A Novel Experimental Apparatus for Determination of Three-Phase Relative Permeabilities at Reservoir Conditions

E. Ebeltoft, J.E. Iversen, K.O. Vatne, M.A. Andersen,[1)] J.E. Nordtvedt

RF-Rogaland Research, Thormøhlensgt. 55, N-5008 Bergen, Norway
[1)]: Amoco Norway Oil Company, N-4001, Stavanger, Norway.

Abstract

A new three-phase flow apparatus is developed and tested by use of the newest pumping system and separator available. The flooding apparatus is designed for simultaneous injection and recycling of one, two, or three phases at reservoir conditions. Highly accurate pumps inject three phases virtually pulsefree into the core sample. The downstream end of the core sample is connected to a three-phase acoustic separator. The entire flow apparatus provides a closed loop and recycling of all phases. As the injection rate of any of the phases can be changed any time, both steady-state as well as unsteady-state type experiments may be performed. Along with production data, the pressure drop across the core sample is measured as a function of time using differential pressure transmitters, and, whenever a steady-state condition is attained, three-phase in-situ saturation profiles are measured using an X-ray system. A full description of this apparatus is given. We outline experimental procedures and show results from the performance tests of the apparatus. A comprehensive comparison of average saturation determination by material balance and saturation profiles for a three-phase gas displacing water and oil cases is reported. We further present and analyze experimental data from a three-phase experiment.

Keywords: Relative permeabilities, reservoir condition, flooding equipment

Introduction

Determination of relative permeability functions from displacement experiments has been receiving a lot of attention for more than fifty years. However, the vast majority of the effort has been directed towards determination of two-phase properties. The three-phase effort has mostly been aimed at the development of correlations which make it possible to extrapolate two-phase relative permeability data into the three-phase region. Although this is tractable, if accurate, a very limited number of data sets are available for testing and verification of these correlations, restricting refinement and modification possibilities. Furthermore, while reservoir condition experimental equipment and data exist in numbers for the two-phase situation, it has rarely been reported for three-phase cases. Our current effort is aimed at improving this situation, and this paper describes the development and testing of a novel experimental apparatus for the determination of three-phase relative permeabilities at reservoir conditions.

Three-Phase Flow Apparatus

The schematic of the flow apparatus is shown in Figure 1. The flow apparatus consist of (1) a pumping system for fluid recirculation, (2) a three-phase acoustic separator to monitor fluid production, (3) an X-ray transparent core holder, and (4) an X-ray scanner system for in-situ saturation measurements. Each of these components in the apparatus is described in details below.

Pumping System and Fluid Recirculation

The pump cylinders with accessories were originally developed for a two-phase system[1] in close co-operation with the vendor. Here we present an extended system consisting of eight computer controlled cylinders that recycle equilibrium reservoir fluids into the core sample. Seven of the cylinders are placed in a heating cabinet, and six of them are paired to act as three pumps working together. These pumps are used for recycling water, oil and gas with accurate, continuous and virtually pulse free flow rates. For each of the pairs (i.e., each of the fluid phases), one cylinder delivers fluid through the pump outlet valve into the core sample. The other cylinder receives, at the same time, fluid from the return line connected to the separator. This cylinder receives fluid through the inlet pump valve at a slightly higher rate than the rate of the delivering cylinder. When the receiving cylinder is full, the inlet valve is closed and the pressure is adjusted to be equal to the pressure in the delivering cylinder. When the delivering cylinder is nearly empty, the outlet valve is opened on both cylinders, and the switch-over to the full cylinder occurs smoothly. The empty cylinder is then closed off, the pressure is adjusted to the back pressure, the inlet valve is opened to the return line, and the cylinder starts retracting to receive the fluid from the return line connected to the separator.

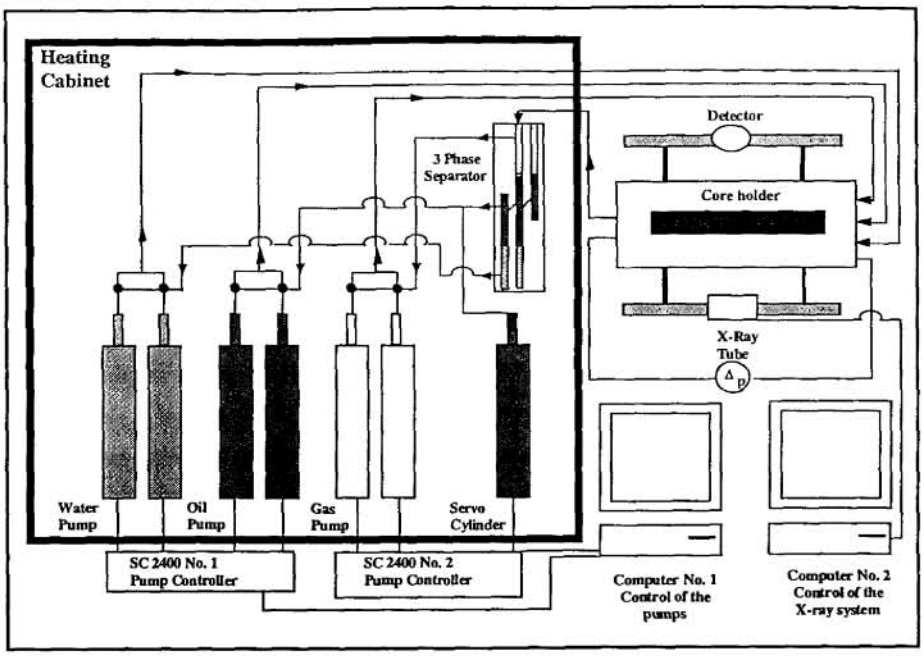

Figure 1: Three-phase flow apparatus.

