SCA-9853

State-of-the-art X-ray Steady State Apparatus for advanced core flow studies.

by

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1. Introduction

In dynamic reservoir flow studies, e.g. for field studies and up-scaling programs, relative permeability curves form indispensable input data. In order to provide such data, steady state flow measurements are carried out on field core plugs. The steady state flow test incorporates the in-situ measurement of 2-phase fluid saturations and pressure drop over the core. These data are in turn used for quality control and validation of the measurements via numerical simulations.

Current steady state experiments suffer from a number of short comings hampering correct analysis and a high output data quality. For instance: gamma-ray equipment is applied for in-situ measurement of saturations. Its principle is based on measuring the attenuation for gamma rays by the fluids in the core. This method suffers from long counting times (e.g. 20 min/data point), when sufficient accuracy (1 sat%) should be obtained. This is due to the limited strength of the radio-active sources and the large attenuation induced by the (metal) core holders and the core. Another drawback of this method is that the absorption contrast between water and oil needs to be enhanced by using dopands in one of the fluid phases. For instance one could apply sodium-iodide in the water phase. This however incorporates the risk of precipitation of dopand onto the rock-surface and altering the wettability characteristics of the rock-fluid system.

As an effort towards improved Special Core Analysis (SCAL), Shell International Exploration and Production, Research and Technology Services (SIEP-RTS) at Rijswijk, The Netherlands has built a new and innovative X-ray Steady State (SSX) apparatus. The objective was to improve the accuracy and speed of measurement of this technique significantly and to provide higher quality output in conjunction with enhanced interpretation. The major innovation comprises the introduction of an X-ray source for in-situ saturation measurement. X-ray sources offer high radiation intensities, are tuneable in energy and are less demanding on the environment than radio-active sources. Other innovations on SSX involve the use of natural un-doped fluids for flow, new X-ray detectors and X-ray transparent core holders. In this note the respective innovations on SSX are presented in subsequent order.

2. Equipment innovations.

2.1. X-ray source.

The use of a high flux industrial X-ray source to provide fast 2-phase saturation measurements with high statistical accuracy enables:

- fast oil/water saturation measurement i.e. 0.2 seconds per position,
- sweep-scanning of the core over a 15 cm range in 12 seconds,
- discrete position scanning of the core over 40 discrete points with +/- 5 μm accuracy,
- a measurement accuracy of +/- 1 sat% using natural, un-doped fluids thereby maintaining the original wettability characteristics of the rock-fluid system and
- environmental low impact as the radioactivity can be switched off.

2.2. X-ray detectors.

Standard X-ray detection by photo counting cannot be applied at high X-ray fluxes beyond $>10^6$ ph/s.cm². Special $CdWO_4$/photodiode X-ray detectors were developed in-house based on current measurement. Using a 125 kV energy spectrum the dynamic range for the detection signal for a change of 100% water to 100% oil is only 4%. The accuracy of the detector system should therefore be high to measure this small difference to 1sat% accurate i.e. +/- 0.04%. The detectors measure the full X-ray continuum with excellent signal to noise ratios.
In order to monitor a possible drift in X-ray source flux a second X-ray detector at the edge of the core-holder was mounted in direct view of the primary X-ray beam. Any drift in source flux would be monitored by this detector and be compensated for in the signal of the main X-ray detector.

2.3. Carbonfibre composite technology for the core holder.

Composite materials exhibit 4-6 time higher strength than steel. A radially wound carbon fibre epoxy tubing was used as core-holder mantle. The maximal pressure drop over the core is 20 bar and the pressure on the sleeved sample is 75 bar. The carbon fibre vessel weakens the X-ray beam considerably less than steel contributing to accurate saturation measurement.

2.4. Multiple pressure ports.

During flood the pressure decline along the core is measured over the full core length as well as 4 positions along the core. The derived pressure profile along the core may reveal the occurrence of heterogeneity in the core plug which may considerably influence the interpretation. (acc. 0.075% FSD).

2.5. Multiple resistivity electrodes.

Resistivity is measured over the full core as well as 4 positions along the core. The resistivities together with in-situ saturations permit bench marking of relative permeability data to the resistivity-saturation data acquired at reservoir temperature with other experimental equipment.

