominant over the capillary forces that favor condensate trapping. That means that the condensate has first to form continuous films on the solid substrate or on the water, if interstitial water is present in the porous medium. These continuous films may still be immobile if gravity forces are not strong enough compared to capillary forces.  $S_{cc}$  is the saturation above which the condensate  $K_r$  takes a non-zero value. It is to be distinguished from the threshold condensate saturation,  $S_{tc}$ , that determines the saturation below which the condensate has a reduced though finite mobility.

In a water-wet porous medium, in presence of irreducible water saturation, a relevant parameter is the spreading coefficient of oil (condensate) on water:  $S = \sigma_{wg} - (\sigma_{wc} + \sigma_{cg})$ . At equilibrium,  $S$  is always negative or equal to zero. It has been already verified through numerous studies on three-phase displacement that fluid distributions depend on the sign of the spreading coefficient of oil on water in presence of gas. For  $S = 0$ , oil (condensate) forms a film spontaneously on water in presence of gas. Spreading oil films assure hydraulic continuity of the oleic phase and can lead to high recoveries. For  $S < 0$ , oil does not spread on water in presence of gas, and a finite contact angle,  $\theta$ , is formed between the gas-condensate and water-condensate interfaces. The above hold rigorously only for a flat solid surface. Wetting on a rough surface is very different, and apparent contact angles depend both on the wetting properties of the flat surface and on the structure of the roughness (Onda et al., 1996). Two types of trapping can be considered: a) continu-

ous phase trapping in the smallest tubes where capillary forces are very strong, and b) discontinuous phase trapping, when  $S < 0$  and the condensate is in disconnected form.

### Spreading condensate trapping ( $S = 0$ )

In absence of water or if the condensate spreads on the water, ( $S = 0$ ), films are spontaneously formed at the moment of condensate apparition. These films automatically ensure hydraulic continuity. The continuous phase trapping is related to the Bond number. In the bundle of capillaries model, introduced above, the condensate occupies the smallest pores, from  $R_\infty$  to  $R_k$  in absence of water, or from  $R_{wi}$  to  $R_k$ , if the tubes from  $R_\infty$  to  $R_{wi}$  are occupied by irreducible water. The Bond number in the tubes  $k$  is  $Bo_k$ . From its definition, it results in

$$\frac{Bo_k}{Bo_0} = \frac{R_k}{R_0}. \quad (18)$$

If  $Bo_k > 1$ , gravity forces predominate and  $R_k$  tubes are emptied under gravity segregation. The critical condensate saturation for mobility of a continuous fluid,  $S_{cc/c}$ , is the one for which  $Bo_k = 1$  and is given by

$$S_{cc/c} = (Bo_0)^{(D_t-2)} - S_{wi}. \quad (19)$$

### Non-spreading condensate trapping ( $S$ )

If  $S < 0$ , in condensate apparition small droplets are formed. If the substrate is flat, these droplets form an angle  $\theta$  for which

$$\cos \theta = 1 + \frac{S}{\sigma_{cg}}. \quad (20)$$

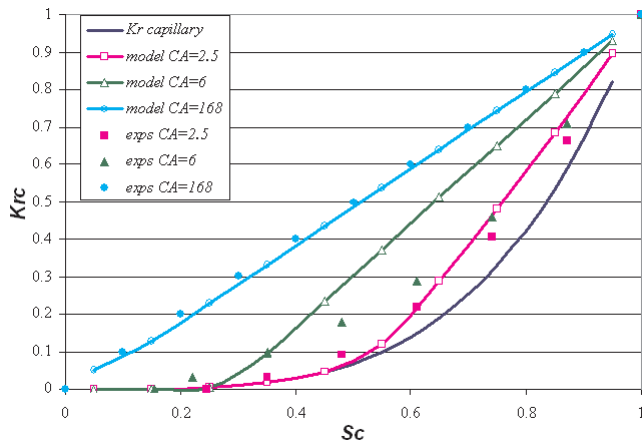


FIG. 7  $K_{rc}$ : Comparison between the model and Bardon and Longeron's experimental results.

