THEORETICAL AND EXPERIMENTAL STUDY OF THE POSITIVE IMBIBITION CAPILLARY PRESSURE CURVES OBTAINED FROM CENTRIFUGE DATA.

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Abstract

This paper presents an analysis of the theory of a moving fluid/fluid level during determination of drainage and spontaneous (positive) imbibition capillary pressure versus saturation. The theoretical analysis shows that the method of moving fluid level gives valid data for all types of cores, independent of entry pressure, permeability and porosity. Earlier literature on the subject indicates that part of the zone experiencing moving fluid level may imbibe during the drainage cycle and drain during the imbibition cycle (so-called crossing zones), thereby creating an interpretation problem. Our paper presents a calculation procedure for quantification of these effects. The results show that, with standard centrifuges and reservoir rocks ranging from low permeability chalk to high permeability sandstone, problems with moving fluid level and crossing zones are minor. For high permeability samples no effect is observed during the drainage process before the centrifuge speed exceeds 5000 rpm. For low permeability samples no crossing zone is encountered at practical centrifuge speeds. For the core- and centrifuge- geometries used in this work the calculations show that the theoretical basis for the determination of drainage and spontaneous imbibition in one experimental cycle is valid. Forbes' correction for radial effects is modified and implemented in this paper for tests with moving fluid levels.

The paper also presents comparisons of spontaneous imbibition capillary pressure curves measured with the centrifuge and the porous plate. The results from the two methods show good coincidence. However, more comparative studies are needed to determine the advantages and disadvantages of this technique in capillary pressure hysteresis studies and wettability determination.

Introduction

Valid capillary pressure data are essential to the development of reliable reservoir descriptions. For a water-oil system the capillary pressure vs. saturation relationship is important for the determination of such parameters as irreducible water saturation, height of the transition zone and oil recovery after displacement by free water imbibition and/or water injection.

The centrifuge has been extensively used to determine drainage and forced imbibition capillary pressure curves for core samples since Hassler and Brunner[1] presented the theory of the centrifuge method. However, complete capillary pressure curves, including forced and spontaneous drainage and imbibition, have not been obtained with the centrifuge method. Until now, the only methods reported to yield complete sets of capillary pressure curves have been modified porous plate techniques using micropore membranes[2,3].

Only a few authors have treated the problem of determining the positive imbibition capillary pressure in a standard centrifuge experiment[4,5,6,7]. Two methods are available; 1) Keeping the fluid/fluid level constant by using complicated centrifuge core holders or 2) using standard core holders and measuring the change in fluid level. The first method is not widely used due to the requirement of specialized and complicated equipment and the second technique has lacked a rigorous method of analyzing the effects of moving fluid contact during the imbibition and drainage cycles.

In this work a commonly used ultracentrifuge with standard core holders was used to determine both drainage and imbibition capillary pressure curves in the same experiment. The method was first introduced by Øyno and Torsæter[8] in connection with their studies on the imbibition mechanism in fractured reservoirs. The procedure is as follows: The core is rotated at given speed until equilibrium is reached and then the speed is increased. The procedure yields a drainage process in the upper part of the core and the produced fluid is directly registered from the fluid/fluid interface around the core. Imbibition occurs during speed reduction after initial water saturation has been reached.

Theory

Moving fluid/fluid contact. The wetting phase saturated core plug is placed inside the transparent part of a traditional drainage coreholder. A small amount of wetting phase already exists in the coreholder. The initial amount of wetting phase assures the validity of the Hassler and Brunner 100 percent core outlet wetting phase saturation throughout the cycle. Non-wetting phase is added until the core is totally submerged. A start level of the fluid/fluid contact, where the two phases meet outside the core, is defined. As the rotational speed successively increases, a drainage front is forced into the core, displacing wetting phase. The fluid/fluid level rises along the core surface, as wetting phase is produced from the core. A slot that has been cut into the core makes it possible to measure the fluid/fluid levels, and from these data mean saturations and core inlet capillary pressures are determined. After reaching the maximum speed of rotation, spontaneous imbibition data may be gathered from successively decreasing speeds of rotation, allowing earlier produced wetting phase to imbibe into the core with the decreasing capillary pressures. The height of the fluid/fluid level decreases along the core surface. Thus drainage and positive imbibition capillary pressure curves may be established in one continuous centrifuge run.