2.6 Pulse-free fluid pumps.

Standard micro HPLC fluid pumps usually introduce undesired pressure pulsations thereby disturbing accurate analysis. A quite unique and low-cost innovation has been introduced to alleviate this problem by a tandem combination of two Pharmacia HPLC fluid supply pumps for each of the fluid phases (water or oil) controlled by a Programmable Logic controller. (Flow-range 0.01 - 20.00 ml/min).

3 Conclusions.

A new and versatile X-ray steady state apparatus has been developed at Shell Research. The equipment offers fast and accurate saturation measurement along a core using natural un-doped fluids, allowing the use of native state core plugs. Drift in X-ray source flux is compensated for by using a monitor detector in the primary beam. In-situ calibration of fluid X-ray absorption coefficients is possible. The measurement is accurate to +/- 1sat% for samples with a porosity as low as 25% PV. The saturation profiles allow correction for entrance (mixing) effects and the capillary tail-effect during the interpretation of the data. The saturation profile data in combination with pressure and resisitivity data along the core permit accurate and fast relative permeability measurement as well as interpretation by numerical simulation. Moreover, these data permit bench marking of relative permeability data obtained with other equipment. The X-ray steady state equipment will serve as a valuable asset to the SCAL portfolio of SIEP-RTS.

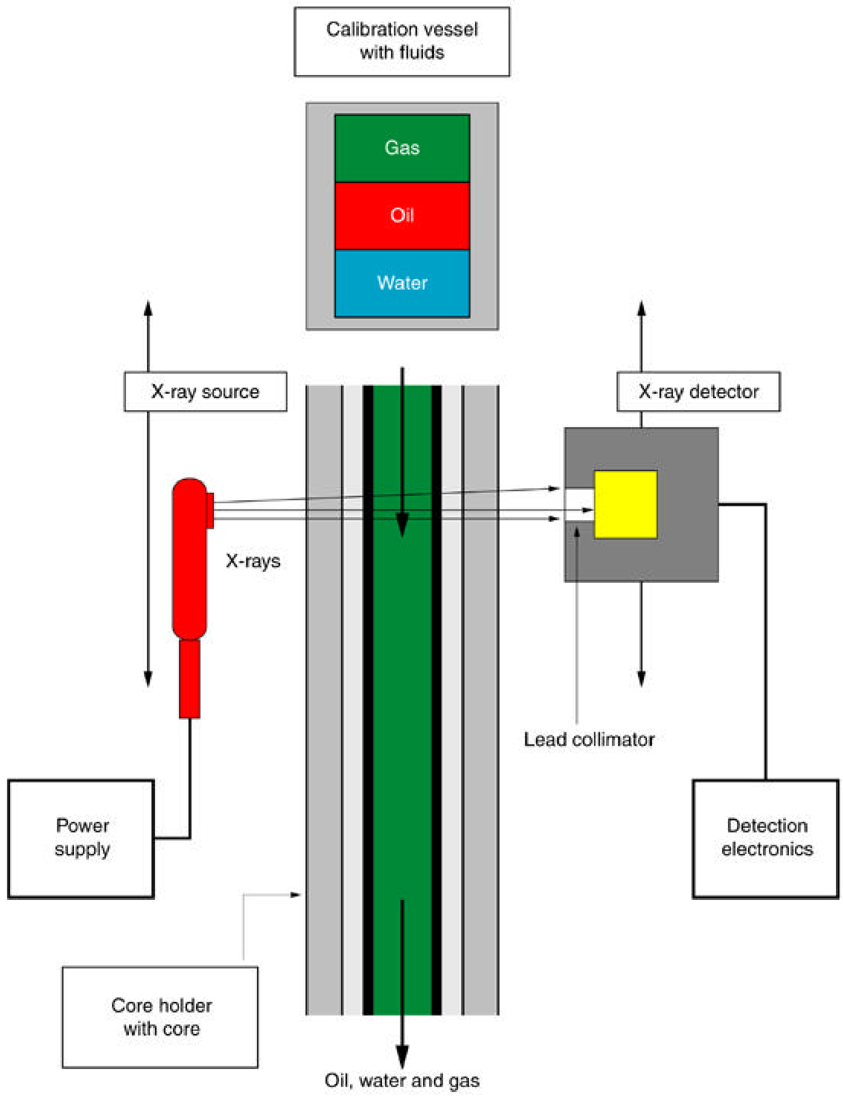

Figure 1. Schematic overview of the X-ray Steady state equipment.
The X-ray source and detector can be moved along core as well as along the calibration vessel. The calibration vessel can also contain core plugs saturated with 100% oil, water and gas.