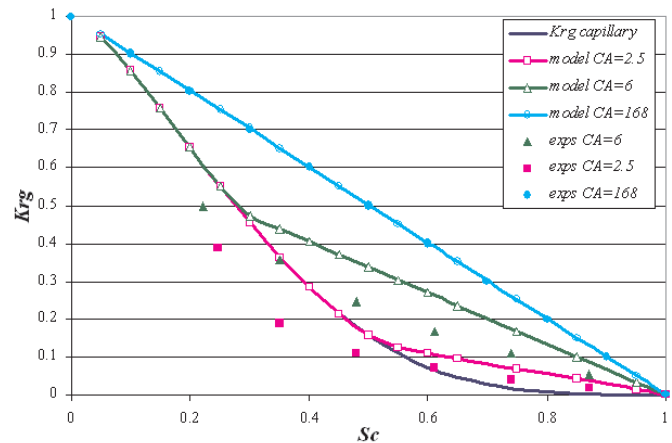


FIG. 8  $K_{rg}$ : Comparison between the model and Bardon and Longeron's experimental results.

On a fractal surface, they form an apparent contact angle,  $\theta_{app}$ , related to  $\theta$  with the following expression (Onda et al., 1996)

$$\cos \theta_{app} = \left( \frac{R_0}{R_k} \right)^{D_L-1} \cos \theta, \quad (21)$$

where  $R_0$  and  $R_k$  are the upper and the lower limits of fractal behavior, respectively. If  $\cos \theta_{app} = 1$ , the non-spreading condensate ( $\cos \theta < 1$ ) remains continuous. The fractal surface induces wetting of a non-spreading liquid. Thus the criterion for spreading phase mobility has to be applied, as explained above. The critical condensate saturation is given by equation 19.

When  $\cos \theta_{app} < 1$ , the condensate forms lenses and remains disconnected. It is considered that the disconnected phase remains immobile and is not subject to gravity segregation. The critical saturation for discontinuous liquid mobility,  $S_{cc/d}$ , is the one occupying tubes up to  $R_k$  for which  $\cos \theta_{app}$  becomes equal to 1. It is given by the following expression as a function of the spreading and interfacial properties of the system and the characteristics of the pore structure here expressed by the fractal dimension  $D_L$ :

$$S_{cc/d} = \frac{1}{\pi^{D_L-1}} (1 - (\cos \theta)^{2-D_L}). \quad (22)$$

Then the critical saturation for mobility of a non-spreading condensate is the sum of the trapped continuous (if any) and trapped discontinuous liquid. Figure 9 shows the critical condensate saturation for a discontinuous phase ( $S < 0$ ,  $\cos \theta_{app} < 1$ ) for various values of the fractal dimension.  $S_{cc/d}$  can take extremely high values for strongly non-spreading fluids ( $\theta = 90^\circ$ ,  $\cos \theta = 0$ ) and highly fractal pore space (high  $D_L$ ).

## CONCLUSIONS

Flow rate and interfacial tension dependence of relative permeability are explained on the basis of the competition between capillary and viscous forces.  $K_r$  curves are shown to deform and approach straight lines when viscous forces overcome capillary forces. This can be achieved either by decreasing the interfacial tension or increasing the flow rate. To account for these effects, a capillary number,  $CA$ , introduced by Dullien (1992) is used. It includes, in addition to fluid properties, porous medium properties.  $CA$  allows precise definition of the flow rate threshold above which (or interfacial tension below which)  $K_r$  curves start to deform. This hypothesis has been validated on experimental results obtained either by modifying the interfacial tension or the flow rate.

A model has been proposed to calculate gas-condensate  $K_r$  curves as functions of the capillary number. The model includes the structural characteristics of the porous medium through its fractal dimension. It predicts the modification of the  $K_r$  curves as the capillary number changes (velocity or interfacial tension changes). The model has been tested against experimental results reported in the literature and a satisfying agreement has been obtained.

A threshold condensate saturation,  $S_{ic}$ , can be predicted below which the condensate mobility is significantly reduced, even though finite.  $S_{ic}$  may be very high in highly fractal (very clayey) sandstones. It decreases with increasing capillary number.

The critical saturation for condensate mobility,  $S_{cc}$ , increases with increasing interfacial tension (decreasing Bond number) and fractal dimension. Non-spreading condensates would be subject to severe trapping, increasing with increasing fractal dimension and decreasing spreading coefficient.

