Best paper award: first honorable mention

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THE CONSTANTLY-ACCELERATING CENTRIFUGE REVISITED

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Abstract

In 1963, Hoffman described the use of a constantly-accelerating centrifuge to determine capillary pressure. Unfortunately, the data reduction techniques available at the time prevented him from fully utilizing his results. It is obvious that a constantly-accelerating centrifuge offers a method to overcome the so-called blind-date problem of determining capillary pressures when using a centrifuge, that is, the problem that using a fixed speed schedule can lead to missed data over large saturation ranges of the curves, particularly near the threshold pressure. The present paper describes a simulation study of the displacement process that occurs during a constantly-accelerating centrifuge experiment; it considers the determination of both capillary pressure and relative permeability. Using Corey-type relative permeability curves and Bentsen-type capillary pressure curves, with parameters typical of water-wet rocks, synthetic production data sets are generated for a simulated primary drainage experiment. The sensitivity of the production history to small changes in the test parameters is then tested. It is shown that remarkably accurate curves can be obtained in relatively short periods of time. A correlation equation is developed to assist in the selection of an appropriate acceleration rate for a given set of experimental parameters. Finally, the method is compared with the single-speed and multi-speed methods, and is shown to offer advantages over both of these techniques.

Introduction

The use of the centrifuge to determine both capillary pressures and relative permeabilities has become very popular over the last decade. The advent of fast personal computers has allowed sophisticated data anaylsis methods to proliferate. However, the data analysis technique can give results only as good as the data that is inputted. Currently, there are two general methods of collecting data:

1. The Single-Speed Method: The speed of rotation of the centrifuge is set at a relatively high value and data is collected, typically until production of the displaced component ends. The results may be analysed by either the numerical simulation (parameter estimation) method or the Hagoort technique (1980) (these methods are described in Ruth 1997). The major drawback of the single speed method is that the capillary pressure curve may not be determined and the relative permeability curve for the injected component can only be determined for a very limited range of combinations of permeability (k) and viscosities of the two fluids (μ_i and μ_d).
2. The Multi-Speed Method: The speed of rotation of the centrifuge is set at a number of successively higher values; the speed is kept at each value for sufficient time to allow production of the displaced component to stop, that is, for equilibrium to obtain. The capillary pressure may be obtained by any of a large number of methods but the relative permeabilities must be found by using a parameter estimation technique. The major drawback of this method is that a speed schedule must be prespecified, that is, at each step the speed is adjusted to a preselected value. The experimenter can have only approximate knowledge

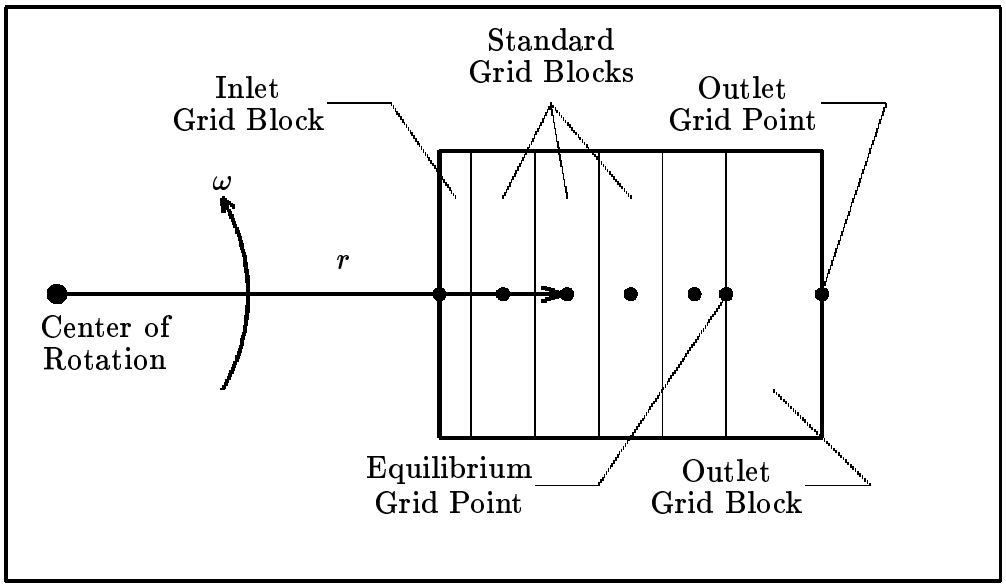

Figure 1 The Finite Difference Grid System

of what the final results will be; therefore, the selection of an optimal speed of rotation scedule is impractical. In extreme cases it is possible to perform an experiment and obtain useless data (for example, if the initial speed is too high, the sample can essentially desaturate at that first speed).