The seventh cylinder works in constant pressure mode, ensuring a constant back pressure. This cylinder is plumbed to the oil return line, but is in connection with the water and gas return lines indirectly through the three-phase separator. The cylinder will respond to any volume changes in the closed system to avoid pressure variations. Any leakage of the system will also be detected by this cylinder.

The eighth cylinder is placed outside the heating cabinet, and is used to maintain constant overburden pressure on the core sample, and for various preparation work. If necessary this cylinder can also be used to refill the flow apparatus at constant pressure with any of the reservoir fluids during an experiment.

The pumping system uses air actuated valves, and the monitoring of the apparatus and the data logging of all measurables are automated and performed by a personal computer (PC).

Three-Phase Acoustic Separator

The three-phase separator is a vital part of the flow apparatus. It has been developed in co-operation with the vendor and is used to determine the volume of each phase produced from (or injected into) the core sample. Figure 2 gives the schematic of the separator design. Three bores connected to each other form the internal volume of the separator. The fluids enter into the top of the middle bore where they are separated. Two measuring bores are connected to the separation bore by a set of channels. The volumes of the phases in the separator are inferred by means of acoustic transducers determining the distance from the transducers to the interfaces formed in the measurement bores. This distance is determined by measuring the time for an acoustic pulse to echo off the interface and return to the transducer. By also measuring the corresponding time for reflection from a calibration stub, which length from the transducer is known, the sound velocity can be

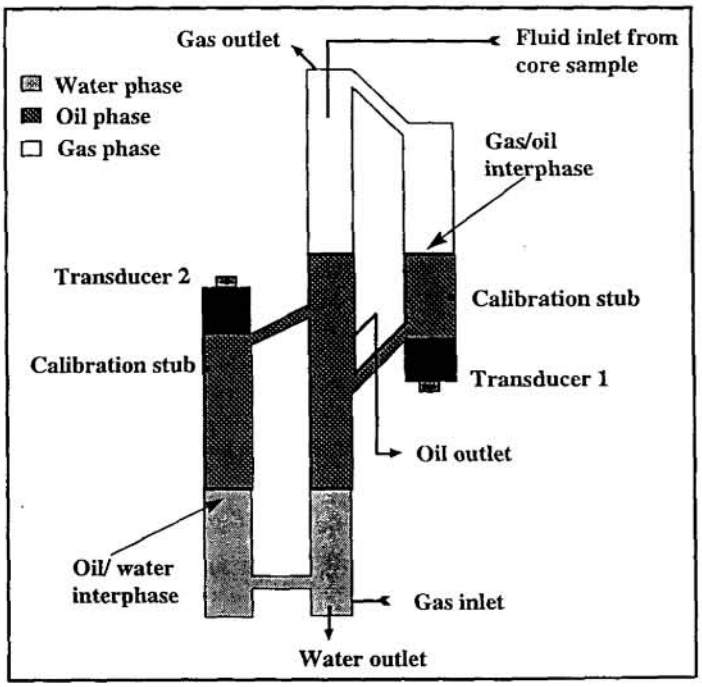

Figure 2: Three-phase acoustic separator.

found, and hence the length from the transducer to the interface can be calculated. One of the transducers is faced upwards towards the oil/gas interface, measuring the distance from the transducer to this interface, while the other is faced downwards measuring the distance to the oil/water interface. By these measurements the amount of water and gas can be determined. The oil volume is determined by subtracting the sum of the water and gas volumes from the total internal volume of the separator.

The fluid inlet is placed in the gas phase, and the separation process between water and oil is therefore not disturbed by gas bubbles. This inlet is placed in the

center of the bore to avoid water and oil adhering to the bore wall and thereby causing a delay in water and oil volume detections. The connecting channels between the separator bores are made with an angle to guide the phases to their desired locations. A gas inlet is also located at the bottom to establish equilibrium between the phases by recirculation. The entire separator is easy to tilt, even when it is placed inside the heating cabinet and is at reservoir conditions. This makes it possible to remove any trapped gas in the oil/water measuring bore or any trapped water in the gas/oil measuring bore.

Core Holder

An X-ray transparent hydrostatic core holder was designed in close co-operation with the vendor (see schematic in Figure 3).

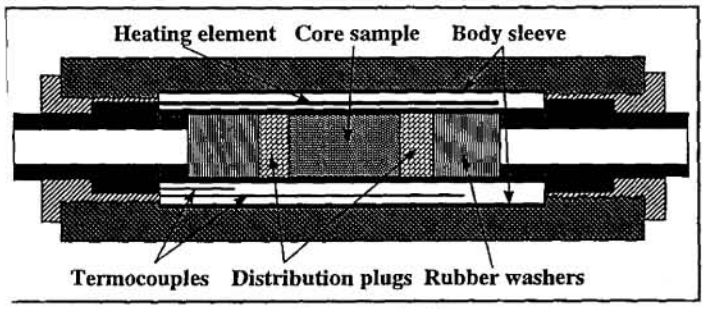

Figure 3: Core holder.