## NOMENCLATURE

$A_k$	Area of the grooves of step $k$
$Ca$	Standard capillary number ( $= \mu v / \sigma$ )
$CA$	Capillary number ( $= 4 Ca / R$ )
$Bo$	Bond number ( $= \Delta \rho g R / \sigma$ )
$D_L$	Linear fractal dimension
$D_S$	Surface fractal dimension
$g$	Acceleration of gravity
$k$	Permeability

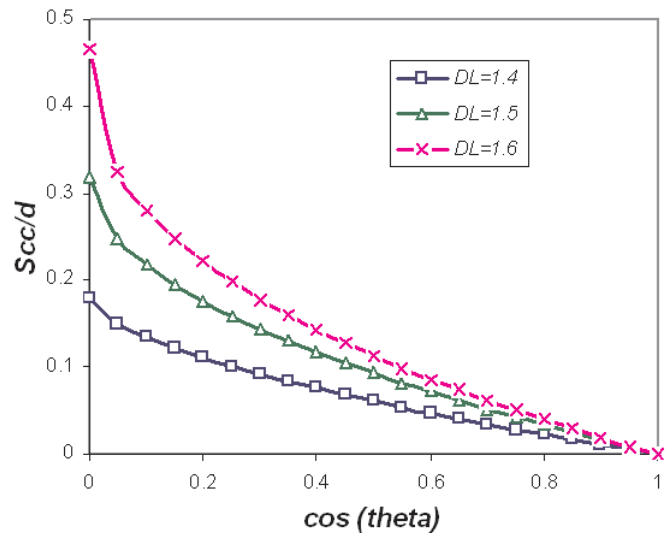


FIG. 9  $K_{rg}$ : Effect of  $\cos \theta$  (negative spreading coefficient) on the critical condensate saturation of a discontinuous phase for various values of the fractal dimension.



$K_r$	Relative permeability
$K_{ri}$	Relative permeability of fluid i
$K_{rgmax}$	maximum gas relative permeability
$l$	Porous medium length
$L$	Perimeter of a section of the fractal object
$N_k$	Number of objects of step k
$P_c$	Capillary pressure
$Q_k$	Flow rate in tube of radius $R_k$
$R$	Entry pore size
$R_0$	Initial capillary tube radius in the fractal pore model
$R_i$	Capillary radius ( $i = 1, 2, \dots, k$ step of the fractal construction)
$R_g$	Radius for gas flow in the fractal pore model
$R_{wi}$	Maximum tube radius occupied by irreducible water
$S$	Saturation
$S$	Spreading coefficient
$S_i$	Saturation of fluid i
$S_{wi}$	Irreducible water saturation
$S_{cc}$	Critical condensate saturation
$S_{cc/c}$	Critical condensate saturation for continuous phase
$S_{cc/d}$	Critical condensate saturation for discontinuous phase
$S_{tc}$	Threshold condensate saturation
$v$	Velocity
$\nabla P$	Pressure gradient
$\Delta\rho$	Density difference
$\eta$	Number of new tubes created at each step
$\theta$	Contact angle between gas-condensate and water-condensate interfaces
$\mu$	Viscosity
$\sigma$	Interfacial tension
$\phi$	Porosity