Hoffmann (1963) proposed the use of a constantly-accelerating centrifuge for use in obtaining capillary pressures. Instead of using a speed schedule, he proposed slowly accelerating the centrifuge through a wide range of speeds, while collecting data in a continuous manner. At the time of Hoffmann's work, data reduction techniques did not allow accurate interpretation of the data from such an experiment. At present these techniques are available. The present paper shows that the constantly-accelerating technique offers a fast and accurate method to determine both capillary pressure and at least some relative permeability characteristics of samples. The present work is based on a simulation study.

Formulation of the Simulation Model

The simulation model is essentially similar to the one described in Ruth (1997). The grid system is summarized in Figure 1. At equilibrium, after the flow has ceased at any rotational speed, the capillary pressure as a function of radius from the center of rotation is given by

$$P_c = \frac{\Delta\rho\,\omega^2}{2}\left(r_o^2 - r^2\right) , \qquad (1)$$

where r_o is the distance to the outlet face of the sample, $\Delta\rho$ is the difference in the densities of the two components, ω is the speed of rotation, and r_o is the distance from the center of rotation to the outside face (bottom) of the sample. In this system, the equilibrium grid point is the location determined by the threshold capillary pressure, P_{ct}. Setting $P_c = P_{ct}$ and solving Equation 1 for r (denoted now

as r_t, the radius to the "top" of the sample) results in the expression

$$r_t = \sqrt{r_o^2 - \frac{2\,P_{ct}}{\Delta\rho\,\omega^2}}\ . \tag{2}$$

For details of the formulation of the flow model, the reader is referred to Ruth (1997).

As in Ruth (1997), the present study considers relative permeability curves specified by Corey equations of the form

$$k_{dr} = k_{dre}\left(\frac{S_d - S_{dr}}{1 - S_{dr}}\right)^{n_d} \tag{3}$$

and

$$k_{ir} = k_{ire}\left(\frac{S_i}{1 - S_{dr}}\right)^{n_i}\ , \tag{4}$$

where the S's are the saturations, and the subscripts denote the following: d, the displaced component; i, the injected component; r (on k), relative; e, endpoint; and r (on S), residual. The capillary pressure is specified by a Bentsen curve

$$P_c = P_{ct} - P_{cp}\,ln\left(\frac{S_d - S_{dr}}{1 - S_{dr}}\right)\ , \tag{5}$$

where P_{ct} is the threshold pressure, and P_{cp} is a second capillary pressure parameter. Capillary pressure curves for which P_c changes significantly as saturation changes are characterized by high values of P_{cp}, while capillary pressure curves that are relatively flat are characterized by low values of P_{cp}.

Strictly speaking, the present study applies only to Corey-type relative permeabilities and Bentsen-type capillary pressures. These equations were used only as a convenience (a limited number of fitting parameters). The complex behaviours observed using these curves will almost certainly be observed regardless of the technique used to model the curves. However, the reader is cautioned that more complex models, such as multi-region spline, contain many more parameters and may show significantly different sensitivities in different saturation regions. The present study is meant to demonstrate the promise of the method, not to defend the use of any particular model. Further, the present model neglects radial and Earth-gravity effects. These effects will undoubtably influence the results; however, they are generally of secondary importance and therefore should not have a major impact on the final conclusions.

Test Parameter Specification

The present study uses a base-case system with the same parameters as those used by Ruth (1997). The parameters of this system are listed in Table 1. The speed of rotation schedule used in the present study consists of a period of uniform acceleration until a fixed final speed obtains (in all cases the final speed was 12000 rpm). Preliminary tests confirmed that the optimal number of grid blocks (N) and the optimal maximum change in saturation in a grid block during any time step ΔS were the same as those used by Ruth (1997) ($N = 40$ and $\Delta S = 0.001$)

