A CAPACITANCE TECHNIQUE FOR MEASURING PRODUCTION WHILE CENTRIFUGING.

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Abstract

The centrifuge technique is a very useful tool for measuring capillary pressure curves and for desaturating core samples. Saturation measurements while spinning are usually performed using optical devices. We present a capacitance based detector measuring a fluid level in the rotating core holder that avoids problems related to optical detection (contrast, low speed limitation). The system is simple and yields an accuracy of about 1.5% of the pore volume at any speed of rotation (from 200 up to 4000 rpm). This accuracy is needed for data interpretation. The capillary pressure range covered is 0.011 to 3.3 Bar in drainage and -0.013 to -5 Bar in forced imbibition for oil-water.

We present different tests and experiments demonstrating the essential aspects of the device: stability and calibration of the detector, sensitivity to temperature, accuracy of production measurements. The same core holder is used for drainage and forced imbibition and four samples can be analyzed at the same time. For Pc curve measurements, the standard plug size is 4 cm in diameter and 6 cm in length. Long samples (9 to 10 cm) can also be centrifuged for further use in water-flooding experiments but production measurements while centrifuging are less precise. Special attention has been paid to the design of the core holders to allow an accurate measurement of effluent production after centrifugation at the end of both drainage and forced imbibition cycles. The centrifuge has also been modified to accelerate slowly (1000 rpm/hr), facilitating production measurements and relative permeability curves calculations.

Introduction

The centrifuge technique has generated an incredible number of studies, especially since the emergence of modern technology for data acquisition. The method can be used at very different degrees of sophistication, from basic core sample de-saturation up to the simultaneous determination of capillary pressure and relative permeability curves. For these reasons, this technique is a very important and unavoidable tool in petrophysics. In the past ten years, effort focused essentially on automated data acquisition systems (e.g. Hirasaki et al. 1992, Munkvold, 1993), data analysis for obtaining capillary pressure curves (for a review, see Forbes, 1997), data analysis for obtaining relative permeability curves (Nortwedt, 1993, among others). However, recent surveys performed by the Society of Core Analysts (Ruth and Chen, 1995, Forbes, 1997) revealed still a large number of

difficulties, despite significant improvements in both experimental and data analysis techniques. These surveys demonstrate that the centrifuge has not yet reached a true standardization level and that recent advances have not been understood properly or taken into account.

The data acquisition system is a key point when expert level centrifuges are used and when relative permeability information is desired. Indeed, automated production measurements while spinning are essential to control capillary equilibrium and provide precise transient data between equilibrium points. The main technique used is based on an optical detection of an air-brine or oil-brine interface. It is a versatile method that has a great efficiency at large speeds of rotation. Despite the difficulties at low speed of rotation (<500 rpm) because of rotor vibrations and bad optical alignment and contrast, the method can be used satisfactorily.

In these conditions, the purpose of developing a new technology for production measurements in centrifuges can be questioned. We think that the full potential of the centrifuge technique has not been utilized yet and more attention should be paid to the experimental aspects rather than data analysis and numerical simulations. For new applications such as the determination of positive imbibition Pc curves (Firoozabadi et al. 1988, Torsaeter, 1994), or full imbibition curves using a combination of centrifuge de-saturation and in situ saturation measurements (Baldwin and Spinler, 1997), a different production measurement system is needed. We describe in this paper a simple production measurement system having an accuracy coherent with data analysis constraints. As a first step, we show that conventional expert level measurements can be performed.

Experimental set-up

We followed general ideas during the design of the apparatus and they are summarized below :

- the experiments should be performed on large samples and the sample diameter should be coherent with other petrophysical equipment available at IFP (micropore membrane cells, flooding cells, etc..)
- the production measurement system should have an accuracy of 1% of the sample porous volume to be coherent with data analysis (Pc and Kr)
- for quality control, end point saturations should be determined by two or three different ways.
- we chose not to develop the system at high temperature (although this is possible), to limit equipment and development costs. The centrifuge technique is viewed as an efficient method for analyzing a large number of samples and therefor, it should be kept simple to operate. Moderate and high temperature experiments can be performed using other methods.