Converting centrifuge data to capillary pressure curves. This method of moving fluid/fluid contact departs from the traditional centrifuge method only by the fact that the point of 100 percent wetting phase saturation and zero capillary pressure is no longer fixed at the core outlet. Assuming an equivalent fluid/fluid contact at the location of the fluid/fluid contact surrounding the core, this point will be known throughout the cycle, allowing the following use of traditional conversion routines. The traditional centrifuge equation is given as follows:

$$\overline{S}\left(P_{c_1}\right)=\frac{1+f}{2\,P_{c_1}}\int_0^{P_{c_1}}\frac{S\left(P_c\right)dP_c}{\sqrt{1-\frac{P_c}{P_{c_1}}\left(1-f^2\right)}} \tag{1}$$

where f being the ratio between the distances from rotation center to the core inlet and core outlet respectively. The moving fluid/fluid contact changes Equation 1 into:

$$P_{c_1}\left(r_2\right)\overline{S}\left(P_{c'}\, r_2\right)=\frac{r_2+r_1}{2\,r_2}\int_0^{P_{c_1}}\frac{S\left(P_c\right)dP_c}{\sqrt{1-\frac{P_c}{P_{c_1}\left(r_2\right)}\left(1-\left[f\left(r_2\right)\right]^2\right)}} \tag{2}$$

From Equation 2, the Hassler and Brunner assumption of f≈1 gives:

$$P_{c_1}\left(r_2\right)\overline{S}\left(P_{c'}\, r_2\right)=\int_0^{P_{c_1}} S\left(P_c\right)dP_c \tag{3}$$

which by derivation gives the Hassler and Brunner expression for local saturation at core inlet:

$$S\left(P_{C_1}\right)=\frac{d}{dP_{c_1}\left(r_2\right)}\left(P_{c_1}\left(r_2\right)\overline{S}\left(P_{c'}\, r_2\right)\right) \tag{4}$$

The capillary pressure at core inlet is given by the following traditional expression, assuming zero capillary pressure at the fluid/fluid contact surrounding the core:

$$P_{c_1}\left(\omega, r_2\right)=\frac{1}{2}\Delta\rho\omega^2\left(r_2^2-r_1^2\right) \tag{5}$$

Note that the capillary pressure in case of a moving equivalent fluid/fluid contact is dependent upon both the speed of rotation and the distance from rotation center to the fluid/fluid contact. Equations 4 and 5 are used for the conversion of both the drainage and imbibition centrifuge data.

Problems. It has been suggested earlier[8,9] that the moving fluid/fluid contact may cause problems when it comes to the validity of important assumptions behind the expressions used for converting centrifuge data to capillary pressure curves. These problems are connected to the phenomenon of crossing zones, which occurs if the drainage front inside the core penetrates the core beyond the level of the fluid/fluid contact that at all times surrounds the core. In such a situation the crossing zone may undergo local spontaneous imbibition in the general drainage mode, as the capillary pressure at a given point in this zone decreases from some positive value to zero when overflowed by the rising fluid/fluid contact. The crossing zone may equally experience local drainage during general imbibition, as the capillary pressure at a given point in the zone increases from zero to some positive value as the fluid/fluid contact falls. Crossing zones represent problems, since the wetting phase saturation is assumed to be 100 percent at the fluid/fluid contact and the capillary pressure at this location is assumed to equal zero. Crossing zones invalid these assumptions.

Analysis of displacement front and fluid/fluid contact. After reaching the core inlet entry pressure, the displacement front will successively penetrate the core with increasing speeds of rotation. Eq. 5 and Fig. 1 gives the following relationship between core entry pressure and position of the displacement front at a given speed of rotation:

$$P_d = \frac{1}{2}\Delta\rho\omega^2\left(r_2^2 - r_d^2\right) \tag{6}$$

Solving Eq. 6 with respect to the front position gives the following expression for the position of the displacement front as a function of core entry pressure, speed of rotation and position of the fluid/fluid contact:

$$r_d = \sqrt{r_2^2 - \frac{2\,P_d}{\Delta\rho\omega^2}} \tag{7}$$

Eq. 7 shows that r_d at a given speed of rotation is always less than r_2, although asymptotically close for high speeds of rotation. Crossing zones may, however, occur if the fluid contact, r_2, overflows a point in the core which earlier experienced penetration of the drainage front, r_d.

If no crossing zones occur during drainage, one would not expect such a problem to occur during imbibition, when the speed of rotation is reduced. The fall of the fluid/fluid contact could however theoretically create such a situation, if the decrease in fluid/fluid level is of greater importance to the capillary pressure than the reduction of speed.