Variable	Value	Units	Variable	Value	Units
ϕ	0.25	-	S_{dr}	0.20	-
k	100.0	md	S_{ir}	0.00	-
Length	5.08	cm	k_{dre}	0.25	-
Diameter	3.18	cm	k_{ire}	1.00	-
r_o	9.38	cm	n_d	2.00	-
ρ_d	1000.0	kg/m^3	n_i	2.00	-
ρ_i	850.0	kg/m^3	μ_d	1.00	cp
P_{ct}	1.00	kPa	μ_i	1.00	cp
P_{cp}	8.00	-			

Table 1 Sample and Fluid Properties

Choice of Acceleration Rate

Analysis of experimental data to determine relative permeability and capillary pressure curves involves a history-matching process using fitting parameters. In the context of the present study, these fitting parameters are the saturation exponents for the relative permeability curves and the values of P_{ct} and P_{cp} for the capillary pressure curve. Typically the values of k_{dre}, k_{ire}, and S_{dr} are not used for fitting purposes (they are determined independently, although there is no fundamental reason why they could not be included in the history-matching procedure). A preliminary study was conducted to determine how the accuracy of the fitting parameters varied as the acceleration rate was changed. The procedure for this study was to choose an acceleration rate and then generate a production history for a given set of parameters. The value of each fitting parameter was then varied and the root-mean-square difference in production was calculated. The change in the fitting parameter required to cause a root-mean-square difference equal to the assumed experimental error ($0.06\,cm^3$) was then determined. This process was repeated for a range of acceleration rates.

The results for the base-case are summarized in Figure 2. The errors (ϵ) in this plot are normalized with the values of their respective parameters, hence represent fractional errors. Rather than plot the value of the acceleration, the elapsed time (Δt) required to reach a speed of 12000 rpm has been used (this makes the results more intuitive). The acceleration is simply 12000 $rpm/\Delta t$.

The accuracy to which both n_d and P_{cp} may be determined is very good (less than 0.1) over a wide range of Δt. The error for n_d increases with increasing values of Δt, while the error for P_{cp} decreases with increasing values of Δt. On the other hand, the error for P_{ct} is large except at high values of Δt. The error for n_i has a minimum at a value of Δt not much different from the value at which the accuracies for n_d and P_{cp} are equal.

At very small values of Δt, there is a small departure from the described behaviours of n_d and n_i. This is due to the fact that at small values of Δt, the sample has not reached the residual saturation of the displaced component by the end of the acceleration period. If a plateau is added to the experiment, these anomalies disappear.

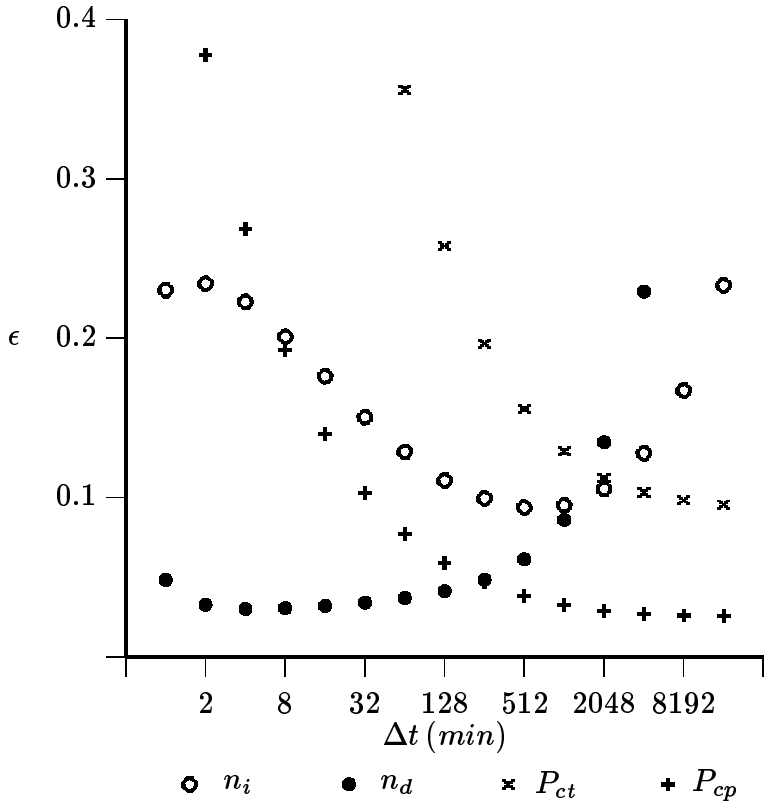

Figure 2 Variation of Error with Acceleration

The behaviour exhibited in Figure 2 was found to be typical for a wide range of system parameters, including the four fitting parameters. The one exception that was identified is that if the viscosity of the displaced component is less than the viscosity of the injected component, then the errors for n_d and P_{cp} never coincide.

