A PROPOSAL FOR A CONSTANT FLOW RATE CENTRIFUGE TECHNIQUE TO MEASURE RELATIVE PERMEABILITY AND CAPILLARY PRESSURE

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ABSTRACT

A new method of performing centrifuge displacement experiments is described. By using a feedback system based on the measured production rate, the rate at which the rotational speed is changed is controlled. The method is compared with the existing methods: single-speed, multi-speed, and constantly-accelerating. It is shown that the other methods result in either long experimental times or uncontrolled, low or high production rates. Because the method relies on the measurement of production rates, the precision to which these rates must be measured is explored. It is found that the required precision is within the range of present centrifuge systems.

INTRODUCTION

There is an extensive literature on the use of a centrifuge to determine relative permeability curves, either by themselves or simultaneously with capillary pressure (Chardaire-Rivière, *et al.*, 1992; Firoozabadi and Aziz, 1991; Fleury *et al.*, 1994; Hagoort, 1974; Hirasaki *et al.*, 1988; Hirasaki *et al.*, 1992a; Hirasaki *et al.*, 1992b; Kantzas *et al.*, 1995; King *et al.*, 1986; King *et al.*, 1990; Munkvold. and Torsaeter, 1990; Nikakhtar *et al.*, 1996; Nikakhtar *et al.*, 1994; Nordtvedt *et al.*, 1992; Nordtvedt *et al.*, 1994; Nordtvedt *et al.*, 1993; O'Meara and Crump, 1985; O'Meara *et al.*, 1992; O'Meara and Lease, 1983; Ruth, 1997; Ruth, 1998; Torsaeter and Munkvold, 1987; van Spronsen, 1982). A centrifuge may be used to measure relative permeability and/or capillary pressure curves in a number of ways. The method that uses a single, high speed can be analyzed numerically to produce relative permeability curves but is not suitable for capillary pressure determination. The multi-speed method, with equilibrium at each speed, can be used to determine relative permeability and capillary pressure curves using independent methods. The constantly-accelerating centrifuge can be used to determine permeability and capillary pressure curves simultaneously by numerical simulation.

For the single-speed technique, the centrifuge is rapidly accelerated to a pre-selected rotational speed, preferably one that will reduce at least the top of the sample to the residual wetting phase saturation. This is typically a very high speed. This speed is then

held constant until production ceases. The analysis of the production versus time history to determine the relative permeability curves requires a pre-knowledge of the capillary pressure curve as this curve cannot be determined from the experimental data. However, because of the high flow rates that occur in this technique, capillary effects are minimized except near the end of the experiment.

The multi-speed technique utilizes a series of pre-selected rotational speeds. The centrifuge is rapidly accelerated to the first speed, and held at that speed until production ceases. The centrifuge is then rapidly accelerated to each successive speed, allowing for production to cease at each step. This experiment is therefore the same as that used to determine capillary pressures; however, in addition to measuring the equilibrium production at each speed, production is measured as a function of time throughout the experiment. The equilibrium points at the end of each speed period may be analyzed independently of the transient stages to determine the capillary pressure. The transient stages of the curve are very sensitive to relative permeabilities. Therefore, multi-speed experiments can be used to determine both capillary pressures and relative permeabilities.

For the constantly-accelerating technique, the centrifuge is accelerated at a small but constant rate up to a pre-selected maximum rotational speed. An appropriate acceleration rate can be chosen based on the properties of the sample (Ruth, 1998). The maximum speed is chosen such that the final saturation of the wetting component at the top of the sample is at its residual value. Although this method does not provide stages where capillary pressure is more or less dominant, the production and rotational speed histories can be analyzed to determine both capillary pressure and relative permeability.

The multi-speed method would appear to be the preferred method because it provides an independent prediction of the capillary pressure curve. However, this method suffers from the problem that, until the capillary pressure and relative permeability curves are known, the most appropriate speed schedule is not obvious. Hence, the experiment cannot be optimized to give the highest quality data. Furthermore, the steps between speeds typically lead to very high total flow rates during which capillary effects are minimized, followed by periods of very low total flow rates during which capillary effects dominate. The constantly-accelerating technique can minimize the total flow rate but the optimum acceleration rate can not be determined with certainty until the experiment is completed. Furthermore, there are still periods of high and low total flow rates.

The most damaging criticism of existing centrifuge techniques is that they allow non-field realistic flow rates to occur at least during a portion of the experiment. A non-centrifuge method of determining relative permeability, the unsteady-state method, uses a displacement process but a constant total flow rate. Therefore, the flow regime (high or low) can be controlled. The present paper proposes a centrifuge method that uses a feed-back system to control the total flow rate in a centrifuge experiment, thereby emulating the unsteady-state method.