The core holder body is made of carbon fiber composite material, which makes it applicable for NMR imaging, microwave and X-ray scanning purposes. The fibrous body is permeable, and a rubber sleeve covers the internal to avoid leakages of the confining fluid through the body. The core holder contains an internal heater system with two thermocouples placed inside the core holder body; they act as a temperature measurement device in a feedback control loop for maintaining constant temperature and protecting the system against over-heating. A 1/8" heater cable is looped back and forth over the top of the core, along its entire length, while the thermocouples are placed on each end of the core sample.

The core sleeve is made of hydrogenated nitrile material. As this rubber material is not resistant to gas diffusion, a barrier is needed between the core and the rubber sleeve; aluminum has been wrapped around the core before assembling the sleeve and the fibrous body. First, however, the core is wrapped with a relatively thick plastic-foil to prevent the aluminum from being in contact with the saline water present in the core. Teflon tape is used to seal the aluminum to the core and to seal the sleeve to the aluminum. Distilled water is used as the confinement fluid, and the pressure is controlled by using the eighth cylinder in the pumping system described above.

The inlet distribution plug has three separate spiral grooves for water, oil and gas, respectively. A screen is placed at the outlet end of the core to avoid particle wash out, and to ensure uniform fluid flow through the entire core cross section area. The outlet distribution plug is of conventional type with three concentric rings and a cross hatch every 45 degrees. Both distribution plugs have pressure ports for measurements of differential pressure between the end faces. Several Viton washers behind the distribution plugs transmit an axial stress proportional to the confinement pressure. All the flow lines are 1/16" corrosion resistant tubes with an inner diameter of 0.5 mm. This inner diameter minimize the hold-up volumes from the core sample to the valves connecting the core holder to the flow apparatus.

X-ray Scanner System

The X-ray absorption method has been used for several years to determine fluid saturations in two- and three-phase relative permeability experiments[2,3]. In this method, an X-ray beam is sent through the core sample and the intensity of this beam is detected after having passed through the sample. As the X-ray absorption depends upon the density of matter through which the beam passes, the measured intensity will vary with the saturations of the fluids in the core sample. A schematic of the X-ray scanner system is shown in Figure 4.

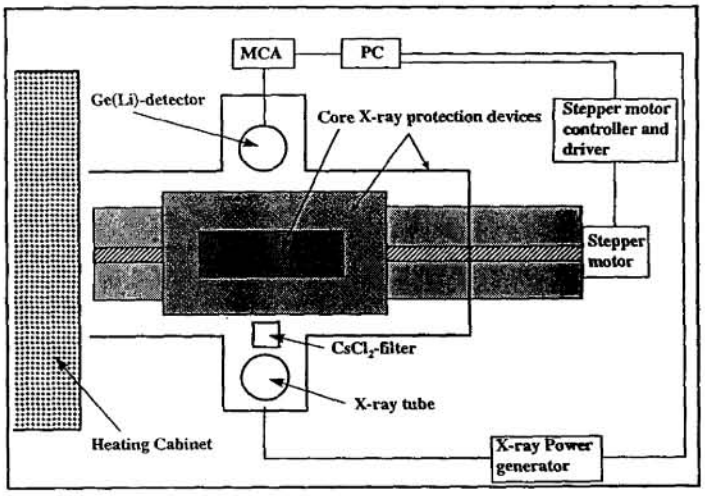

Figure 4: X-ray scanner.

The X-rays are generated by a spectrometric X-ray tube equipped with a tungsten target with a matching power generator. A Germanium-Lithium detector is connected to a multichannel analyzer which determines the intensity of the beam after it has passed through the core sample. The X-ray tube and the detector are enclosed by a lead-lined X-ray protection device and mounted on a track. This is called the X-ray scanner, and is moveable along the core by a stepper motor device. This set-up allows fluid saturations to be determined at various discrete positions along the core. The resolution of the stepper motor is 0.127mm, and the accuracy of the position is empirically determined to be less than 0.1mm, which is satisfactory for most applications.

The three-phase saturation determination is based on Beer-Lambert's absorption law, and consequently, two (discrete) energy levels are necessary (see Oak [2] for details). This is approximately obtained by utilizing a $CsCl_2$-solution in a glass container between the core and the X-ray tube. This cesium-filter strains the polychromatic X-rays down to two relatively narrow

wavelength bands. However, the cesium-filter reduces the intensity significantly, and about 10 minutes counting time is required at each position to obtain sufficient statistics. Consequently, this method can only be used for saturation determination in steady-state situations. However, for a two-phase situation, the cesium-filter is not necessary, and saturations can be measured dynamically.

When X-rays are generated, radiation will occur in all spatial directions, and a radiation protection system is implemented to keep the radiation in the laboratory at a level not above the background. The X-ray tube itself is covered, and have a shutter system to avoid radiation leakage. The shutter is opened whenever radiation is measured, otherwise it is closed. To prevent radiation when operated, the entire core holder and the scanner device are covered by lead. Figure 4 also shows the radiation protecting device enclosing the X-ray scanner.

Additional Accessories

The differential pressure across the core sample is measured using a high resolution transmitter with adjustable range. Two transmitters are placed across capillary tubes in the water and oil flow lines, monitoring viscosity variation during flooding.