Figure 2 suggests that only limited accuracy may be obtained for n_i and that accurate values for P_{ct} may be difficult to obtain. The latter suggestion is however not true. Assuming that data (both rotational speed and production) can be collected at short time intervals (fractions of a second), then the threshold pressure can be determined with very good accuracy. Using an appropriate curve fitting routine, the production versus rotational speed data can be analysed to determine the speed at which production begins. This speed characterizes the threshold pressure, which can then be calculated directly from Equation 1 with $r = r_t$.

An extensive parametric study was conducted to determine what accelerations should be used to optimize the constantly-accelerating centrifuge method. Based on the preliminary study, it was decided to define the optimal acceleration (which is characterized by Δt_o) as the acceleration that causes the errors in n_d and P_{cp} to be equal. This recognizes the fact that P_{ct} can be determined independently, and that the accuracy for n_i is problematic in some cases, and further that the accuracy of n_i is best near the value of Δt that causes the errors in n_d and P_{cp} to be equal.

The result of the parametric study is a correlation equation that allows the optimal acceleration to be calculated from the parameters. However, the parameters are of two distinct types: those that are known *a priori* (k, μ_i, μ_d, ϕ, r_o, ρ_i, ρ_d)

Parameter	$\Delta t_o\ (min)$	$\epsilon\ (n_d, P_{cp})$	$\epsilon\ (n_i)$
Base-Case	242	0.0477	0.1000
$k = 10\,md$	2420	0.0477	0.1001
$k = 1000\,md$	24.2	0.0477	0.1001
$\mu_i = 0.01\,cp$	352	0.0503	0.5867
$\mu_i = 0.10\,cp$	329	0.0495	0.2127
$\mu_i = 10.0\,cp$	179	0.0525	0.0963
$\mu_d = 3.0\,cp$	889	0.0485	0.1314
$\mu_d = 10.0\,cp$	3295	0.0494	0.2123
$\mu_d = 30.0\,cp$	10360	0.0500	0.3670
$\rho_i = 1.0\,kg/m^3$	612	0.0478	0.1005
$\rho_i = 925.0\,kg/m^3$	165	0.0473	0.0997
$\rho_d = 925.0\,kg/m^3$	166	0.0473	0.0996
$r_o = 12.5\,cm$	275	0.0484	0.1062
$r_o = 15.0\,cm$	302	0.0493	0.1087
$\phi = 0.125$	121	0.0964	0.2017
$\phi = 0.0625$	60.3	0.1973	0.4123

Table 2a Data from the Parametric Study
(*a priori* parameters)

and those that are known *a posteriori* (n_i, n_d, P_{ct}, P_{cp}, k_{ire}, k_{dre}, S_{dr}). Ideally, the correlation should not depend strongly on the *a posteriori* parameters or its utility would be limited.

Table 2a shows data for the *a priori* parameters. As k decreases or μ_d increases, Δt_o increases. For other parameters, Δt_o is less sensitive. The errors for n_d and P_{cp} are consistently good and remarkably constant for all parameters except ϕ. As ϕ decreases, the error increases markedly. A careful study of the data shows that the error at the optimal value of Δt_o varies inversely with the mobile pore volume and directly with the experimental error. The error for n_i is sometimes close to 0.1 but for some parameters is almost 0.6.

Table 2b shows data for the *a posteriori* parameters. As P_{cp} declines or n_d increases, Δt_o increases. For other parameters, Δt_o is less sensitive. Again the errors for n_d and P_{cp} are consistently good. The error for n_i is actually improved for many of the parameters studied although it never approaches the errors in the other two parameters.

Figure 3 shows a plot of the entire parametric study data set versus the following prediction equation:

$$\Delta t_o = \frac{1679.9\ \phi\ \mu_d^{1.117}\ P_{ct}^{0.051}\ n_d^{4.016}\ \Delta\rho^{0.496}\ r_o^{0.460}\ k_{ire}^{0.135}\ \Delta S_d^{1.086}}{k\ \mu_i^{0.098}\ P_{cp}^{1.548}\ n_i^{0.582}\ k_{dre}^{1.172}} \tag{6}$$

The agreement in all cases is excellent. The equation may therefore be used to determine test values for Δt_o, hence acceleration, assuming that all of the parameters are known or can be estimated.