THE CONSTANT FLOW RATE METHOD

The constant flow rate method proceeds as follows:

1. The experiment starts as a constantly-accelerating technique until production begins.
2. Once production begins, the rotational speed is incremented based on the measured production rate (the total flow rate, hereafter referred to as "flow rate"). The rotational speed is increased until a pre-selected maximum value of flow rate is detected. The rotational speed is then held constant until a pre-selected minimum value of flow rate is detected. By alternately increasing the rotational speed at a constant rate until the maximum flow rate is detected, then holding the rotational speed constant until a minimum flow rate is detected, the flow rate is confined within a band between the pre-selected minimum and the maximum values.
3. Once a maximum rotational speed is achieved, the experiment is completed at that rotational speed.
4. The production and rotational speed versus time histories are analyzed using numerical simulation to determine capillary pressures and relative permeabilities.

A THEORETICAL STUDY OF THE METHOD

Using numerical simulation, a theoretical study was performed to compare a constant flow rate experiment with the three conventional techniques. The simulator is essentially the same as that described by Ruth (1997, 1998). In order to keep the comparison relevant, a set of real capillary pressure and relative permeability curves, as determined from a multi-speed experiment, were used. The multi-speed experiment was then used as the base case. The ramp-up rate (3500 *rpm/min*) and the final rotational speed (7000 *rpm*) used in the multi-speed experiment were used to simulate a single-speed experiment. The constantly-accelerating technique was simulated using an optimized acceleration rate as predicted in Ruth (1998) (29 *rpm/min*) and the same final rotational speed as the multi-speed experiment; however, the experiment was cut-off when the final speed was reached. The constant flow rate technique used the ramp-up rate and the final rotational speed from the multi-speed experiment.

Figure 1 shows the speed schedules for the four experimental modes. The time is plotted in log time format. It is obvious from this plot that the four experiments have very different characteristic times.

Figure 2 shows the production versus time for the four modes. The final production is approximately the same in all cases. However, the other three experiments are essentially finished before the multi-speed experiment has begun. This is due to the fact that equilibrium is allowed to obtain at each rotational speed. The constantly-accelerating centrifuge mode could be allowed to finish by not cutting it off but allowing a constant rotational speed stage at the end.

Figure 3 shows the flow rates for the four modes. The flow rate for the single-speed mode is an order of magnitude higher than the other modes and is plotted on a separate scale.

The multi-speed mode shows sharp spikes in the flow rate while the constant flow rate mode shows flow rates in a tight band, as it must by design. The flow rate for the constantly-accelerating mode peaks near the constant flow rate value but is below this value for most of its history.

The single-speed mode may result in fast experiments but capillary effects would be absent due to the high flow rates. These rates are well above reservoir values. The multi-speed mode will also minimize capillary effects over parts of the experiment but maximizes their effects over other parts of the experiment. The biggest drawbacks of this mode are the extended experimental times and the fact that the optimal schedule cannot be know *a priori*. The constantly-accelerating mode provides reservoir realistic flow rates in reasonable time frames; however, flow rates are variable. The constant flow rate mode provides control for the experiment and the experiments can be performed in reasonable times, even faster than the optimized constantly-accelerating mode.

CONTROLLING THE FLOW RATE

Controlling the flow rate in a simulation is simple; controlling the flow rate during an experiment may not be straightforward. The biggest difficulty will be that the flow rate must be calculated from differences in the total production in the presence of experimental error. Differencing experimental data is a notoriously difficult problem in data analysis.

Consider a typical experiment with a flow rate is 0.00111 *cc/s* (4 *cc/hr*), which corresponds to a field rate of 2 *ft/day* in a 1.5 *in* sample. Assume a precision of measurement is 0.01 *cc*, and that the control algorithm is implemented every second. In one second the total production would be 0.00111 *cc* but the error in reading this production would be $\pm 0.01 cc$. The error is therefore greater than the reading! Even if the control algorithm is implemented every 30 seconds, the error is still approaching $\pm 30\%$.