Three high pressure titanium piston cells are used as reservoirs for the fluids; we here use formation water, oil, and gas. They are all located inside the heating cabinet and are operated at high pressure. The purpose of the cells is to load the three-phase flow apparatus with live reservoir fluids at reservoir conditions. They are located in the cabinet on a hinge, and sufficient space is allowed to have the possibilities of shaking the fluids if having sat for a while. To ensure good mixing, a titanium ball is placed on the reservoir fluid side of the piston. All piston cells are closed off during the recycling experiments.

A membrane-type back-pressure regulator is used to decrease the pressure from the operating pressure to atmospheric pressure in a controlled manner. It is only used prior to experimentation when reservoir fluids are introduced into the system at reservoir conditions, and is closed off during experiments.

The entire flow apparatus is connected with tubes and several types of adapters, either manufactured of Hasteloy-C or SS-316. Air actuated two- or three-way valves are used in the entire system, except for the valves used on the core holder and the piston cells. To avoid pressure shock to the core sample and from the piston cells, non-rotating stem valves are used to connect the core holder and the piston cells to the system. These valves make it possible to bleed pressure carefully when these parts are connected to the flow apparatus.

Everything, except the X-ray system and the core holder, is placed in an electrically heated cabinet where the temperature in the interior is continuously controlled by a microprocessor. Air circulation within the heating cabinet is ensured by a fan. The temperature accuracy within the cabinet was empirically determined to be ± 0.2°C. Two hydrocarbon detectors (HC-detectors) are used to detect any leakage of highly flammable hydrocarbon gases; one is placed inside the cabinet, while the other is placed on the outside.

Calibration and Testing

A calibration and a comprehensive test of the flow apparatus were performed. As all relative permeability calculations are based on saturation and pressure drop data, particular attention was paid to how these quantities may be measured with the present system. Particularly, we here report on the accuracy of the pump volumes (controlling the flow rate accuracy), the pressure, the leakage in the system, and, finally, the accuracy of the saturation determinations obtained by the X-ray and by means of the separator.

Pumping system

To get correct flow rates from the pumping system, the cylinder volumes and cylinder pressures need to be correctly calibrated at all times. During operation, the pumping system calculates the cylinder volume from the number of steps the stepper motor makes during the piston movement. The conversion factor (calibration) is factory set. We checked this calibration by measuring the volumes displaced from each cylinder gravimetrically. Our results showed that the deviation between the volume estimated gravimetrically and the readings from the pumps deviated less than the error in the weight measurements (typically, a deviation of 0.003ml was observed). A conservative estimate of the errors in the pump volume readings is ±0.01ml (which is ±0.1% of the cylinder pump volume). The pumps are to be kept at the same temperature as the rest of the apparatus during experimentation, and hence any expansion of the fluids caused by temperature variations is avoided.

One of the transducers connected to the pump cylinders was calibrated against a dead weight tester. It was linear with maximum deviation between true pressure and measured pressure of 70kPa, which is 0.1% of maximum range of 70,000kPa. All the other transducers were calibrated against this transducer; the zeros, spans and deviation of these transducers are equal to the dead weight calibrated transducer. During recycling experiments, all transducers are calibrated against this transducer each time a cylinder starts to retract. The pressures in all cylinders will therefore be precisely calibrated to each other during an experiment, and secure a smooth switch-over between each cylinder pair.

The variation of the back-pressure (maintained by cylinder 7) was within 7kPa when operating the pumping system at 2ml/min, while the variation increased to be within 14kPa at 10ml/min. This variation is too small to impact the observed pressure drop across the core sample or the volume readings from the separator, and is regarded as being acceptable. In general it is of high importance that the back-pressure is kept within these limits during the experiment. When operating at high system pressures, small oscillations in the pressure will significantly affect the relatively small pressure drop across the core sample. However, in this system, the hold-up volumes in the pumps in front of the

core sample are small, and even amplified oscillations can be permitted.

One of the major challenges during building and testing of the apparatus was controlling and monitoring the leakage in the pump cylinders. To avoid leakage of gas, distilled water was used in the gas pumps, hydraulically transmitting the gas through two high pressure containers into the core sample. Only negligible leakage was observed. Both water and oil are injected directly into the core without any use of hydraulic transmission. The leakage from the entire apparatus is kept less than 0.1 ml/day for all phases. This leakage rate may seem to be large as a typical three-phase experiment may last for about three weeks. However, the total leakage is tracked throughout the experiment, and the volume readings are corrected to obtain accurate average saturation estimates. The leakage of each phase is determined prior and subsequent to the experiment, and at any steady-state conditions attained during the experiment.

Acoustic separator

Initial calibration checks of the separator showed a relatively large hysteresis of the water volume between increasing and decreasing volumes, corresponding to upward and downward movement of the interface between the oil and water phases (i.e., the meniscus). No such hysteresis was observed for the gas volume (i.e., the meniscus between the oil and gas phases). During recirculation of the phases, there will be a rate difference between the cylinders that deliver and receive fluids. This results in a volume compensation by cylinder 7 (which is controlling the back-pressure). Hence, the meniscuses will be continuously going up and down throughout an experiment. The accuracy in the saturation measurements will be affected by this meniscus hysteresis. Though, by connecting the back pressure cylinder to the oil return line, the hysteresis will only occur during water recirculation.

