SCA-9810

CENTRIFUGE FORWARD MODELLING: THE KEY TO IMPROVED CAPILLARY PRESSURE DETERMINATION

Simon Clinch

Abstract

The Society of Core Analysts recently conducted a survey on techniques used for evaluating centrifuge capillary pressure data. Results of this survey show that there are some good techniques for evaluating centrifuge capillary pressure, but there is still room for developing new and improved techniques. The centrifuge forward modelling technique is a new method where by the production data is simulated from an estimated capillary pressure curve for the particular geometry of the centrifuge experiment. This estimated capillary pressure curve can then be modified until simulated production data matches measured production data. This technique does not require the use of curve fitting or smoothing of production data, similarly differentiation is not required in the solution process. As such the centrifuge forward modelling technique is ideally suited to noisy centrifuge data. The real advantage of the centrifuge forward modelling technique is that radial effects are accounted for intrinsically in the solution, gravitational effects can also be accounted for when required. An analysis of data presented in the Society of Core Analysts centrifuge capillary pressure survey shows that at least 75% of the evaluated capillary pressure curve falls within errors of measurement, and 85% of the evaluated capillary pressure curve falls within 3 saturation units of the true solution. The outflow boundary condition can fail in some centrifuge experiments; when this occurs it is possible to determine the capillary pressure curve using the centrifuge forward modelling technique. Failure of the outflow boundary condition appears to be one reason why many centrifuge capillary pressure experiments do not match porous plate experiments. If core plugs resistivities are measured whilst centrifuging it is possible to invert this data concurrently with the forward modelled solution to produce resistivity index data.

Introduction

The forward modelling technique was originally implemented to ensure that curve fitting or smoothing of data used in the interpretation obeyed the measured data, and did not introduce extra noise into the solution. It was quickly realised that the centrifuge forward modelling technique was much more useful than just to check data. By obeying all the physics associated with centrifuge capillary pressure experiments, such as radial and geometrical effects a robust and accurate method for evaluating centrifuge capillary pressure data was developed.

The literature cites many cases where centrifuge and porous plate capillary pressure data generated on the same core samples show significant discrepancies (Williams, 1996). Some of these centrifuge experiments produced much better agreement after it was realised that the outflow boundary condition had failed, making it impossible for traditional evaluation techniques to invert the data correctly. The centrifuge modelling technique has no trouble evaluating experiments where the outflow boundary condition is not met.

Method

Through knowledge of the centrifuge geometry in conjunction with an estimated capillary pressure curve it is possible to generate an average fluid saturation at every rotational speed used in the experiment. By comparing the modelled average water saturation with the measured average water saturation a measure of how good the estimated capillary pressure curve is generated. This estimated capillary pressure curve can then be modified to improve the fit between the modelled and measured average water saturation at every rotational speed. When the modelled average water saturation fits all measured average water saturation within experimental errors the estimated capillary pressure curve is deemed to be good (figure 3).

Given any centrifuge geometry (figure 1) the forces that act on the fluids inside the porous media are governed by the following equations. Radial force in the ith slice are given by;

$$Pc_r = \tfrac{1}{2}\Delta\rho\omega^2\left[\left(r_4 + x_{Po}\right)^2 - \left(\frac{r_i + r_{i+1}}{2}\right)^2\right]$$

The cos(θ) terms have been dropped in this equation because θ is usually small and hence cos(θ) is approximately 1.

Gravitational force in the jth layer are given by;

$$Pc_g = \Delta\rho g\left[\left(\frac{h_j + h_{j+1}}{2}\right) + x_{Po}\sin(\theta)\right]$$

Combined capillary pressure is then given by;

$$Pc = \sqrt{Pc_r^{\,2} + Pc_g^{\,2}}$$

The porous media is divided up into many elements. For each element the bulk and pore volumes are calculated. At each rotational speed the total capillary pressure on each element is determined as is the water volume. The average water saturation of the porous media is then determined, this process is repeated for every rotational speed used in the experiment. When choosing the number of increments in the radial direction it is recommended that a minimum of 50 increments are used or at least one for every millimetre in length of the core plug. The gravitational component is usually very small so ten increments usually suffice. In many cases the gravitational effects can be ignored with no noticeable errors introduced into the modelled data.

To define the estimated capillary pressure curve often only between ten and twenty points will be used. As such the estimated capillary pressure curve needs to be interpolated between data points. This can be achieved using either linear interpolation or cubic spline fitting (figure 2). Linear interpolation is the simplest method but is poor when the rate of change in slope is large, it is for this reason that more data points are concentrated in these regions. Cubic spline methods are superior in most cases although care needs to be taken to avoid unrealistic capillary pressure curve shapes. All work presented in this paper used linear interpolation, as it was found to be very difficult to control spline functions in all cases.

