A VALID APPROACH TO CORRECT CAPILLARY PRESSURE CURVES- A CASE STUDY OF BEREA AND TIGHT GAS SANDS

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ABSTRACT
Capillary pressure data have been used over the years to estimate important petrophysical parameters that are being employed to predict hydrocarbon reserves. However, little or no attention is given to the accuracy of the capillary pressure curves obtained from the mercury injection technique. Primary drainage capillary pressure data are crucial to determining the percentage of water saturation, irreducible water saturation above the original oil-water contact or gas-water contact, thickness of the transition zone, and the hydrocarbon-in-place, Honarpour *et al*. [1]. A laboratory study was carried out to evaluate the importance of applying corrections to the capillary pressure data from mercury injection method. This paper evaluates the effects of blank and modified blank corrections on the capillary pressure curves from tight gas and Berea core samples. The tight gas samples are from the East Texas and North Louisiana formations. The capillary pressure curves were measured by means of high-pressure mercury injection (HPMI), using an Autopore IV instrument, which measures up to 60,000 *psia*.

Blank correction was applied to the curves developed from the samples. In order to incorporate the compressibility of the core samples, a modified blank correction approach was developed and applied, and the differences of the two corrections were studied. Six core samples, comprising three Berea and three tight gas sands, were analyzed. This study suggests that the effect of both correction methods is minimal on tight gas samples, but significant on Berea samples. The modified blank correction method gives more accurate corrections to capillary pressure curves obtained from high porous rocks like Berea, and hence more accurate estimates of water saturation and resource-in-place, because it incorporates the compressibility of reservoir rocks.

INTRODUCTION
The Berea samples are well consolidated with porosities of about 22%. Unlike the Berea sands, tight gas sands are characterized by small pore throat sizes, high capillary pressures, low porosity, low permeability, and high connate wetting phase saturation. The porosity of the tight gas samples used in this study ranges between 5-7%. Wells *et al*. [2] wrote in their paper that tight gas sands account for a significant percentage of the US natural gas resource base and offer huge potential for future gas production. Newsham *et al*. [3] quoted the Gas Technology Institute (GTI) to have estimated production from tight gas to be about 70% of all unconventional gas resources. The study also attributed 11% of the total gas production from both conventional and unconventional sources to tight gas sands. GTI estimated total producible tight gas resources as 600 *TCF*, out of which 185 *TCF* are economically recoverable.

High pressure mercury injection offers a rapid method of developing capillary pressure curves to very high pressure. Webb [4] stated that HPMI is capable of measuring up to 60,000 *psia*, covering the entire range of water saturation for both tight gas and highly porous rocks like Berea sandstone.

This paper evaluates two methods of correcting apparent injectivity for system and mercury composition effects.

FUNDAMENTAL CONCEPT OF CAPILLARY PRESSURE WITH HIGH-PRESSURE MERCURY INJECTION

Melrose *et al.* [5] suggests that mercury injection capillary pressure experiments assume air to be the wetting phase within a porous medium while mercury is the non-wetting phase. In order words, air represents formation water (wetting fluid) while mercury represents hydrocarbon (non-wetting fluid) in porous media. A wetting fluid is retained within a porous medium both by the surface forces holding the fluid as a film completely covering the rock surfaces and by capillary forces separating the liquid and vapor phases. The capillary pressure can be calculated using the Young-Laplace equation:

$$P_c = \frac{2\sigma \cos\theta}{r} \tag{1}$$

Where, P_c is the capillary pressure, σ is the interfacial tension between the two fluid phases, θ is the contact angle and r is the pore throat radius. Equation 1 indicates the inverse relationship between capillary pressure and pore throat size. The capillary pressure disappears as the interfacial tension approaches zero.

THEORY OF MODIFIED BLANK CORRECTION

According to Abrams *et al*. [6], the blank correction does not take into account the compressibility of the rock sample used for analysis. In other words, blank correction assumes that the rock sample used in the experiment does not get compressed. This is not true, as rocks generally get compressed at high pressure. An approach was then developed to account for the compressibility of mercury, grease oil (which transmits pressure to mercury), penetrometer, and rock sample used in the experiment. This compressibility is referred to as the “effective compressibility.” Both the Berea and tight gas samples are rich in quartz. As a result, a non-porous quartz sample was used in the correction runs to account for the compressibility of test samples.

The penetrometer, filled with quartz grains, was loaded into the low-pressure chamber of an Autopore IV to fill the remaining space in the penetrometer with mercury. The total assembly (penetrometer, quartz grains, and mercury) was then transferred to the high-pressure chamber. Mercury does not enter into the quartz matrix because it has no pore spaces. Any recorded intrusion is due to effective compressibility of the total system. The Autopore IV was set on correction mode “none” and data were reported as “without correction”. This was normalized for the weight of the quartz grains used in the experiment. There must be, at least, three such runs with different bulk volumes of non-porous quartz matrix to allow for linear extrapolation to any bulk volume of test sample. These runs must be performed with the same penetrometer and instrument port as would be used for the test sample. A plot of normalized incremental intrusions versus bulk volumes for each pressure point of the runs was developed and a linear equation obtained from the line of best fit for each of these pressure steps. Figures 1 and 2 show two of the plots.