The source of the hysteresis is the interfacial tension between the water and the oil phase. In the gas/oil interface, which has a lower interfacial tension, we observe a suppressed hysteresis behavior. This indication of less hysteresis with decreasing interfacial tension was experimental verified by measuring the hysteresis on several fluids with different interfacial tensions. The lower separator bores, which is where the oil-water meniscus is located, were treated with a thin layer of PTFE Teflon. The hysteresis of the oil-water meniscus was far less severe (also; the shape of the acoustic signal from the interface did not change significantly between upward and downward movement of the meniscus). The treatment with the PTFE Teflon may affect the wettability of the core sample during experimentation. A liner of Teflon should therefore be installed in the bores to avoid any solubility of the Teflon into the fluids, particularly at high temperatures.

At calibration, the separator was initially filled with distilled water, white oil and air at atmospheric pressure. Distilled water was then injected into the separator to increase the volume of water, and air was produced from the separator. Distilled water was then drained from the separator to check the hysteresis effect in the separator. As can be seen from Figure 5, th linearity is good; the slope is only slightly differer from unity, and the zero offset is small. A deviatio between increasing and decreasing water volum (hysteresis) can be observed, and is shown in Figure 6 However, the maximum difference never exceeds 0. cc. These results were verified at 20.700kPa and 30°C.

Estimating the maximum error to be ±0.3cc, th errors in the measured production volumes from a cor sample with 55ml pore volume (typical for ou applications) correspond to 0.5% of the pore volume This error is acceptable, as a pore volume of 55m represents a core sample of diameter 3.78cm with 12cn length and a porosity of 40% (chalk), or a 20cm sampl with 25% porosity (sandstone). The separator hysteresi and the separator calibration are checked with the pumps at test conditions prior to each experiment, and potentially, new error estimates and corrections can be made in the average saturation calculations.

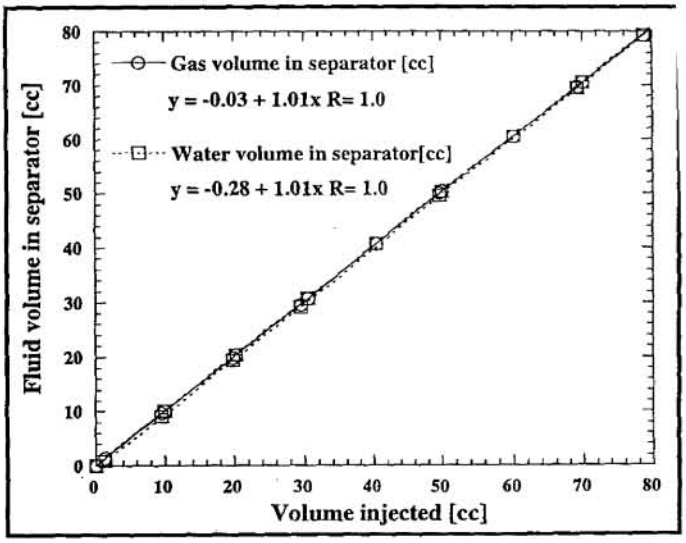

Figure 5: Separator calibration.

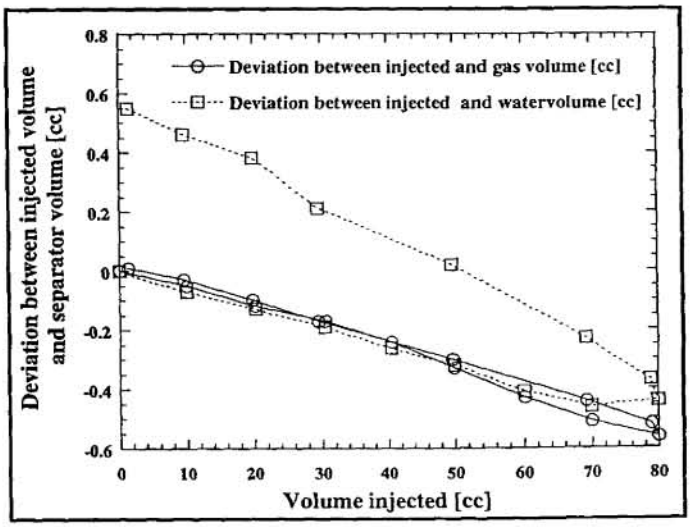

Figure 6: Separator hysteresis.

The hysteresis of the meniscus and thereby the volume measurements will be affected by the flow rates of the fluids through the core sample. When performing experiments on chalk samples, the rates will typically be relatively low. At such conditions, very small oscillations in measured production have been observed (see the magnified part of Figure 9). We have further reduced the hysteresis by optimizing the interactions between the receiving cylinder and the delivering cylinder in each pump.

Determination of average fluid saturation

A three-phase steady state flow experiment was conducted on a water-wet Berea sample to test the performance of the apparatus and to compare saturation measurements by the volume balance and X-ray absorption methods. First, a primary drainage two-phase flow experiment (denoted DIC[1]) was conducted, in which oil displaced the water in the core until an intermediate water saturation was obtained. Subsequently, a DDI three-phase steady-state experiment was performed by decreasing the total water and oil flow rate and/or increasing the gas flow rate in steps (in this test all three phases were injected simultaneously). The Berea sample used in this experiment was of length 29.80cm, had a diameter of 3.78cm, a porosity of 19.5%, and a water permeability of 171.4md. Synthetic formation water and white oil were used as the water and oil phase respectively, while nitrogen was used as the gas phase. The viscosities for the water, oil, and gas phases were 1.071cP, 1.279cP, and 0.0187cP, respectively. The experiment was carried out at 5000kPa pore pressure and at ambient temperature.