A special machine has been developed in collaboration with the centrifuge manufacturer (Jouan, France). The model (KR4-22) is a large radius centrifuge (30 cm) with a maximum rotation speed of 5000 rpm at a maximum temperature of 40 °C. It is equipped by the manufacturer with a special rotor where 4 core holders can be implemented. Compared to

standard machines devoted to biomedical applications, different modifications or enhancements were specified and successfully tested:

- a speed regulation of ±5 rpm at any speed from 200 up to 5000 rpm. This is particularly important at low speed of rotation. The speed overshooting between speed steps is also limited to 5 rpm
- a capability for programming speed steps
- a capability for slow acceleration; between speed steps, the acceleration can be set as low as 1000 rpm/hr to optimize Kr calculation.

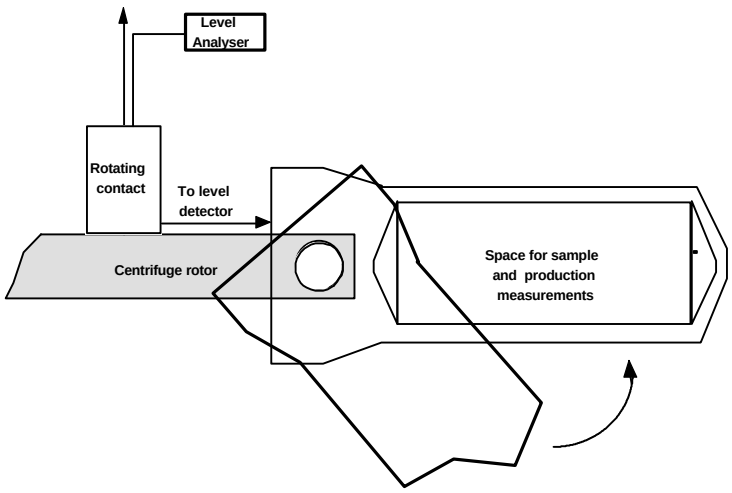

Figure 1: Schematic of the core holders in the centrifuge. The rotating contact allows the signals from the level detectors in the 4 core holders to be transmitted to the level analyzer outside the centrifuge. At rest, the core holders tilt in a vertical position.

Other equipments such as the rotating contact, the core holders and the data acquisition system (Figure 1) were designed by IFP. The rotating contact is a low cost 12 channel slip ring assembly from Air Précision (France , model T13) with a life time of 250 million rounds at a maximum speed of 3500 rpm (at an average non stop speed of 1000 rpm, this components will last 174 days). Several channels are used for a single wire to obtain high quality electrical transmission. Such components have been used in the past in other studies (Fleury and Lenormand, 1993) and proved to be reliable. However, the rotating contact itself is not critical to our apparatus and new contact-less systems could be used instead (e.g. Pohjoisrinne et al., 1996). It is rather the way it is mounted onto the centrifuge rotor which is critical to avoid vibrations and mechanical constraints.

Using a multi-channel acquisition system, the following data are recorded :

- the level in the 4 core holders, to be calibrated to volume produced by the 4 samples
- the temperature of the air in the centrifuge bowl
- the speed of rotation using a frequency meter.

Core holders

The core holders are designed in a very different way than those implemented in optical based production systems. There is basically a cylinder (Figure 1) of diameter 4.2 cm and length 13 cm where the sample and an end-piece for production measurements are located. On the side of this cylinder, there is a level detector (Figure 2) capable of measuring the variation of height of a brine-oil or brine-air interface in the cylinder. The core holders are the same in both drainage and imbibition mode.