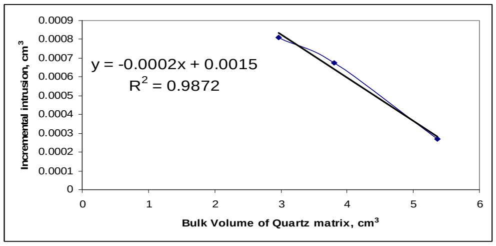

Figure 1: Shows an equation to determine the amount of intrusion for any sample bulk volume at pressure of 14121.5 psia

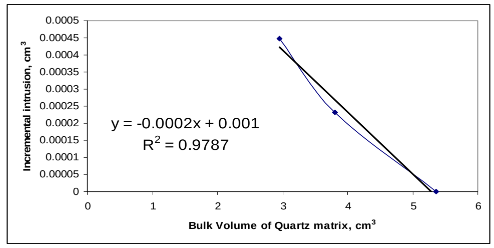

Figure 2: Shows an equation to determine the amount of intrusion for any sample bulk volume at pressure of 59552.9 psia

The linear equation obtained is in the form of:

$$y_i = mx_j + c \tag{2}$$

where
y = incremental intrusion at any pressure point, i, cm^3
m = slope of the line of best fit,
x = sample bulk volume, j, cm^3
c = intercept along the y- axis

An experimental run was then performed on the test sample using the same penetrometer without applying any correction, that is, the Autopore was set to the correction mode of "none." The incremental intrusion was reported as *ml/g*. This was multiplied by the weight of test sample in order to obtain the volume of mercury intrusion. In order to apply the modified blank correction, which corrects for effective compressibility of the total system, the intrusion data obtained from the developed equation for each pressure point (after substituting for the value of bulk volume of the test sample) was subtracted from the uncorrected intrusion obtained from the run made with the test sample at that pressure point. By this subtraction, data obtained from the run made with the test sample is said to have undergone modified blank correction and the capillary curve developed from this corrected data is referred to as a modified capillary pressure curve. The procedures above were strictly followed for all the experimental runs, and modified capillary pressure curves were developed for both the Berea and tight gas sands.

DATA ANALYSES, DISCUSSIONS, AND RESULTS

Analyses of the test results were carried out. Figures 3, 4, and 5 present the capillary pressure curves for tight gas sands of varying weights. The purpose of presenting the three figures is to establish the validity of the correction method by establishing the repeatability of the method for any sample volume. There are no significant differences in the three capillary curves for each of the test runs for tight gas samples. As seen in Figure 3, small variations in the curves occur between 17,000-27,000 *psia*. These variations result from the corrections. At pressure above 27,000 *psia*, there seemed to be no difference in the three curves for each test sample. This shows that the system's compressibility has no impact in developing capillary pressure curve for tight gas sands at high pressure. The implication is that, making correction (either blank or modified blank) in tight gas samples does not significantly change the shape of the capillary curves. In other words, compressibility of test sample, mercury, greasing oil, and penetrometer has negligible effect on the capillary pressure curve for tight gas sands. Hence, the percentage of water saturation and the resource-in-place can be estimated without necessarily correcting for system expansion and compression. For tight gas sands, the displacement pressure is very high (about 10,000 *psia*), indicating relatively small pore throat size. The pore throat radius for our test samples was between 0.0015 and 18.0997 μm.

Figures 6, 7, and 8 show the capillary pressure curves developed for Berea samples. Just as in the tight gas samples, the three figures establish a trend, which show the developed method is valid for any sample volume. Berea samples are generally more porous, unlike tight gas samples, and they compress very much easier than tight gas samples with increase in pressure. The effect of the corrections is very obvious, and is of great importance to make corrections for total system compressibility when developing true capillary pressure curves in high porosity reservoir rocks. The estimated water saturation is lower than when correction was not applied and the reduction increases with increase in pressure to about 10,000 *psia*. Also, it was noted that the application of the two correction methods results in different capillary curves. The estimated water saturation at a particular pressure point is less with blank correction method than with the modified blank correction method. This is not surprising because a higher volume of mercury requires greater correction because most of the compressibility effect comes from mercury. The modified blank correction contains less volume of mercury. Blank correction assumes that the reservoir rock does not compress with increase in pressure. The modified correction method presents a more accurate capillary curve because it takes into account the compressibility of rock samples. At pressures about 12,000 *psia*, the two corrections give the same result. There is practically no intrusion at pressures above 12,000 *psia*. What is observed is the compressibility of the total system. Above this pressure point, the Berea sample accounts for most of the compressibility effect. The displacement pressure for the Berea sample is about 6 *psia*, indicating large pore throat radii. It is worth emphasizing that, for any formation with high porosity and permeability, it is important to apply corrections to the capillary curve in order to obtain more accurate estimates of water saturation and resource-in-place. The modified blank correction presents an improvement over the blank correction method.

CONCLUSIONS

1. It is not necessary to make corrections to the capillary curve obtained from tight gas formation. Any correction applied to it does not have a significant effect on the estimation of water saturation and hydrocarbon-in-place.