The production of all three phases from the core sample was collected and measured in the three-phase separator. To determine the average saturation of the fluids in the core, the separator readings were corrected by performing a total mass balance calculation for the entire system. Particular attention was paid to the hold-up volumes into the core and from the core to the separator. As the outlet hold-up volume is dependent upon the fractional flow of the phases, a post-experiment correction is made. The hold-up volumes are minimized to minimize the importance of errors in the hold-up volume estimates on the accuracy of the average saturation estimates. For details, see Ebeltoft et al. [4].

The X-ray absorption method was used to determine average fluid saturation in the core[2]. Simulated formation water and white oil were traced with cesium and iodine compounds ($CsCl_2$ and 1-Iodooctane), respectively, to enhance the X-ray absorption and provide better accuracy in the saturation determination. Water and oil saturation were calculated from the absorption at the two selected energy bands (strained by the cesium-filter) by using Beer-Lambert's absorption law. The absorption constants needed for the calculations were obtained from three reference X-ray scans, one with the dry core, one with the core 100% saturated with water, and one with the core 100% saturated with oil. Gas saturation was calculated utilizing that the sum of all saturations equals unity. The X-ray absorption method provides average saturations within a cylinder through the core (perpendicular to the length). The area of this cylinder is 0.2 cm^2, defined by the collimator geometry. The X-ray absorption measurements are carried out at a number of axial positions (here 12 locations are selected at 2%, 7%, 12%, 18%, 35%, 52%, 65%, 82%, 88%, 93%, and 98% of the core length specified from the inlet end face). The average saturation in the entire core sample is determined by linear interpolation and integration. X-ray intensities were measured for 10 minutes at each position at steady-state conditions.

The average saturations determined by the two methods are represented in the cross-plots in Figure 7.

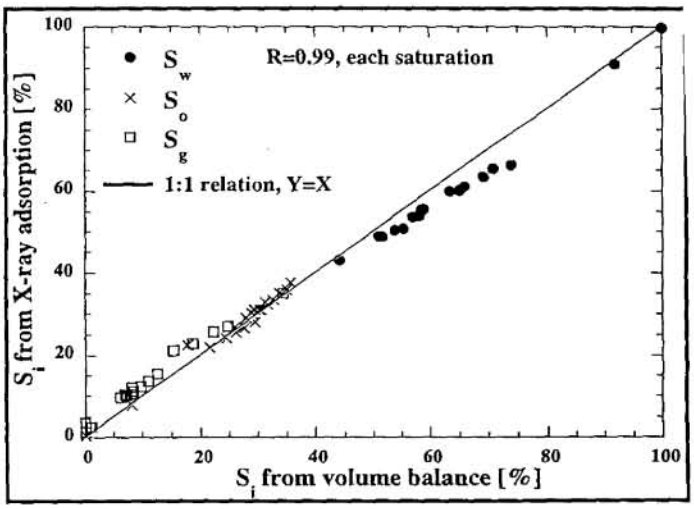

Figure 7: Average saturations from X-ray absorption and volume balance.

Linear regression has been performed for each phase separately to assess the methods. Saturation estimates from both experiments are used. As can be seen from these figures, a good linearity is obtained over the entire saturation range (see linear regression coefficient). An offset is experienced in the water and gas saturation estimates, while the oil saturation estimates are in full compliance. Assuming the separator measurements to be correct, this offset may be caused by $CsCl_2$ adsorption phenomenon on the rock surface between each reference scan, and/or by cesium-filter vaporization (which increased the filter concentration during these tests). Both these phenomenas will lead to underestimation of the water saturation by the X-ray absorption method. This is supported by Figure 7, where the water saturation from the X-ray method is below that from the volume balance method. Oil saturations are in full compliance from the two methods, and consequently the gas saturations are overestimated by the X-ray method since we assume that the sum of all saturations equal unity.

The notation DIC refers to Decreasing water saturation, Increasing oil saturation, and Constant gas saturation, and follows Oak[2]. The three letters indicate the direction for the average saturation change for each of the fluid phases within the core sample (water, oil and gas, respectively).

Table 1: Specifications for the three-phase flow apparatus.

Maximum operation pressure [kPa]	70,000 ± 70 [1]
Minimum / maximum rate [ml/min]	0.001 / 10.0 ± 0.2% of set rate
Maximum temperature [°C]	160 ± 0.1
Separator volume, each phase [cc]	95 ± 0.5
Available amount of fluids	Unlimited, recycling of fluids
Wetted parts	Hasteloy C-276 or silicon carbide
Saturation accuracy [% of PV][2]	
Volume balance, S_w / S_o / S_g	±2 / ±2.5 /±1.5
X-ray adsorption, S_w / S_o / S_g	±2.5 / ± 2.5 / ±5
Differential pressure accuracy	±2% of measured value
Types of experiments	Steady-state and unsteady-state or combination. Injection of one, two, or three phases simultaneously. Change of saturation direction without interuption.

[1] Operating line pressure to the differential pressure transmitters: 42,000kPa
[2] Assuming a porevolume of 33cc

The errors in the average saturation for the two above outlined methods are estimated through error propagation calculations for the respective saturation expressions, and are shown in Table 1. The error will vary from phase to phase, saturation and total pore volume accessible. The stated errors are approximate maximum errors given in saturation units, and are for an experiment on a sample with porosity of 40%, length of 7.5 cm and diameter of 3.8cm. Table 1 summarize the specifications of the three-phase flow apparatus.