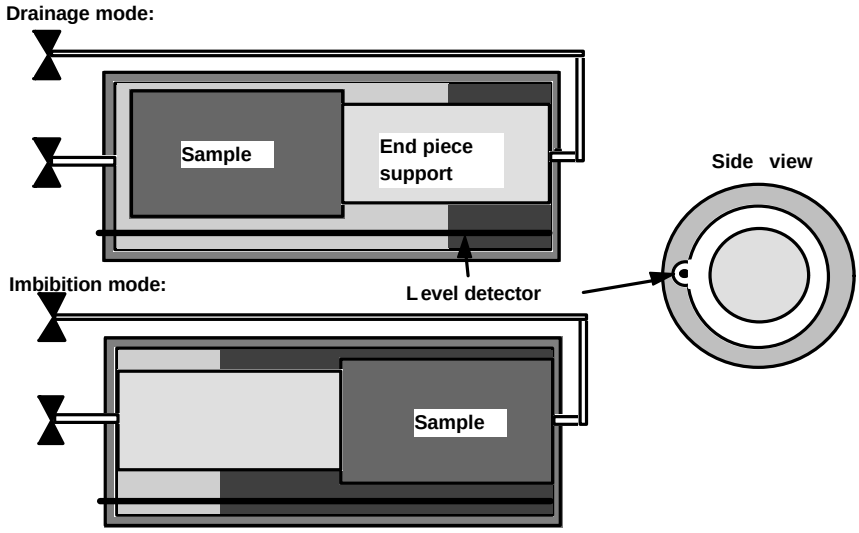

Figure 2: Centrifuge core holders in drainage and forced imbibition mode. The level detector located on the side (top view) is connected to the level analyzer through a rotating contact (slip ring assembly). Tubes are used during the preparation of the experiments and at the end to collect produced fluids.

In the drainage mode (sample immersed in oil), the sample is located near the top (smaller radius of rotation) of the core holder while the end piece is located at the bottom (Figure 2). For standard conditions, the length of the sample and the end piece should be both 6 cm, and the diameter of the end piece is such that the volume around it corresponds to the porous volume of the sample. Hence, nearly half of the length of the core holder is devoted to production measurements while the other half is occupied by the sample when water is produced. The end piece has also an appropriate shape (not shown in Figure 2) to avoid trapping of water going out of the sample. In the imbibition mode (sample immersed in brine), the sample is placed at the bottom of the core holder and the end piece on top of it. For a 6 cm long sample, the radii of rotation are 12.0/18.0 cm in drainage and 19.0/25.0 cm in imbibition.

In addition, two tubes connected to the top or the bottom allow (Figure 2):

- oil or water to be introduced (zero settings as initial levels, see experimental procedure) ,
- the core holder to be flushed with oil or brine for precise end point volume measurements

- the core holder to be pressurized
- the level detector to be calibrated (see below)

Production measurements: principle and calibration

Production is measured using a low cost capacitance based system. The detector is a simple metallic rod with a thin isolating ceramic coating. The device is basically sensitive to the height of a conductive fluid (brine) in which the sensor is immersed (Figure 3) while a non conductive fluid (air or oil) can be present above. In practice, we measure a capacity C between the rod and the brine (Figure 3), which is proportional to the height h immersed in brine:

(1) $$C = 2\pi\varepsilon_0\varepsilon_r h / \ln\left(\frac{R+e}{R}\right) \approx 2\pi\varepsilon_0\varepsilon_r \frac{R}{e} h \quad \text{(assuming } e \ll R\text{)}$$

where $\varepsilon_r R/e$ determines the sensitivity of the device which depends only on the coating (of the order of 100pF/cm). Measurements do not depend on the salinity of the brine (for usual salinity > 10 g/l). They are also weakly dependent on temperature (of the order of 0.04cc/°C in the experiments described below). Capacity is measured at 30 kHz using a low cost specialized circuit available commercially (VEGAMET 407Z, from VEGA Tech.) but an impedance meter could also be used.

For each detector, a low level (h=0, S=0) and a high level (h=10 cm, S=100 arbitrary units) must be set for calibration points to optimize the amplifier. Then, brine is injected in the core holder at the bottom and the volume recorded, as shown in Figure 4. In this case (drainage mode), the signal from the detector is perfectly linear in a range of about 13 cc. Below 8 cc, there is a dead volume at the bottom of the core holder and above 21cc, the conical sample support is reached. By adjusting the diameter of the end piece, the volume range can be optimized as a function of the pore volume of the sample. Therefore, the accuracy of the volume measurements can be expressed as a fraction of pore volume independently of its value (a height is measured, not directly a volume). For the example above, the resolution of our system is 0.1 arbitrary units and hence, we have a volume resolution of 13/1000=0.013 cc. The calibration in imbibition mode is similar and we verified that the same slope is obtained.