One solution to this problem would be to take a large number of production readings and fit them with a linear equation to calculate the flow rate. It is well known that the error in the slope of a fitted line decreases with the number of points used to determine it. Specifically, to within a confidence of 95%, the standard error in the slope is given by the equation (Draper and Smith, 1966)

$$s.e. = \frac{1.96\,\sigma_V}{\sqrt{\sum_{I=1}^{N}\left(t_i - \bar{t}\right)^2}}$$

where σ_V is the standard deviation of the measurement of the produced volume, t_i is the time at which the *i*-th reading is taken, N is the total number of readings, and $\bar{t}$ is the mean time of the sample interval under consideration. The factor 1.96 is the value related to the 95% confidence limit by the Student-*t* test. This equation provides a simple method to explore the required performance of the measuring system.

Figure 4 shows an analysis of the resulting standard error in the production rate given that the control algorithm is implemented every 30 seconds. The tested variables are the frequency of data sampling (1 per second and 10 per second) and the error of observation in the production. This figure can be used to determine the system requirements in order for the constant flow rate method to be applied.

The remaining question that needs to be answered is how large of a standard error in the flow rate can be tolerated for the control algorithm to operate properly. In order to answer this, simulations were conducted in which the predicted flow rates were corrupted by introducing errors into them before they were used to either stop changes, or re-commence changes, in the rotational speed. The fractional errors considered were 0.01, 0.05, 0.1 and 0.5. The production versus-time histories are shown in Figure 5-

For the lowest error, the control band about the constant production rate is relatively broad; this region is compressed for larger errors. The reason for this compression is that, with increased errors, the chance of changing the speed or detecting a value that stops the speed from changing, increases. This has the effect of decreased periods of constant speed, hence reducing the control band. For a fractional error of 0.1 and in a more pronounced manner for a fractional error of 0.5, the increased error leads to a production rate "hump" in the curves. The conclusion to be drawn from these curves is that, even for a fractional error of 0.1, the production rate is reasonably well controlled.

Returning now to Figure 4, for a flow rate of 0.00111 *cc/s* and a fractional error of 0.1 the resultant standard error is 0.000111 *cc/s*. In order to achieve this error, the error of observation would need to be less than 0.01 *cc* for a 0.1 *s* sampling step. Shorter sampling steps would allow larger errors of observation and *visa versa*. These values are within the performance parameters of present systems.

The currently proposed control algorithm is very primitive. More advanced algorithms should provide better control.

CONCLUSIONS

The present work supports the following conclusions:

1. A constant flow rate centrifuge experiment would provide benefits in experimental run time and representative flow rates not provided by other centrifuge techniques.
2. A constant flow rate centrifuge experiment should be feasible using existing systems.

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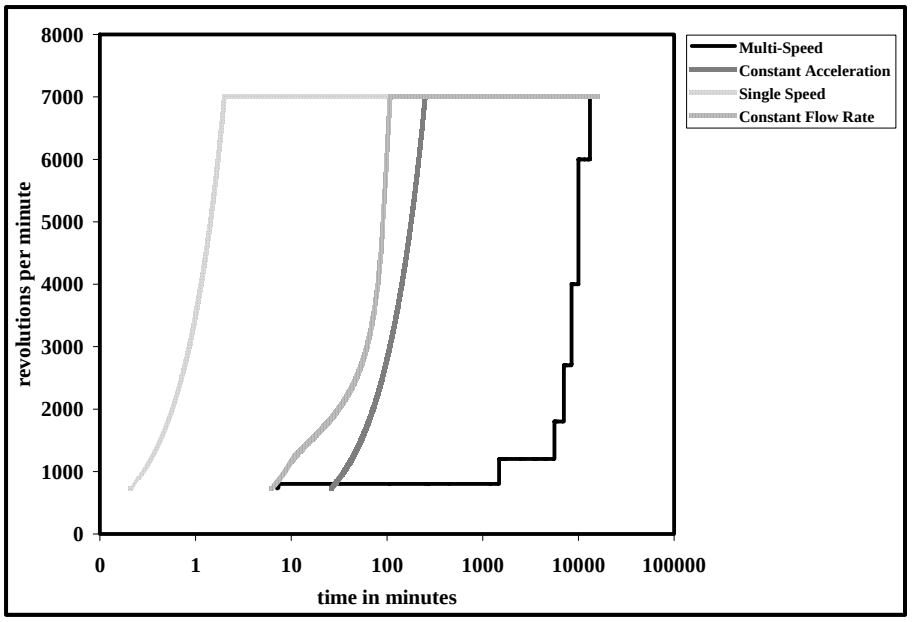

Figure 1 A comparison of rotational speeds for the four modes.