Three-Phase Experimentation

Three carefully designed steady-state type three-phase experiments were conducted on one chalk sample[5]. The chalk sample had a water permeability of 2.27md, a porosity of 39.8%, a length of 12.26cm, and a diameter of 3.80cm.

Different types of interpretation techniques exist for determining relative permeabilities. In principle, either explicit methods (like the JBN technique[9] frequently used for determining two-phase relative permeabilities) or implicit, or so-called "history matching" techniques, can be utilized. The explicit techniques require that high viscous forces are applied in order for the influence of capillary forces to be negligible. The second approach, which is used in this work, can be used on data from experiments conducted at a rate close to those experienced in the reservoirs as the capillary pressure is included in the analysis; see [6,8]. This method for determining the flow functions from flooding data is based on the principle that the estimated flow functions should lead to simulated data which in some sense "match" (or reconcile) the measured ones. A general purpose three-phase simulator has been developed for this purpose[8]. This simulator allows for simulation of any injection strategy that is possible to run in this apparatus. By parameterizing the flow functions, we select as the estimate those parameters that minimize the objective functions defined as the weighted sum of squared differences between measured and simulated flooding data. Here, a tensor product B-spline representation is utilized for each of the flow functions as each relative permeability (and capillary pressure) function will be surfaces when plotted as a function of two independent saturations; see details in [8]. Note that we in the interpretation methodology utilize data from all the experiments simultaneously.

For chalk, this approach is particularly tractable. In experiments conducted to be utilized in conjunction with the JBN technique, the flow rates should be high in order for the assumption of zero capillary pressure to be valid. For chalk, however, this is definitely not desirable, as a high flow rate will cause a high pressure drop across the low permeable medium, and may damage the fragile material. In a two-phase situation, this has been overcome by utilizing low flow rate, and conducting the experiments as a series of steady-state steps, measuring the produced volume and pressure drop across the core as a function of time (see [10]). The experiments and interpretations shown here are the extension of that methodology to three phases.

The three-phase experiment was designed to determine water, oil and gas relative permeability functions simultaneously with the capillary pressure functions when water is injected into an oil and gas filled zone in the field. This means that the water should be injected into the core at low initial water saturation. The initial water saturation in chalk fields is in general very low, and quite hard to establish in the laboratory. The initial water saturation was therefore set to zero, and the core was initially saturated 100% with oil. First, a two-phase water-oil flow experiment was conducted (IDC). Upon completion, the core was cleaned and saturated with oil. Then, a two-phase oil-gas flood was conducted to an intermediate gas saturation (a CDI to approximately 40% gas saturation), before water was injected (in a series of steady-state steps) simultaneously with oil and gas (IDD-1). Upon completion, the core was again cleaned, dried and saturated with oil. A new CDI followed by an IDD experiment (denoted IDD-2) was conducted; this time the water was introduced at a gas saturation of about 30%.

During the three-phase experiments, oil and gas rates were kept constant while the water rate was increased in steps. In each of the IDD experiments, the final step was

with a 100% rate fraction of water. Figure 8 shows a ternary diagram of the trajectories for all the three experiments (average saturation of the three phases at different times during the experiments). For all experiments, production of all phases were obtained together with the differential pressure across the sample as a function of time. The experiments were conducted at 20,700kPa and 30°C, with a net overburden pressure of 7000kPa. Synthetic formation water, dodecane, and nitrogen were used as the water, oil, and gas phases, respectively. The respective fluid viscosities are 1.280cP, 1.238cP, and 0.0187cP.

All three experiments shown in Figure 8 is utilized in the estimation procedure. We here show the volume produced and pressure drop data from the experiment where water is injected at approximately 40% gas saturation (i.e., the IDC followed by IDD-1). Figure 9 and 10 show the measured data along with simulated data using relative permeability and capillary pressure functions resulting from our estimation procedure. Details of this procedure can be found in Nordtvedt et al. [8], and details on the interpretations of the experiments can be found in Nordtvedt et al. [11]. Figure 11 show the estimated oil relative permeability surface. Figures 9 and 10 also show typical experimental data magnified to visualize the variation in the measured data. The oscillations for the volume measurements are less than ± 0.2cc, while the oscillations in the differential pressure measurements are typically ± 2% of measured value.

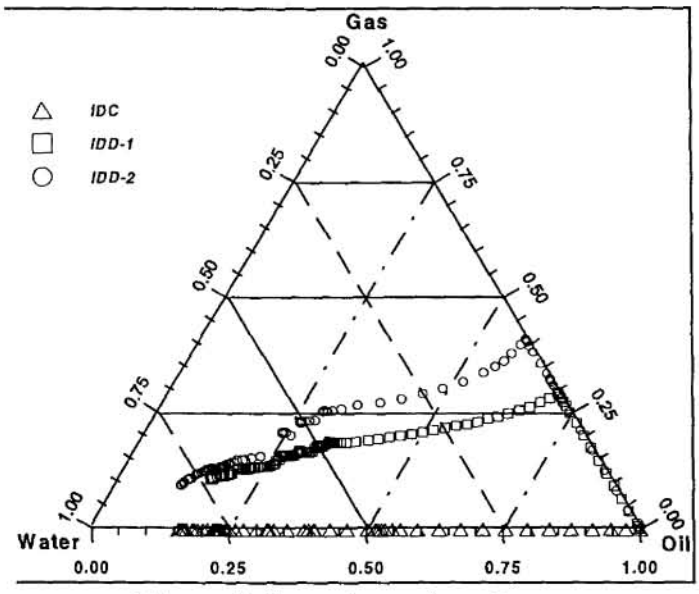

Figure 8: Saturation trajectories.

