COMPARING DIFFERENT METHODS FOR CAPILLARY PRESSURE MEASUREMENTS

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Abstract
Capillary pressure for gas (air)-oil (C_{19}: Nona-Decane) fluid system has been measured for Berea cores by different methods. The methods/techniques used in our experiments for capillary pressure measurement are similar to the traditional centrifuge approach of Hassler-Brunner, free gravity drainage and freezing in-situ saturation measurement after centrifugation. In this paper we refer the last method as " saturation monitoring (SM) method ". In this method, we established a fluid saturation by centrifuging the core for 24 hours at a fixed rpm. Keeping the centrifuge running and simultaneously lowering the ambient temperature from 40^0C to 20^0C maintain the established fluid profile. Saturation measurements were made by gamma-adsorption. The drainage capillary pressure from this method is shown to be repeatable, and compares well to porous plate capillary pressure method. Analytical calculated capillary pressure from centrifuge is generally higher than measurement by saturation monitoring method, or porous plate.

Introduction
Fluid distribution in reservoirs is normally predicted by drainage capillary pressure (Pc)-saturation (S_w) function. This functional relationship is often obtained in the laboratory by Hassler-Brunner [1)] method. The main advantage by this method is that it is fast compared to other available methods. However this indirect method may produce a saturation error of 10% due to interpretation of the experimental data [2)]. The other methods such as porous-plate and gravity-drainage are by our evaluation more accurate, but are very time consuming.

Baldwin et al [3)] used a NMR image technique in order to determine saturation profile for the centrifuged core plugs directly. This method is quick and directly obtained saturation images at several sections of the cores provide a direct capillary pressure-saturation relationship if radial and gravity effects are neglected. Chen and Ruth [4)] showed that effect of gravity is negligible if the centrifuge is run at or above 500 rpm. Therefore, Baldwin et al approach may be used satisfactorily to estimate Pc-Sw if centrifuge experiment is run above the critical rpm.

However, radial effect will be increasingly prominent all along the core sample if the experiment is conducted at increasing rpm. Baldwin et al did not take any attempt to dampen the radial effect. In this manuscript, we apply a similar method of Baldwin et al, referred here as saturation monitoring (SM) method, however we take into account the radial effect and compare results with other capillary pressure measurements. In order to negate the radial effect, we calculate average Pc over the thin cross-section (1mm) where saturation is measured directly. The measured saturation essentially represents the average saturation over the thin cross-section, therefore, correlating average Pc with measured in situ saturation, we eliminate the radial effect.

In this paper we present drainage capillary pressure data obtained by various methods in our laboratory and compare them with the published data [3,5,6,7,8]. The main objective of this study is to see the effect of various methods on capillary pressure-saturation function. In our experiments, drainage capillary pressure-saturation relationship was determined by free gravity-drainage, Hassler-Brunner iterative method (without any correction) and SM method, however instead of NMR, we used a γ-ray scanner (source: ^{241}Am ; half life: 433 years)

Methodology used for direct method

The Hassler-Brunner type centrifuge method and free gravity-drainage will not be described here due to page limitation. However, other than these two methods, we used SM method for obtaining capillary pressure-saturation function. The SM method used in this experiment consist of following steps: 1) Cores are first cleaned by a mixture (50% toluene/50% methanol) in a Dean-Stark extractor and dried in a vacuum drier for 24 hours. 2) The dried cores were wrapped by heat-shrinking sleeve allowing only the end faces remain open. 3) The sleeved cores are then scanned which is designated as dry-scan of the sample. 4) Installing a back-pressure regulator [20 bar], the sample is then saturated by C_{19}. After the cease of air bubble production from the sample, it was allowed to cool down from 40^0C to room temperature. The pump pressure was maintained during the cooling time so that any void due to shrinking (2%) effect of C_{19} could be filled in by additional liquid drawn from the pump. 5) The saturated sample was scanned and designated as saturated-scan. 6) The sample was then centrifuged at a fixed speed (500/2000-rpm) under an ambient temperature of 40^0C in an ultra centrifuge (Beckman L8-55/P). Reference capillary pressure was obtained by maintaining a gas-oil contact (GOC) about 3~5 mm from the bottom of the sample. A large diameter cup was intentionally selected so that movement of initial GOC as a result of de-saturation could be arrested significantly. This allows capillary pressure hysteresis effect minimized between initial and final GOC. At the final GOC, capillary pressure was assumed to be zero at the periphery of the sample. 7) The centrifuged core is then cooled to room temperature to lock the saturation profile. The sample is then scanned and is designated as two-phase-scan. γ-ray detection efficiency for a single scan was optimized to 20 minutes by trial and error. High saturation resolution was obtained by scanning every "mm" along the axis of the samples. Average fluid saturation and average capillary pressure are then calculated from equation (1)&(2)

$$\langle S_W \rangle = \frac{\ln D - \ln T}{\ln D - \ln S} \cdots (1)$$

Where, D,T,S and S_w refer dry, two-phase, saturated scan and wetting fluid saturation.

$$\langle P_C \rangle = \frac{1}{2}(\Delta r w^2)(r_2^2 - r_1^2 + \frac{3}{4}R^2) \cdots (2)$$

Where, Pc, $\Delta\rho$, ω, R, r_1 and r_2 refers as Capillary pressure, density difference between wetting and non-wetting fluid, angular velocity of the centrifuge, sample radius, distance between inner face and rotational axis and distance between final GOC and the rotational axis of the centrifuge.