Parameter	$\Delta t_o\ (min)$	$\epsilon\ (n_d, P_{cp})$	$\epsilon\ (n_i)$
Base-Case	242	0.0477	0.1000
$P_{ct} = 0.5\ kPa$	237	0.0466	0.0931
$P_{ct} = 2.0\ kPa$	251	0.0495	0.1135
$P_{ct} = 4.0\ kPa$	262	0.0530	0.1417
$P_{cp} = 1.0\ kPa$	6121	0.0593	0.2047
$P_{cp} = 2.0\ kPa$	2075	0.0533	0.1428
$P_{cp} = 4.0\ kPa$	697	0.0500	0.1144
$P_{cp} = 16.0\ kPa$	84.5	0.0462	0.0920
$n_i = 1.5$	279	0.0492	0.1402
$n_i = 3.0$	183	0.0443	0.0731
$n_i = 4.0$	159	0.0414	0.0630
$n_i = 5.0$	146	0.0389	0.0578
$n_d = 1.5$	95.2	0.0551	0.1083
$n_d = 3.0$	1102	0.0412	0.1044
$n_d = 4.0$	3675	0.0381	0.1313
$n_d = 5.0$	11390	0.0361	0.1958
$k_{ire} = 0.0625$	174	0.0571	0.1054
$k_{ire} = 0.125$	182	0.0510	0.0935
$k_{ire} = 0.25$	190	0.0483	0.0898
$k_{ire} = 0.5$	212	0.0476	0.0920
$k_{dre} = 0.0625$	1235	0.0498	0.1454
$k_{dre} = 0.125$	543	0.0483	0.1168
$k_{dre} = 0.5$	107	0.0475	0.0918
$k_{dre} = 1.0$	48.0	0.0482	0.0895
$S_{dr} = 0.1$	274	0.0422	0.0887
$S_{dr} = 0.4$	177	0.0638	0.1342

Table 2b Data from the Parametric Study
(*a posteriori* parameters)

The correlation equation for just the *a priori* parameters is

$$\Delta t'_o = \frac{2703.6\ \phi\ \mu_d^{1.120}\ \Delta\rho^{0.498}\ r_o^{0.478}}{k\ \mu_i^{0.099}} \tag{7}$$

It has already been shown in Table 2b that Δt_o can depend strongly on the *a posteriori* parameters. Therefore, the utility of Equation 7 depends on how the errors vary with $\Delta t'_o$, that is, on if the $\Delta t'_o$ predicted by Equation 7 leads to small errors despite the fact that it differs greatly from the value of Δt_o predicted by Equation 6. There is optimism for this view because it has already been shown in Figure 2 that the errors change relatively slowly with changes in Δt, over large ranges of Δt.

Table 3 documents a study performed to evaluate the utility of Equation 7. In all cases, Δt_o was assumed to be 242 *min*, the optimal value for the base-case. It

Parameter	$\epsilon\ (n_d)$	$\epsilon\ (P_{cp})$	$\epsilon\ (n_i)$
Base-Case	0.0477	0.0477	0.1000
$P_{ct} = 0.5\ kPa$	0.0469	0.0463	0.0927
$P_{ct} = 2.0\ kPa$	0.0491	0.0501	0.1140
$P_{ct} = 4.0\ kPa$	0.0519	0.0430	0.1422
$P_{cp} = 1.0\ kPa$	0.0340	0.1938	0.2437
$P_{cp} = 2.0\ kPa$	0.0359	0.1158	0.1834
$P_{cp} = 4.0\ kPa$	0.0396	0.0721	0.1333
$P_{cp} = 16.0\ kPa$	0.0676	0.0341	0.0838
$n_i = 1.5$	0.0474	0.0516	0.1411
$n_i = 3.0$	0.0475	0.0410	0.0693
$n_i = 4.0$	0.0464	0.0363	0.0575
$n_i = 5.0$	0.0448	0.0330	0.0515
$n_d = 1.5$	0.0736	0.0406	0.0920
$n_d = 3.0$	0.0309	0.0653	0.1135
$n_d = 4.0$	0.0256	0.0853	0.1231
$n_d = 5.0$	0.0234	0.1066	0.1291
$k_{ire} = 0.0625$	0.0616	0.0504	0.0960
$k_{ire} = 0.125$	0.0548	0.0463	0.0874
$k_{ire} = 0.25$	0.0512	0.0450	0.0856
$k_{ire} = 0.5$	0.0492	0.0457	0.0899
$k_{dre} = 0.0625$	0.0350	0.0910	0.1708
$k_{dre} = 0.125$	0.0442	0.0671	0.1157
$k_{dre} = 0.5$	0.0614	0.0374	0.0819
$k_{dre} = 1.0$	0.0865	0.0313	0.0716
$S_{dr} = 0.1$	0.0410	0.0439	0.0903
$S_{dr} = 0.4$	0.0694	0.0584	0.1295