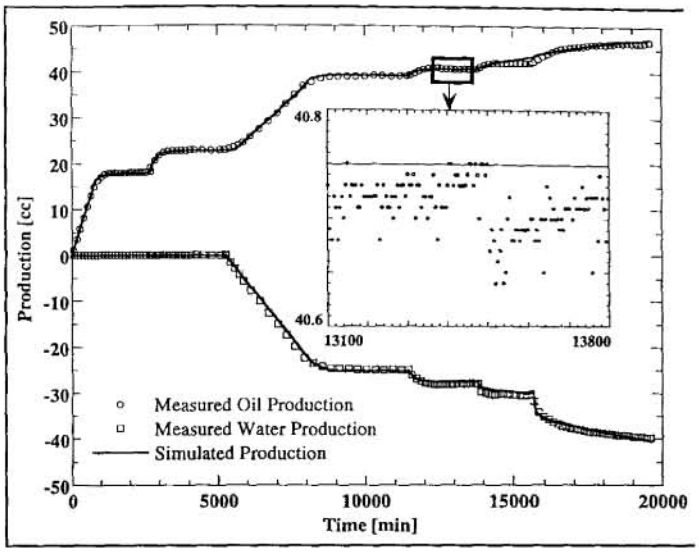

Figure 9: Experimental and simulated production data.

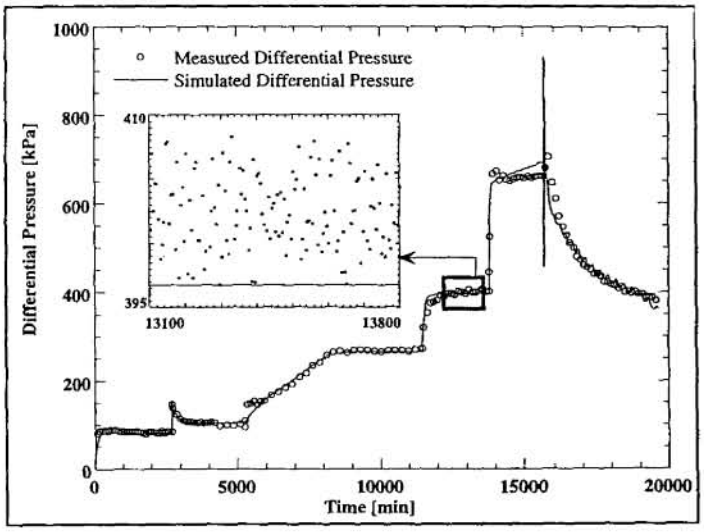

Figure 10: Experimental and simulated differential pressure data.

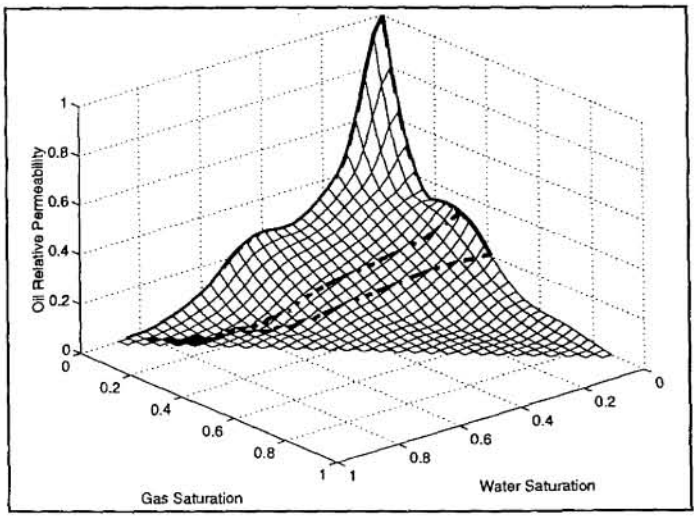

Figure 11: Estimated three-phase oil relative permeability.

Discussion

The apparatus described and tested above provide high quality three-phase core analysis data at reservoir conditions. It is very flexible; both steady-state type and unsteady-state type experiments can be performed, either alone or in combinations. It is of great current interest to the industry to study WAG processes at reservoir conditions. This apparatus has the capability to alternate injection of all phases without any stop of fluid flow through the porous media. This avoids the hysteresis effects that may occur while flow is interrupted, and the saturation directions are changed. The control of the fractional flow of the phases into the media, makes the apparatus well suited for studying hysteresis when direction saturation changes are varied in selected saturation ranges where two or three phases flow. The apparatus also makes it possible to force the saturations in different directions to provide data of most interest for field applications.

Conclusions

1. A novel three-phase flow apparatus has been designed, constructed and tested. It allows simultaneously injection of one, two, or three phases into a porous media. Both steady-state type and unsteady-state type experiments can be conducted;
2. Average saturation determinations by the methods of volume balance and the X-ray absorption is in good compliance;
3. A three-phase acoustic separator has been developed to measure production of three phases; and
4. A core holder has been designed and built for in-situ saturation measurements at reservoir conditions.

Acknowledgments

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