Results and Discussions

Physical properties of the five Berea cores (B1, B2, B3, B9 and B12) whose capillary pressure-saturation function (Pc-Sw) determined by different methods are given in Table-1. Hassler-Brunner type experiment (Centrifuge Model: Beckman J-6B) was conducted to the samples B1, B2 and B3 (r_1=10.96cm; r_2=17.4cm) while SM method was applied to all the five samples. After finishing the Hassler-Brunner type experiment, sample B1, B2 and B3 were drilled again to reduce the diameter from 3.8cm to 2.54cm so that samples pore volume reduced significantly. This ensures minimum movement of initial GOC in SM method. In SM method, value of r_2 depends on final GOC and maximum r_2 (12.39cm). Once r_2 being calculated r_1 can be readily calculated, although it has no special significance for SM method.

Figure-1 shows all the five drainage Pc curves determined by SM method scaled to a common basis (200mD permeability and 18.5% porosity) assuming a single J $(S_w)= (Pc/\sigma)\ (k/(\phi)^{1/2}$ function. Each curve in Figure-1 consists of two parts: 500-rpm part and 2000 rpm part. 500-rpm-centrifuge run was primarily designed to determine the entry pressure while 2000-rpm run was conducted for the extension of Pc at least to 100 Kpa. An analytical function of the form $Pc(S_w) = C_1+C_2/(S_w-S_{wor})^{n}{}_{1} - C_3/(1-S_w)^{n}{}_{2}$ was fit to the data sets with the following Parameters : C_1=2.35, C_2=0.6, C_3= 0.004, n_1=1.9, n_2= 1.25, S_{wor}=0.07 . The data sets are also fitted to a Leverett J-function $J(S_w)=a*(Sw\ \%)^b$, giving constant a=1.51, and saturation power exponent of b= -1.65.

Berea drainage Pc-Sw data from literature [3,5,6,7,8)] mostly direct (Free gravity drainage and NMRI and Porous plate was compared with our best fit analytical function in Figure-2. The properties of the various core plugs used in Figure-2 are shown in Table-2. All the drainage Pc data from the literature was scaled to 16 mN/m interfacial tension (IFT), 200mD permeability and 18.5% porosity so that they dimensionally represents our fluid and rock system. The Pc (analytical) function seems to be in good agreement with the published data.

In Figure-3, we present our laboratory measured Berea Pc drainage data for plug number B1 ,B2 and B3 obtained by Hassler-Brunner type approach. For each plug, three sets of Pc drainage data consisting of different interpretation procedures are presented. Rajan's[8], Hassler-Brunner iterative method (H-B) and solution with radial effects proposed by Forbes et al.[10] (F-R) were chosen arbitrarily (among many that were tried) as an interpretation procedure to see the effect of different approach. The best fit analytical Pc function obtained earlier by γ-ray for plug number B1,B2, B3,B9 and B12 was also drawn in the same figure to compare different methods. The Pc drainage data obtained analytical calculations are in poor agreement with the average data from the capillary pressure function.

Figure-4 shows drainage Pc-Sw for plug number B1, B2 and B3 obtained by SM method and Hassler-Brunner type approach interpreted by considering radial effects[10]. Analytical calculated solution (Pc-Sw) found to be higher for each plug than that of the SM method.

Conclusions

The drainage capillary pressure from freezing and measuring in-situ saturation in a centrifuge gravity field is shown to be repeatable, and compares well to porous plate capillary pressure.

Analytical calculated capillary pressure from centrifuge is generally higher than measurement by SM method, or porous plate.

References

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Table-1: Physical properties for core plugs used for drainage Pc experiments by γ-adsorption and Hassler-Brunner approach

Core ID	Length (cm)	Diameter (cm)	Porosity (%)	Permeability (md)
B1	6.44	3.8/2.54	21.8	319
B2	6.44	3.8/2.54	22.3	382
B3	6.44	3.8/2.54	21.7	317
B9	4.69	2.52	18.5	197
B12	6.05	2.5	18.5	190

Table-2: Physical properties for core plugs used in Figure-2 obtained from literature.