### Subscripts

$c, g, w$  Condensate, gas, wetting phase

## REFERENCES

- Asar, H., and Handy, L.L., 1988, Influence of interfacial tension on gas-oil relative permeability in a gas-condensate system: *SPERE*, February, 257 p.
- Bale, H. D., and Schmidt, P. W., 1984, Small-angle X-ray-scattering investigation of submicroscopic porosity with fractal properties: *Physical Review Letters*, vol. 53, 596 p.
- Bardon, C. and Longeron, D., 1980, Influence of very low interfacial tensions on relative permeability: *Society of Petroleum Engineers Journal*, October, p. 391–401.
- Barnum, R. S., Brinkman, F. P., Richardson, T. W. and Spillette, A. G., 1995, Gas condensate reservoir behaviour: productivity and recovery reduction due to condensation, SPE 30767, in SPE Annual Technical Conference and Exhibition, Dallas, Texas.
- Blom, S. M.P., Hagoort, J., and Soetekouw, D. P. N., 1997, Relative permeability at near-critical conditions, SPE 38935: Society of Petroleum Engineers, presented at the 1997 SPE Annual Technical Conference and Exhibition.
- Davis, H. T., 1989, On the fractal character of the porosity of natural sandstone: *Europhysics Letters*, vol. 8, no. 7, p. 629–632.
- de Gennes, P. G., 1985, Partial filling of a fractal structure by a wetting fluid, in Adler, Fritzche, Ovshinsky, eds., *Physics of Disordered Materials*, Plenum Publishing Corporation, p. 227–241.
- Dullien, F.A.L., 1992, *Fluid transport and pore structure*, 2nd Edition, Academic Press Inc.
- Haniff, M. S., and Ali, J. K., 1990, Relative permeability and low tension fluid flow in gas condensate systems: SPE 20917: presented at the 1990 SPE European Petroleum Conference.
- Henderson, G. D., Danesh, A., Tehrani, D. H., and Peden, J. M., 1993, An investigation into the processes governing flow and recovery in different flow regimes present in gas-condensate reservoirs: SPE 26661, presented at the 1993 SPE Annual Conference and Exhibition.
- Henderson, G. D., Danesh, A., Tehrani, D. H., Al-Shaidi, S., and Peden, J. M., 1995, Measurement and correlation of gas condensate relative permeability by the steady-state method, SPE 30770, presented at the 1995 SPE Annual Technical Conference and Exhibition.
- Kalaydjian, F. J-M., Bourbiaux, B. J., and Lombard, J-M., 1996, Predicting gas-condensate reservoir performance: how flow parameters are altered when approaching production wells: SPE 36715, presented at the 1996 SPE Annual Technical Conference and Exhibition.
- Kalaydjian, F. J-M., Moulou, J-C., Vizika, O. and Munkerud, P-K., 1997, Three-phase flow in water-wet porous media: gas/oil relative permeabilities for various spreading conditions: *Journal of Petroleum Science Engineering*, vol. 17, 275–290.
- Katz, A. J. and Thompson, A. H., 1985, Fractal sandstone pores: implications for conductivity and pore formation: *Physical Review Letters*, vol. 54, no. 12, p. 1325–1328.
- Lenormand, R., 1990, Gravity-assisted inert gas injection: micro-model experiments and model based on fractal roughness: presented at the 1990 European Oil and Gas Conference.
- Morel, D. C., Lomer, J.-F., Morineau, Y. M., and Putz, A. G., 1992, Mobility of hydrocarbon liquids in gas condensate reservoirs: interpretation of depletion laboratory experiments: SPE 24939, presented at the 1992 SPE Annual Technical Conference and Exhibition.
- Moulou, J. C., Vizika, O., Kalaydjian, F., and Duquerroix, J-P., 1997, A new model for three-phase relative permeabilities based on a fractal representation of the porous medium: SPE 38891, presented at the 1997 SPE Annual Technical Conference and Exhibition.
- Onda, T., Shibuichi, S., Satoh, N., and Tsujii, K., 1996, Super-water-repellent fractal surfaces: *Langmuir*, vol. 12, no. 9, p. 2125–2127.
- Radlinski A. P., Radlinska, E. Z., Agamalian, M. Wingall, G. D., Lindner, P., and Randl, O.G., 1999, Fractal geometry of rocks: *Physical Review Letters*, vol. 82., no. 15, p. 3078–3081.

- Ragil, K., Bonn, D., Broseta, D., Indekeu, J., Kalaydjian, F., and Meunier, J., 1998, The wetting behavior of alkanes on water: *Journal of Petroleum Science Engineering*, vol. 20, p. 177–183.
- Schechter, D. S. and Haynes, J. M., 1992, Relative permeabilities of a near critical binary fluid: *Transport in Porous Media*, vol. 9, p. 241–260.
- Schechter, D. S., Zhou, D., and Orr, Jr., F. M., 1994, Low IFT drainage and imbibition: *Journal of Petroleum Science Engineering*, vol. 11, p. 283–300.
- Vizika, O., 1993, Effect of the spreading coefficient on the efficiency of oil recovery with gravity drainage: presented at the 1993 Symposium on Enhanced Oil Recovery, 205th National Meeting of ACS.
- Williams, J. K. and Dawe, R. A., 1989, Near-critical condensate fluid behavior in porous media – a modeling approach: *SPE*, May, p. 221–227.

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