The capillary pressure in the core at the location where P_C equals P_d at the last speed of drainage may be expressed as follows:

$$P_c^*(\omega, r_2) = \frac{1}{2}\Delta\rho\omega^2\left(r_2^2 - r^{*2}\right) \tag{8}$$

where r* is r_d at the last speed of drainage.

The change in P_C*, due respectively to the change in the speed of rotation and change in the fluid/fluid level, is given by the following partial derivatives:

$$\frac{\partial P_c^*}{\partial\omega} = \Delta\rho\omega\left(r_2^2 - r^{*2}\right) \tag{9}$$

$$\frac{\partial P_c^*}{\partial r_2} = \Delta\rho\omega^2 r_2 \tag{10}$$

The resulting change in capillary pressure at this location is given by superposition:

$$\Delta P_c^*(\Delta\omega, \Delta r_2) = \frac{\partial P_c^*}{\partial\omega}\Delta\omega + \frac{\partial P_c^*}{\partial r_2}\Delta r_2 \tag{11}$$

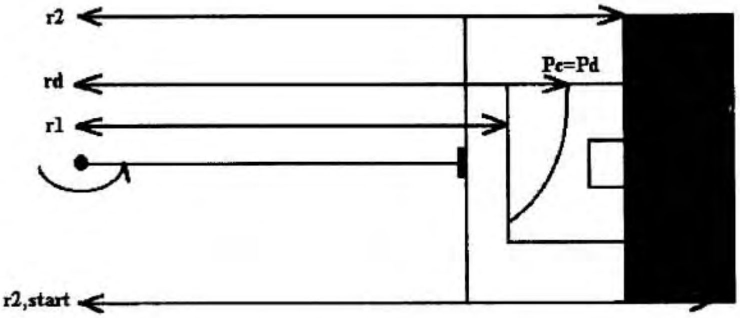

Figure 1: Drainage front and fluid/fluid contact during centrifuging

Eq. 11 with the substitution of Eq. 9 and 10 becomes;

$$\Delta P_c^*(\Delta\omega, \Delta r_2) = \Delta\rho\omega\left(r_2^2 - r^{*2}\right)\Delta\omega + \Delta\rho\omega^2\, r_2\, \Delta r_2 \tag{12}$$

If ΔP_C^* at any speed of imbibition turns positive, the drainage front penetrates further down the core, and the risk of obtaining crossing zones still exists. In this paper, Eqs. 7 and 12 are used to calculate the position of the transition zone, or zone of moving fluid/fluid contact, to assure that the zones do not cross without our knowledge.

Experimental

To test the experimental and calculation procedures several sets of cores were centrifuged to determine both the drainage and imbibition capillary pressures. Table 1 presents properties of the cores. The density difference between Exxsol D60 and brine is 235 kg/m^3. The centrifuged core plugs were of 2,5 cm diameter and 3,4 cm length. For registration of the fluid/fluid interface around the core plug, a slot of 0,36 cm width is cut approximately 2 cm into the core (Fig. 1). The centrifuge experiments were performed with an automated centrifuge and the overall accuracy of the volume measurements is 0,03 ml[10]. The core preparation and the porous plate experiments were performed with standard procedures and equipment.

Table 1 Rock properties

Core no.	Rock type	Absolute permeability 10^{-12} m^2	Porosity (%)
c2	Chalk	0.003	39,7
d1	Berea	0.450	24,4
d3	Berea	0.400	24,1
d4	Berea	0.420	24,4
d8	Berea	0.420	24,5
p2	Berea	0.530	23,8
p3	Berea	0.470	24,0

Results and discussion

Transition zone/crossing zones. Figure 2 shows the movement of the displacement front and the fluid/fluid contact during primary drainage of Berea sandstone and low permeability limestone. The figure shows that crossing zones did not occur during drainage of Berea sandstone or limestone. The limestone plot shows that low permeability and high entry pressure give a high security against crossing zones. The reason is of course, according to Eq. 7, that higher entry pressure for any speed of rotation gives a shorter distance of drainage front penetration.

Eq. 12 was used to check the position of the transition zone during the imbibition process. The change in capillary pressure at the last location of the drainage front proved to be negative with a good margin throughout the imbibition run. This indicates that the transition zone should not cause any problems during decreasing speeds of rotation.

Centrifuge and porous plate method. Fig. 3 shows relatively good consistency between twin core plugs, using centrifuge and porous plate method. Some differences exist however between the centrifuge- and porous plate curves at higher capillary pressures, and the reason for this discrepancy is not clear.