2. It is important to apply corrections to the capillary curves obtained from Berea sands. The corrections will lower the water saturations as compared to the curve generated without applying corrections. The reduction in water saturation increases with increase in capillary pressure.

3. The modified blank correction method gives more accurate capillary curves and hence more accurate estimates of water saturations and resource-in-place, because it incorporates the compressibility of reservoir rocks.

NOMENCLATURE

P_c = Capillary pressure, *dynes/cm*^{2}
σ = interfacial tension between fluid phases, *dynes/cm*
θ = contact angle, *degrees*
r = pore throat radius, *cm*
HPMI = High Pressure Mercury Injection

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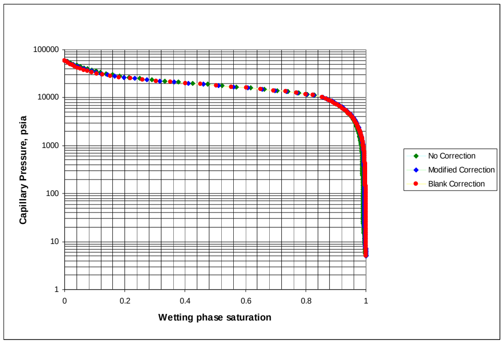

Figure 3: Shows the capillary pressure curves for 1.71 cm^3 bulk volume of a tight gas sample

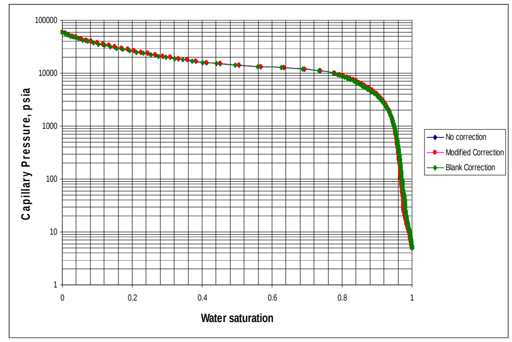

Figure 4: Shows the capillary pressure curves for 2.97 cm^3 bulk volume of a tight gas sample

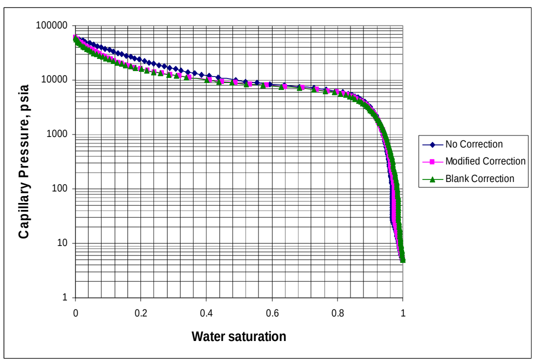

Figure 5: Shows the capillary pressure curves for 3.67 cm^3 bulk volume of a tight gas sample

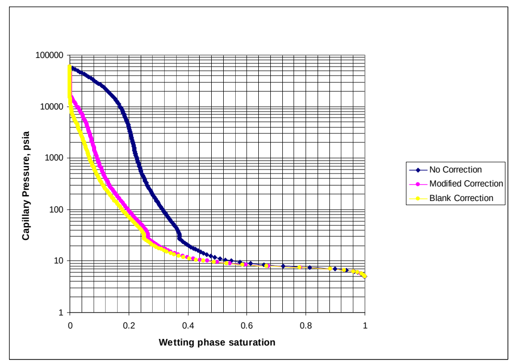

Figure 6: Shows the capillary pressure curves for 0.61 cm^3 bulk volume of a Berea sample

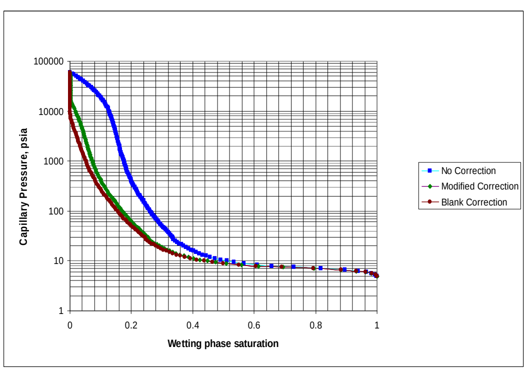

Figure 7: Shows the capillary pressure curves for 0.81 cm^3 bulk volume of a Berea sample

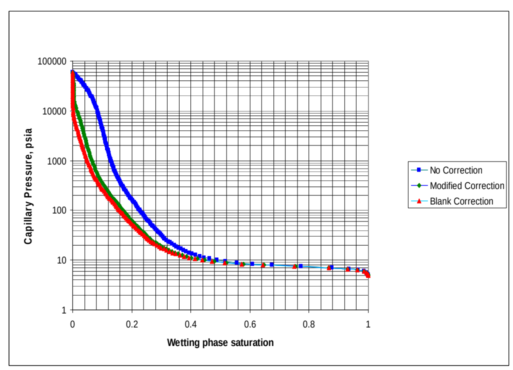

Figure 8: Shows the capillary pressure curves for 1.25 cm^3 bulk volume of a Berea sample