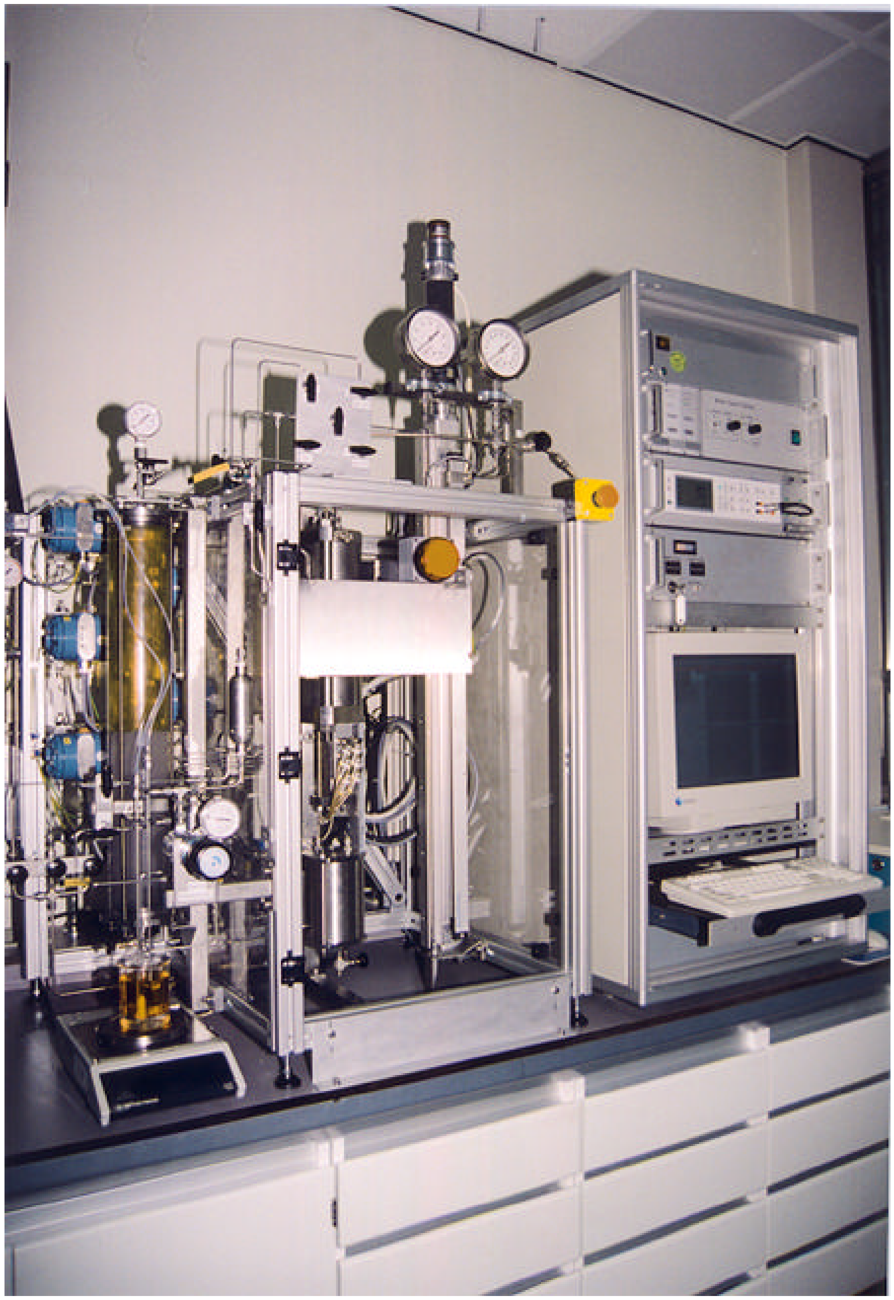

Figure 2. Overview on the X-ray Steady state equipment at SIEP-RTS.
The core holder with the X-ray source is in the centre.