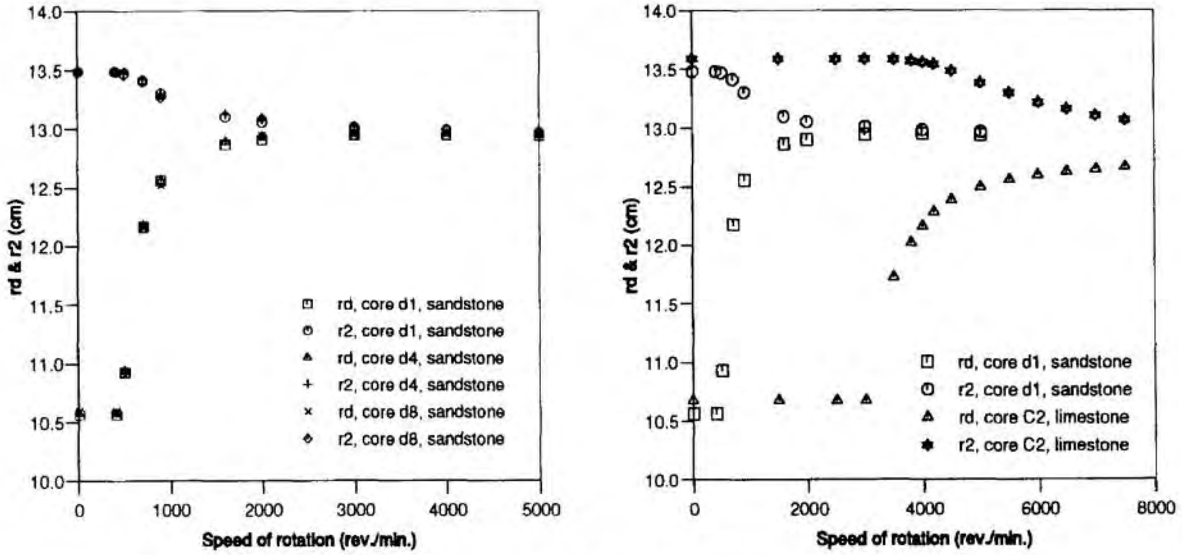

Figure 2: Movement of displacement front and fluid/fluid contact during primary drainage of Berea sandstone and low permeability limestone

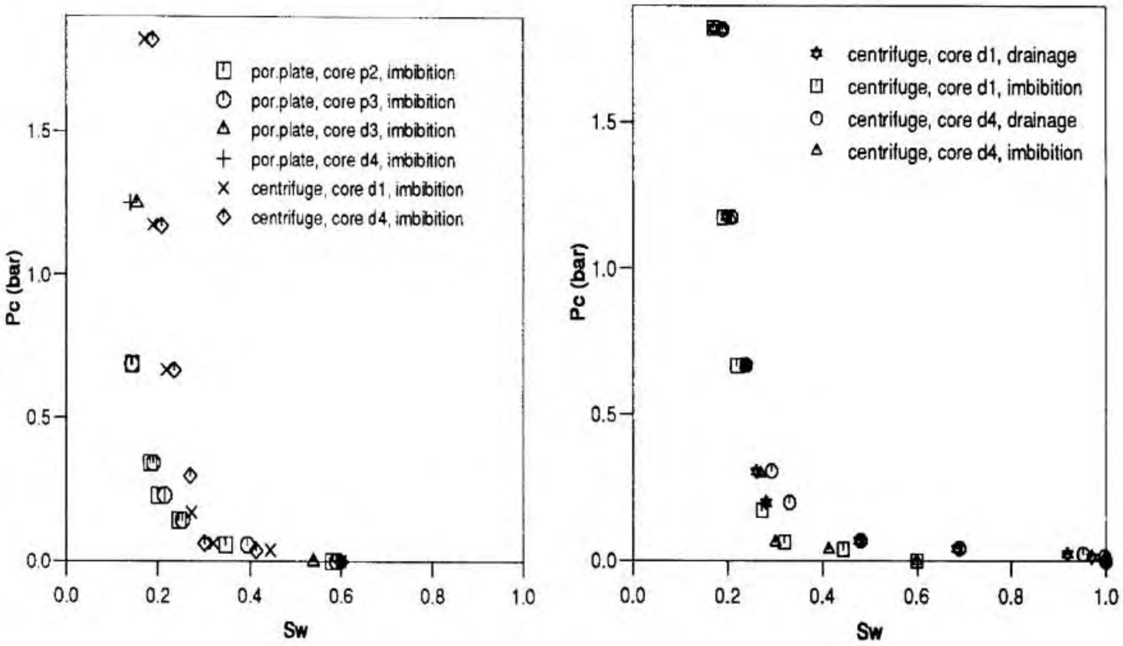

Figure 3: Capillary pressure curves for Berea sandstone, using centrifuge and porous plate method