Table 3 Errors for $\Delta t = 242\ min$

can be seen that, except for the cases of low P_{cp} and high n_d, the error for n_d and P_{cp} are less than 0.1.

As an additional test of Equation 7, 60 simulated tests were performed for which the densities of the fluids and the radius of rotation were held at their base-values, and the remaining parameters were varied simulataneously. The resulting errors in n_d ranged from 0.024 to 0.066, with a mean of 0.039 and a standard deviation of 0.010; for P_{cp} the errors were 0.034 to 0.453, with a mean of 0.110 and a standard deviation of 0.098. The results for P_{cp} were strongly skewed by several large error cases, associated with low values of P_{cp}. Inspection of the individual cases showed that the equation tended to predict values of Δt_o that lead to low errors in n_d, and higher errors in P_{cp}, that is, non-optimal values of ΔP_{cp}. This suggests that further correlation work will lead to a better predictive equation.

Comparison of Techniques

The constantly-accelerating centrifuge provides a fast and accurate method of si-

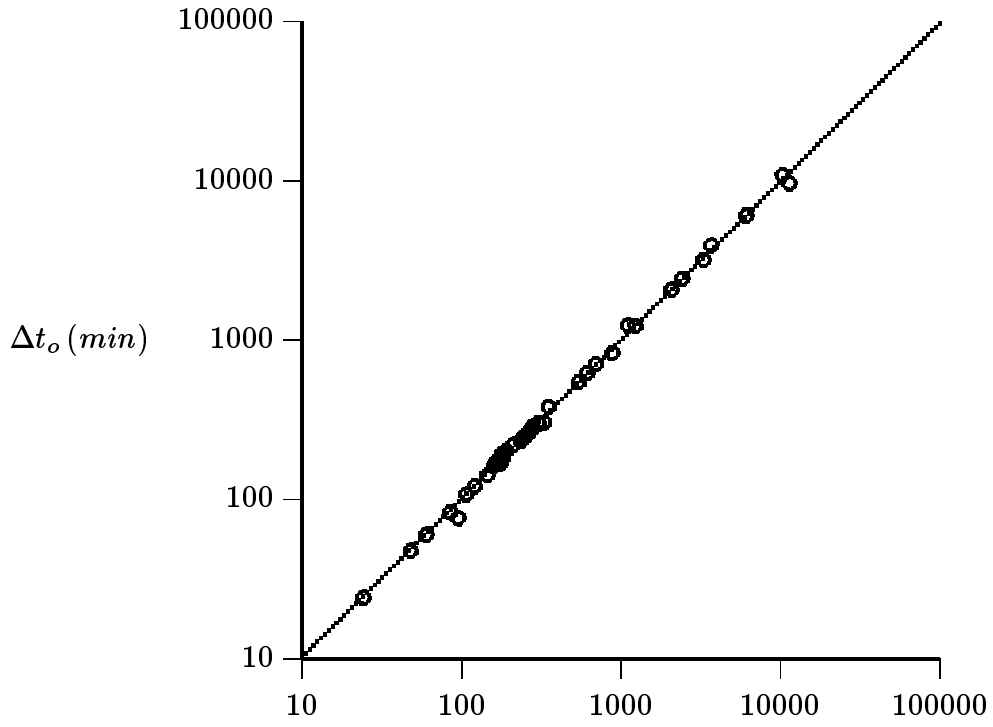

Figure 3 Quality of Fit

multaneously determining capillary pressures and relative permeabilities. Below, the method is compared with the two current centrifuge techniques:

1. Single-Speed: Figure 4 shows errors for a single-speed experiment simulated for the base-case conditions and various plateau speeds. It can be seen that for some plateau speeds both n_d and P_{cp} can be determined with good accuracy. Figure 4 also shows the total volume of fluid displaced (V_d). At plateau speeds for which the accuracy of P_{cp} is good, the value of V_d is significantly less than the total moveable pore volume ($\approx 11.5\,cc$). Therefore, although the study implies that an accurate value of P_{cp} can be obtained, this is only true if the capillary pressure curve conforms completely with the Bentsen equation. If the curve in the unsampled region (that part of the saturation curve not represented by the data) does not continue exactly the same Bentsen curve as that which occurs in the sampled region, the results for the unsampled region will be meaningless. Therefore, as a general comment, the single-speed method does not allow determination of the capillary pressure curve.
2. Multi-Speed: Ruth (1997) gave results for the multi-speed method, results that in general showed larger errors than those calculated for the constantly-accelerating centrifuge. It is probably possible to optimize the multi-speed schedule to improve the overall accuracy; however, such an optimization would be very tedious because it would involve choosing a number of speed plateaus, each of which could depend on the sample and operating parameters in different manners. Furthermore, the multi-speed method requires considerably more time to accomplish because equilibrium must be attained at each speed.

Conclusions

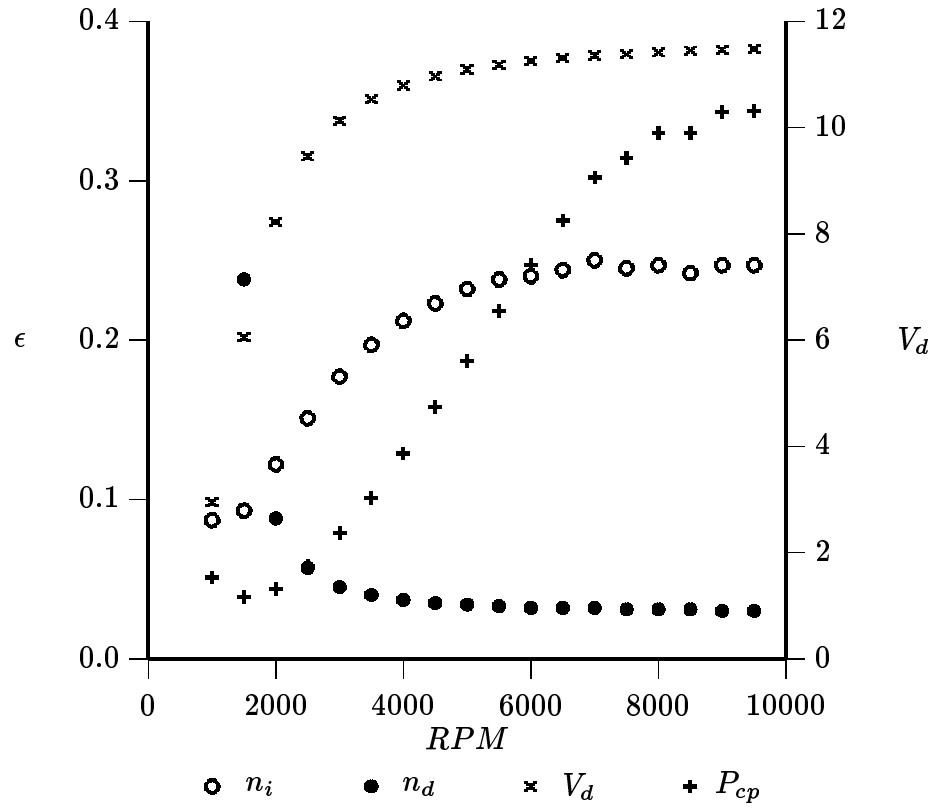

Figure 4 Single-Speed Technique Results

The present work supports the following conclusions:

1. The constantly-accelerating centrifuge technique combined with numerical simulation provides a fast and accurate method for determining capillary pressures and displaced component relative permeabilities.
2. For some combinations of parameters, the method will also provide information on the injected component relative permeabilities.
3. The errors in determining the parameters will improve with improved experimental accuracy, and deteriorate with reduced volume of movable fluid.
4. An equation has been provide with which to estimate the appropriate rate of acceleration for various sample and operating parameters.

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