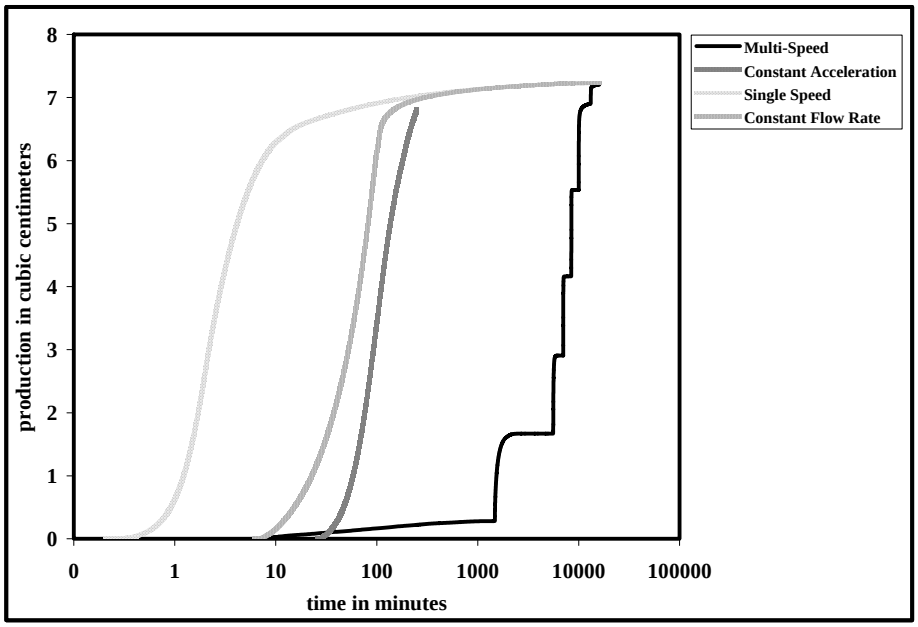

Figure 2 A comparison of the production for the four modes.

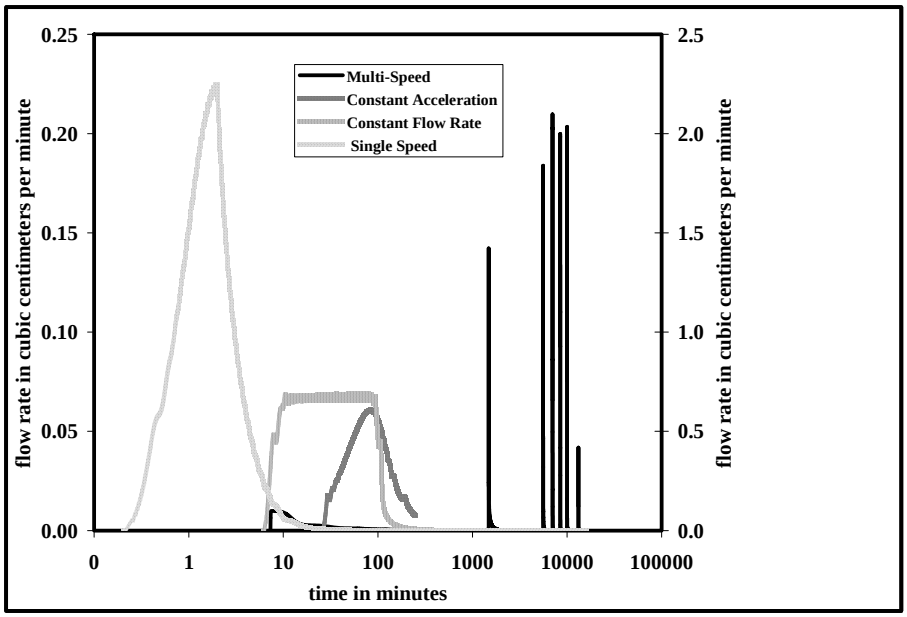

Figure 3 A comparison of flow rates for the four modes.