When the centrifuge forward modelling technique is applied radial effects are corrected for intrinsically in the centrifuge interpretation process. Thus no post processing of the centrifuge forward modelling data is required to account for radial effects, this is required with many other evaluation techniques.

The forward modelling technique is more flexible than the parameter estimation technique (Bentsen, 1977) because the estimated capillary pressure curve does not need to fit any specific equation functional form. It is also very similar to the method presented by Nordtvedt (1991) but has been simplified by replacing the integration process with a finite difference approach.

Results

All synthetic samples came from the SCA centrifuge data survey. Interpretations of these samples show that more than 75% of data points fall within the error bars of measurement (Table 1) and more than 85% of data points fall within three saturation units of the correct solution (Table 2). Measurement errors of centrifuge experiments should be minimised so that evaluated capillary pressure curves can be evaluated more reliably. Tables 1 and 2 present data in the same format as the paper by Forbes (1997), with table 2 containing data that is consistent with Forbes (1997, figure 11).

Table 1 -   Evaluated data points within measurement error

Sample	**Within**	**Upper**	**Lower**
1	9	1	5
2	11	1	3
3	10	0	5
4	12	0	3
5	7	0	2
6	11	1	4
7	20	0	0
8	13	0	3
9	21	0	0
10	21	1	3
Totals (%)	80.8	2.4	16.8

Table 2 - Evaluated data points within three saturation units

Sample	Within	Upper	Lower
1	13	0	2
2	14	0	1
3	15	0	0
4	14	0	1
5	8	0	1
6	11	1	4
7	20	0	0
8	13	0	3
9	21	0	0
10	22	1	2
Totals (%)	90.4	1.2	8.4

In the previous two tables; "within" is defined as within the prescribed error limits, "lower" means below the lowest error bar limit and "upper" means above the highest error bar limit. The number of data points is actually the number of points used to define the capillary pressure curve, not the number of experimental data points. Tables 1 and 2 show that significantly more data points fall into the lower category than the upper category. This is caused by; using a linear interpolation between data points, not concentrating enough estimated capillary pressure points in the high curvature regions of the curve, it is also a function of the capillary pressure curve shape itself.

Uses of this Technique

Boundary Condition Failure

If centrifuge experiments are conducted poorly the outflow boundary condition may not be satisfied, this can occur when the support disk becomes partially wetted by the displaced phase (O'Meara et al., 1992). When the boundary condition fails the zero capillary pressure boundary is not located at the outflow face of the porous media, and conventional interpretation techniques can not correctly invert the measured data. This is not the case with the centrifuge forward modelling technique, providing the problem is identified. Using the centrifuge forward modelling technique old experiments can be reinterpreted where the support disk had become preferentially wetted by the displaced phase to produce more reliable capillary pressure curves. This is achieved by estimating the distance to Pc = 0, it is usually the thickness of the support disk.

Boundary condition failure may be a common problem with some service companies running centrifuge capillary pressure, and may be one of the major sources of discrepancies between centrifuge and porous plate capillary pressure measurements (Williams, 1996). Traditional techniques will produce a capillary pressure curve shifted towards a lower displaced phase saturation than the true capillary pressure curve (example 3, figure 6).

Radially Dominated Experiments

Traditional interpretation techniques need to be post processed to account for the radial effects when they become significant (Fleury, 1995). The centrifuge forward modelling technique does not suffer from this problem as radial effects are accounted for intrinsically in the modelling process (example 2) and as such post processing of results for radial effects must not be conducted. Correcting for radial effects during the inversion process should be better than post processing, providing they are accounted for correctly. It is therefore ideally suited to the evaluation of centrifuge experiments where radial effects are significant, *i.e.* ultra-centrifuge experiments.

Smoothing of Noisy Data

When a centrifuge experiment has been run poorly the produced fluid versus rotational speed data may be very noisy. All interpretation techniques will therefore require the production data to be smoothed or curve fitted prior to interpretation. This approach is the correct one to take, but after the capillary pressure curve has been evaluated the production data needs to be simulated to check the smoothing or curve fitting. The centrifuge forward modelling technique has a significant advantage because no smoothing or curve fitting is required, and production data is simulated to ensure the estimated capillary pressure curve is a reliable one.