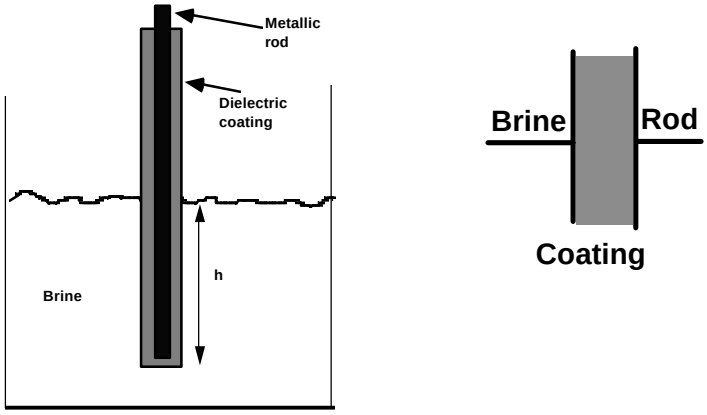

Figure 3 : Principle of the fluid level detector for production measurements (left) and simplified equivalent circuit (right). Measurements are independent on fluids electrical properties.

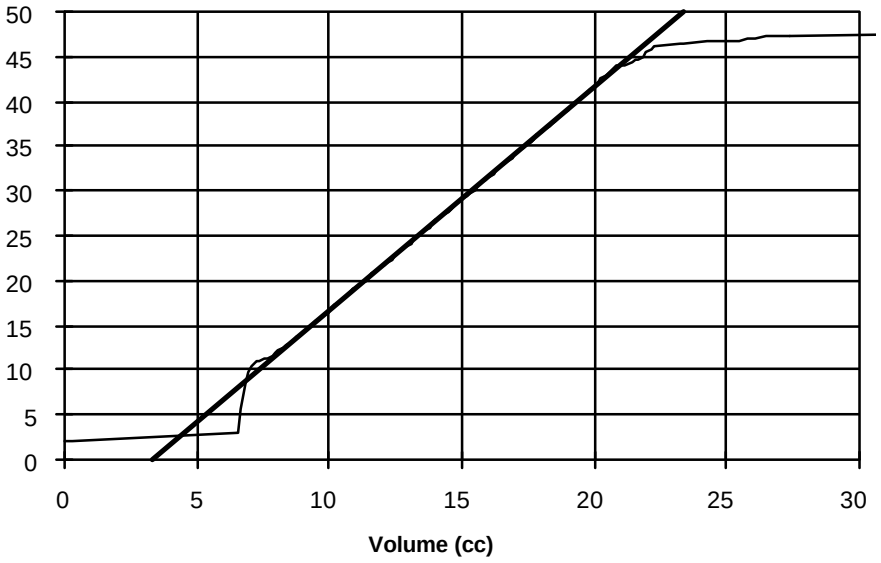

Figure 4 : Calibration of the production measurements in drainage mode for an end-piece designed for a 25 % porosity sample. Thin line: measurements, thick line: regression line. The linear region yields a volume range of 13 cc.

Experimental procedure

The experimental procedure takes advantage of the tubes connecting the top and the bottom of the core holder. In oil-water drainage mode, the following operations are successively performed:

- the core holder is filled with oil (end piece at the bottom)

- the sample is inserted and the core holder closed
- air is removed by flushing the core holder with oil; water produced spontaneously, if any, is collected and measured
- a known volume of brine is introduced at the bottom to set the zero level (e.g. S=15, from calibration curve, Figure 4)
- at the end of drainage, the core holder is flushed again with oil (top to bottom) to collect and measure the produced fluids
- the core holder is opened and the sample weighted

Therefore, the final average saturation of the sample after drainage is estimated using 3 different measurements: sample weight, effluent volume and production while spinning. Any incoherence will be detected and the errors can be quantified. There is a similar procedure for forced imbibition experiments when the sample is immersed in brine. When air-brine experiments are performed, the procedure is simpler and some steps can be removed.