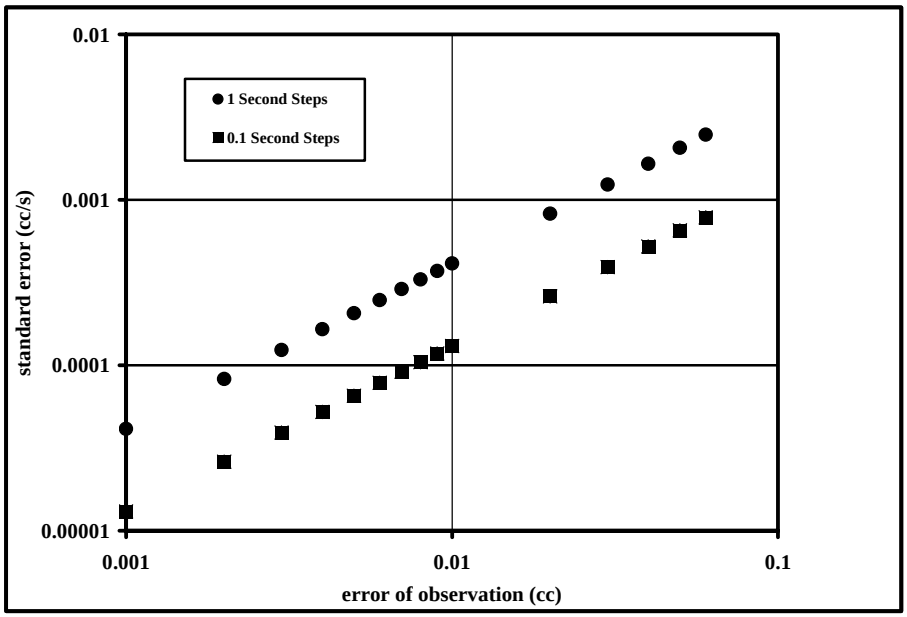

Figure 4 The resulting standard error for a control algorithm that is implemented every 30 seconds as a function of the time step between readings and the error of observation for the production.

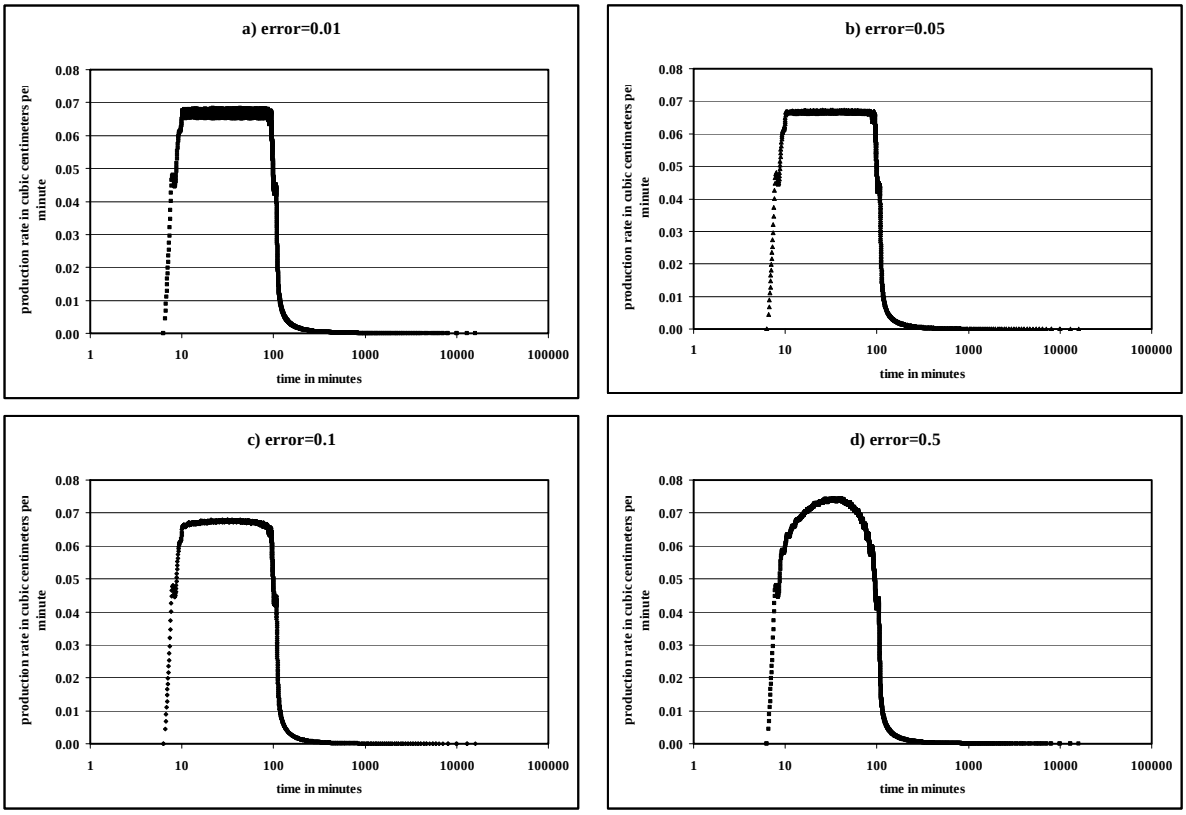

Figure 5 The production rates that result from the control algorithm in the presence of various fractional errors in the measured production rate.