Examples

Example 1 is a synthetic capillary pressure curve where radial effects are minimal (SCA centrifuge survey, sample 5). The evaluated capillary pressure curve and the upper and lower bounds of the true solution are shown in figure 4. Most of the evaluated curve falls within the error bars of "measurement", indicating the good quality of the forward modelled solution.

Example 2 is a synthetic capillary pressure curve with significant radial effects (SCA centrifuge survey, sample 4). The interpreted data shows a bimodal pore distribution. The evaluated capillary pressure curve and upper and lower bounds of the true solution are shown (figure 5). Once again most of the evaluated curve falls within the error bars of "measurement", indicating the good quality of the forward modelled solution.

Example 3 is a real system, where both porous plate and centrifuge capillary pressure data were determined on the same core plug. A standard interpretation (using any inversion technique) of the centrifuge data did not match the porous plate data, assuming the boundary condition was satisfied. By moving the zero capillary pressure boundary to the outflow face of the support disk, and knowing the thickness of the support disk, a greatly improved correlation between centrifuge and porous plate data was established (figure 6).

Extensions of this Technique

When resistivity measurements are made on the core plug whilst centrifuging (Durand and Lenormand, 1997) it is possible to invert these measurements to produce a full resistivity index measurement. This is possible because at every rotational speed the centrifuge forward modelling technique produces a saturation versus length function.

By combining both resistivity and centrifuge capillary pressure measurements into one experiment it is possible to obtain results more quickly than traditional techniques. Givens (1992) showed that it was important to measure electrical resistivity on cores when the fluids are in capillary equilibrium.

Conclusions

The centrifuge forward modelling technique has five significant advantages over most other centrifuge capillary pressure reduction technique currently in use. They are;

- Boundary conditions do not need to be met, any condition can be forward modelled
- No approximations to the differentiation process are required
- Any centrifuge geometry can be used with this technique
- Radial effects are corrected for through the modelling process
- Gravity effects can be incorporated into the model when they become significant
- Numerical differentiation of the measured data is not required

To apply this method a dedicated computer program must be written to process the data.

When this method is applied correctly a minimum of 75% of the evaluated capillary pressure curve points fall within the errors of measurement. When measurement errors are small a minimum of 85% of the evaluated capillary pressure curve points are within three saturation units of the true solution.

As a full saturation distribution through the core is calculated at every rotational speed it is possible to invert resistivity measurements determined during the centrifuge experiment to produce resistivity index curves.

Nomenclature

D = diameter of porous media
g = gravitational acceleration
h = vertical height at the given centrifuge geometry
L = length of porous media
Pc = capillary pressure at any point in the porous media at any given rotational speed
Pc_g = gravitational component of capillary pressure
Pc_r = radial component of capillary pressure
r = radial location in the centrifuge (measured from the centre of rotation)
S = wetting phase saturation
$\overline{S}$ = average saturation
x_{Po} = distance from r_4 to the position at which $Pc_r = 0$

$\Delta\rho$ = fluid density difference
θ = angle subtended from the centrifuge cup to the horizontal plane
ω = rotational speed

subscripts
1 = inflow face shortest radius
2 = inflow face longest radius
3 = outflow face shortest radius
4 = outflow face longest radius
i = case i (radial location)
i-1 = case i-1 (radial location)
j = case j (vertical location)
j-1 = case j-1 (vertical location)

References

Bentsen, R.G., "Using Parameter Estimation Techniques to Convert Centrifuge Data Into Capillary Pressure Curves", *SPEJ*, 1977.

Durand C., Lenormand R., "Resistivity Measurements While Centrifuging", *SCA*, 1997.
Fleury M., Forbes P.L., "Experimental Evidence of Radial Effects on Centrifuge Capillary Pressure Curves", *SPWLA*, 1995.

Forbes P., "Centrifuge Data Analysis Techniques: An SCA Survey on the Calculation of Drainage Capillary Pressure Curves from Centrifuge Measurements", *SCA*, 1997.

Givens W.W., "A Method that Ensures the Measurement of Equilibrium Electrical and Capillary Properties of Rock Samples", *SPWLA*, 1992.

Nordtvedt J., Kolltveit K., "Capillary Pressure Curves from Centrifuge Data by use of Spline Functions.", *SPE Res Eng*, 1991, Nov, pp497-501.

O'Meara D.J., Hirasaki G.J., Rohan J.A., "Centrifuge Measurements of Capillary Pressure: Part 1 Outflow Boundary Condition", *SPE Res Eng*, 1992, Feb, pp133-142.

Williams N.V., "Some Practical Applications of Recent Core Analysis Advances", *SCA*, 1996.