Core ID	Len. (cm)	Dia (cm)	Poro (%)	Perm. (md)	System	IFT (mN/m)
FGD: Free Gravity Drainage[6)]	91.5	5.03	22.6	780	Air-Water	32
S-B: NMR[5)]	4.78	2.52	20.0	612	C_{18}-Water	50
B-Y: NMR[3)]	4.97	2.52	20.1	612	Air-water	70
H-S1: Porous-Diaphragm[7)]	-	-	21.0	609	Air-water	70
H-S2: Porous-Diaphragm[7)]	-	-	19.4	217	Air-water	70
D-M: Porous plate [8)]	-	3.8	20	350	Oil-Water	40

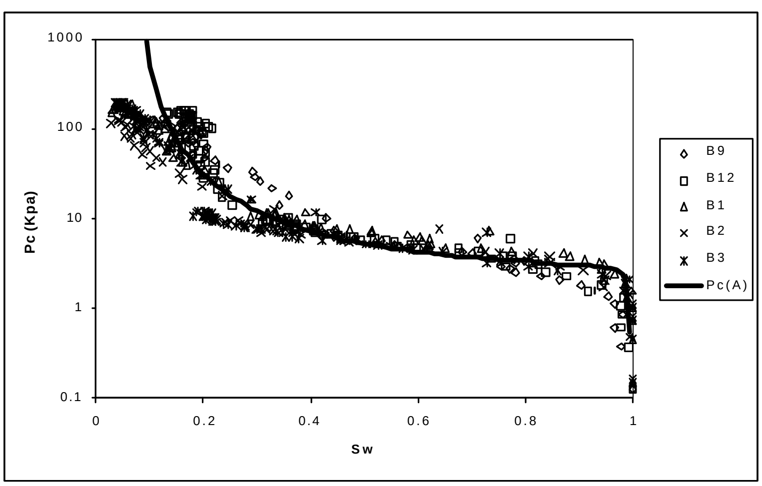

Figure-1: Drainage Pc- Sw (Berea) directly measured by γ-ray fit to an analytical function

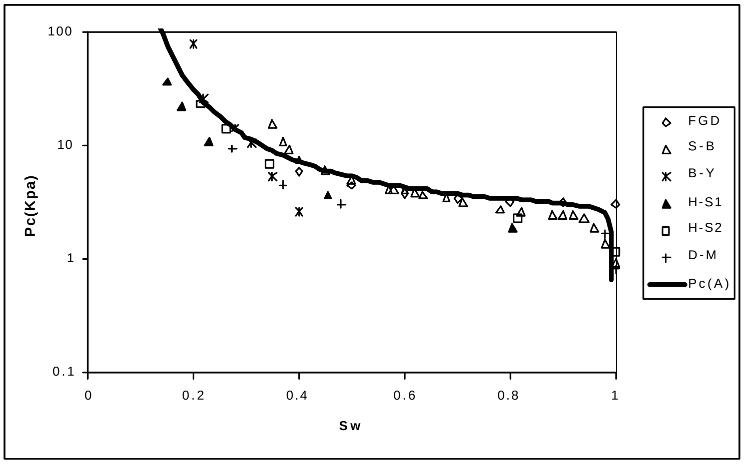

Figure-2: Drainage Pc-Sw (Berea) obtained from literature compared with analytical Pc

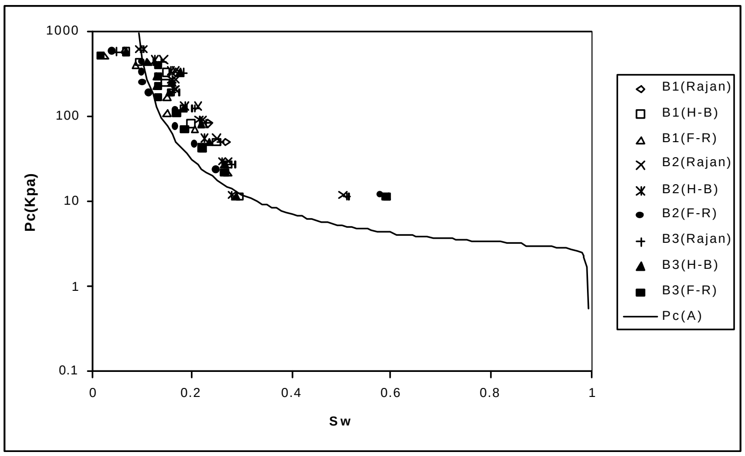

Figure-3: Analytical Pc-Sw (Berea) compared with Hassler-Brunner type approach

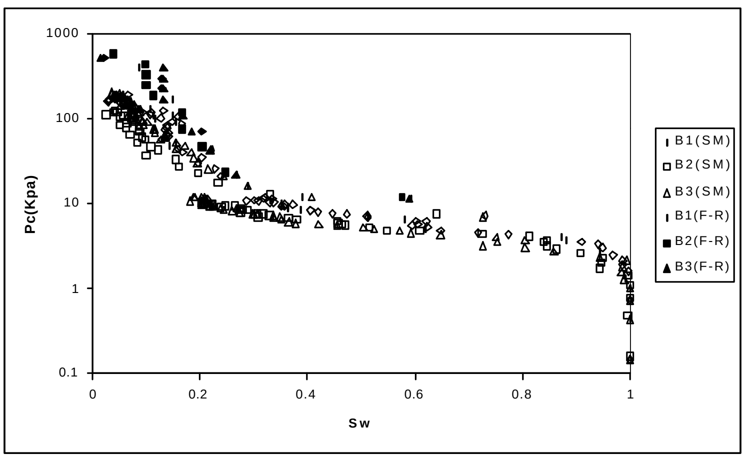

Figure-4: Drainage Pc-Sw (Berea) obtained by SM method compared with analytical calculated solution with radial effects.