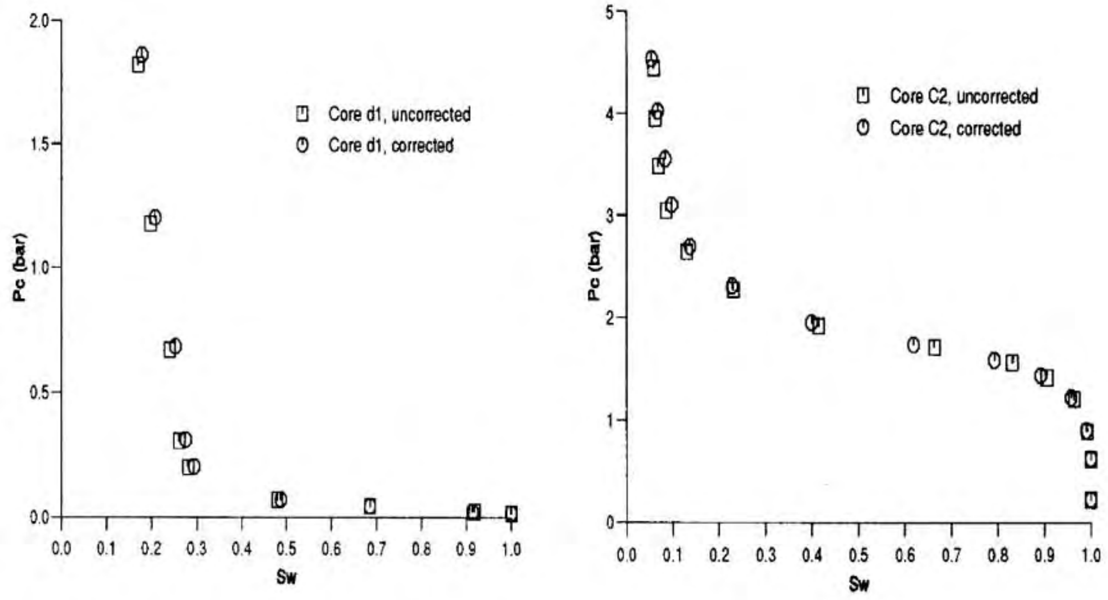

Figure 4: Effect of radial correction on moving fluid/fluid level capillary pressure curves.

Radial correction. The radial correction of centrifuge data proposed by Forbes et al.[11] is in this paper implemented for moving fluid/fluid levels. Fig. 4 shows the effect of this correction using sand- and limestone capillary pressure curves. The figure shows that this correction has a minor effect applied to the centrifuge- and core geometries used in this work. According to the methods of Forbes et al.[11], the radial effect decreases with increasing distance from center of rotation to core outlet. Taking into account the effect of moving fluid/fluid levels, the distance from rotation center to producing core outlet varies between 13.48 cm and 12.96 cm for our test fixture, which is 5 cm longer than the centrifuge geometry used by Forbes et al.[11]. The magnitude of the radial correction varies with varying fluid levels and has its largest values at high fluid/fluid levels, or short distances from rotation center to producing core outlet.

Conclusions

- A centrifuge method for obtaining positive imbibition and drainage capillary pressure curves is tested. The method involves changing boundary level during the drainage and imbibition process.
- The method gives both imbibition and drainage curves in a single centrifuge run. The method is easy and inexpensive.
- The assumption of 100% saturation at the bottom end of the core is valid in these experiments. All combinations of drainage and positive imbibition hysteresis curves can be determined.
- An automated centrifuge is not necessary but is very useful because the accuracy of the measurements is increased.

Nomenclature

f	r_1/r
P_c	capillary pressure (Pa)
P_c^*	capillary pressure at r^* (Pa)
P_{c1}	capillary pressure at core inlet (Pa)
P_d	core displacement pressure (Pa)
r^*	r_d at last speed of drainage (m)
r_1	distance from rotation center to core inlet (m)
r_2	distance from rotation center to core outlet (m)
r_d	distance from rotation center to the point in the core where $P_c=P_d$ (m)
S	wetting phase saturation
$\overline{S}$	average wetting phase saturation
$\Delta\rho$	density difference between wetting phase and nonwetting phase (kg/m^3)
ω	speed of rotation (s^{-1})

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