Example of measurements

Air-brine drainage

The device was tested using two Vosges sandstone samples (Kg=680 mD) and two plastic plugs to demonstrate the stability of the measurements (Figure **5**). For channel P1 and P3, we observe the expected production profiles during centrifugation. At the first speed step (200 rpm), the entry pressure is not reached and there is no production. Note that the production measurements are weakly affected by the core holder tilting when the centrifuge is accelerating from 0 up to 200 rpm (all channels).

The stability of production measurements are best seen on core holders P2 and P4 where plastic plugs are used instead of porous samples (the end pieces are identical). For P2, the signal, set at the lowest position near the bottom, is insensitive to speed and temperature fluctuations; the stability is better than 0.2 cc in the range covered (0-3000 rpm). For P4, set at the top of the core holder (initial setting for an imbibition experiment), there is a slight drift at low speed (200 rpm) and some speed changes can be detected ; for this core holder, we suspect that air has not been removed totally. For all channels, a small drift due to temperature is seen at high speed (3000 rpm) because the mean temperature is shifted from 20 up to 22°C. This temperature effect can be corrected easily.

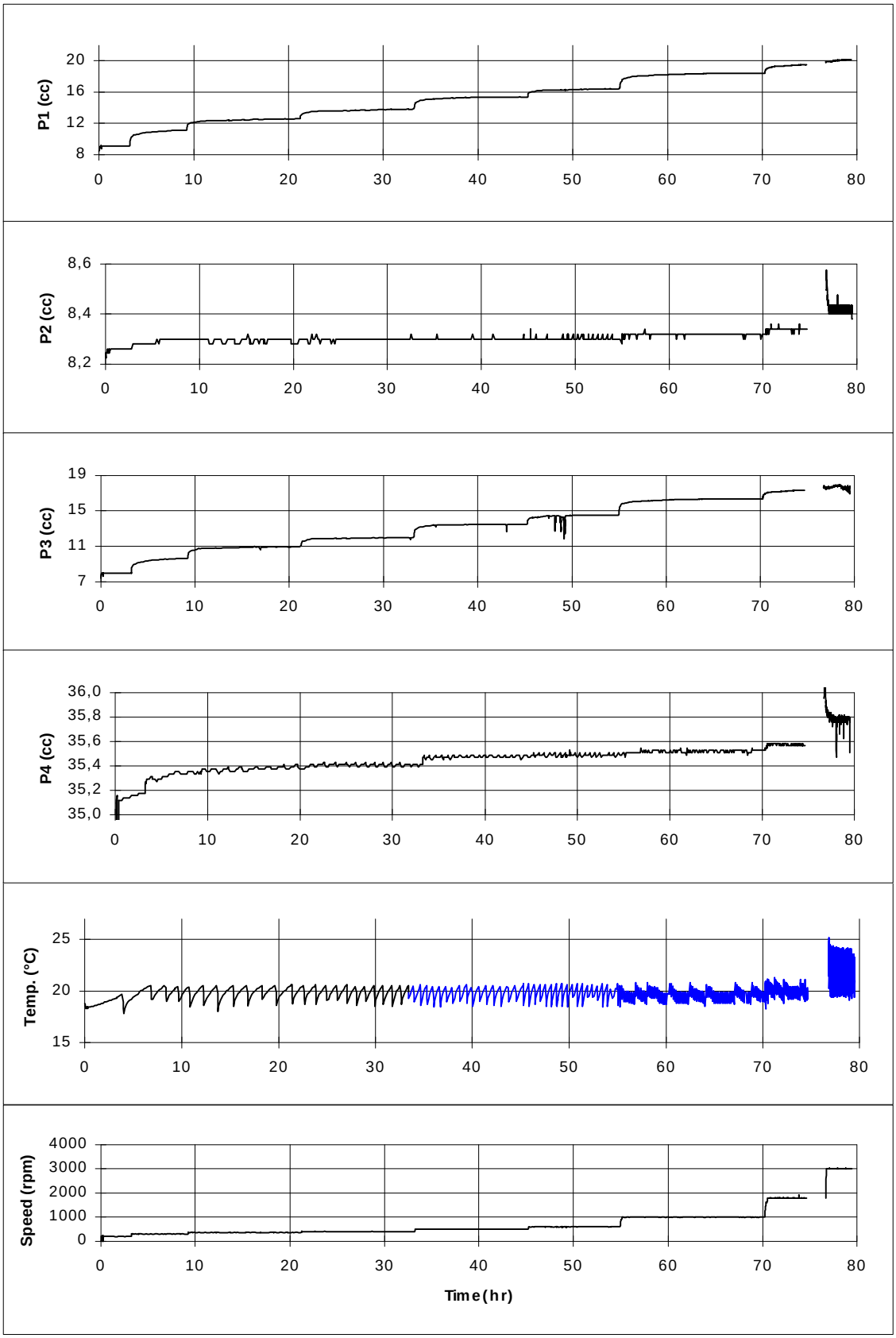
P1 (cc)
20
16
12
8
0 10 20 30 40 50 60 70 80
P2 (cc)
8,6
8,4
8,2
0 10 20 30 40 50 60 70 80
P3 (cc)
19
15
11
7
0 10 20 30 40 50 60 70 80
P4 (cc)
36,0
35,8
35,6
35,4
35,2
35,0
0 10 20 30 40 50 60 70 80
Temp. (°C)
25
20
15
0 10 20 30 40 50 60 70 80
Speed (rpm)
4000
3000
2000
1000
0
0 10 20 30 40 50 60 70 80
Time (hr)

Figure 5 : Production measurements in the 4 core holders (P1 to P4), temperature in the centrifuge bowl and speed of rotation. During this air-brine drainage, only two samples were used (P1 and P3) ; P2 and P4 channels are used here to demonstrate the stability of production measurements.

From the equilibrium production data obtained at the end of each speed step, a capillary pressure curve (Figure 6) is calculated using the method of Forbes (1992) including radial effects (Forbes et al., 1994). The coherence of the experimental data is seen when the average saturation (input) data are compared to the calculated average saturation curve (Figure 6). Such a comparison is always performed to check the quality of the calculations.

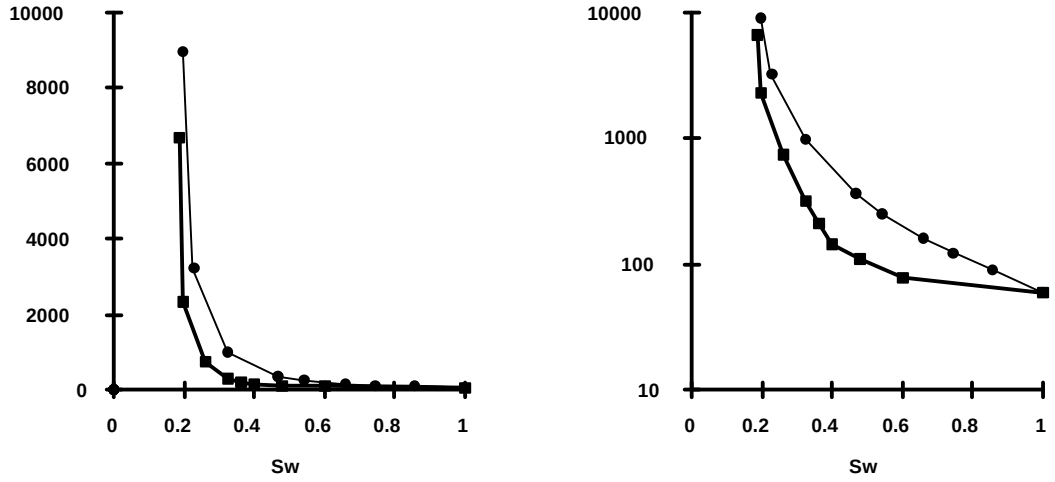

Figure 6: Capillary pressure curves from equilibrium saturation data (P1 channel) in lin-lin (left) and semi-log (right) scales. Squares: calculated Pc curve, circles: average saturation input data, thin line: recalculated average saturation curve from Pc curve.

Oil-water forced imbibition

The capability of the apparatus to measure production at low speeds is particularly useful for forced imbibition experiments on samples of intermediate wettability. For the case presented in Figure 7 (an oil-water forced imbibition experiment), the initial level is set to a high position near the top of the core holder (P1=36 cc, Figure 7) and is decreasing when oil is produced. Oil production is occurring mainly in the range 200-500 rpm (-12 up to -80 mBar). For this sample, a spontaneous imbibition is also observed and we do not separate the volume produced spontaneously from the volume produced at 200 rpm. However, the experimental procedure and the design of the core holders allow a precise measurement of the produced oil during theses processes by flushing the core holder.

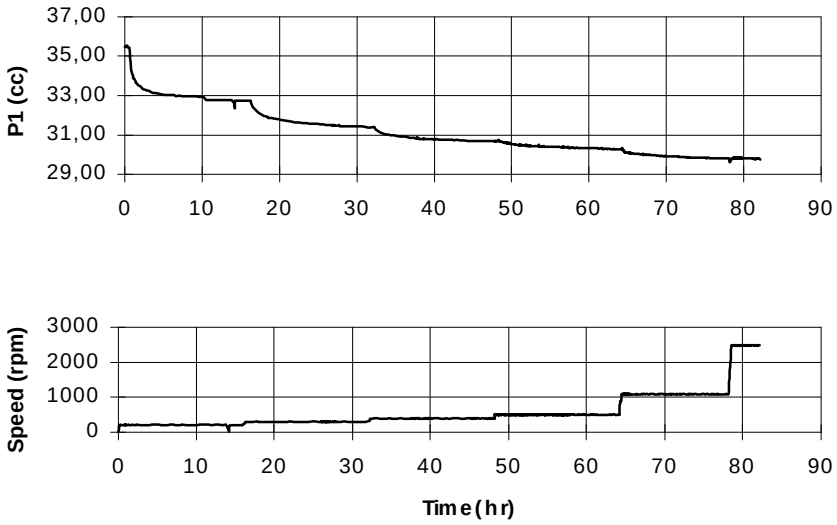

Figure 7: Production measurements during a forced imbibition experiment. The sample is of intermediate wettability.

Conclusions

An innovative method for measuring production while centrifuging is presented. The technique is a capacitance based measurement independent of the electrical properties of the fluids used in the centrifuge experiments. It requires one of the fluids to be conductive but the value of conductivity does not enter into account in the calibration curve. The centrifuge and core holders are designed to analyze samples of length 6 cm and diameter 4 cm, at a rotation radius between 12 and 25 cm, at a maximum speed of 4000 rpm and at a maximum temperature of 40°C. These characteristics yield a range of capillary pressure of 0.011 up to 3.3 Bar in drainage and -0.013 down to -5 Bar in forced imbibition for oil-water experiments. The device is particularly adapted to measure medium to low capillary pressure curves because production measurements are accurate at low speeds of rotation.

Drainage and forced imbibition tests performed on samples and plastic plugs indicate that the accuracy of measurements is between 1 and 2% of the sample porous volume. This accuracy can always be obtained with an appropriate end piece support. Traditional difficulties associated with spontaneous production processes occurring at the beginning of the experiments are overcome by a specific design of the core holders.

The production measurement system presented here has also large potentials for future applications such as:

- desaturation of long samples (9-10 cm) for water flooding experiments
- determination of full imbibition curves using local saturation measurements (Baldwin and Spinler, 1996)

- determination of full imbibition curves using a free level technique (Torsaeter, 1994)
- determination of full imbibition curves using a fixed level technique (Firoozabadi et al., 1988)
- optimization of relative permeability curve calculation by a slow acceleration between speed steps.

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