CASE STORY: X-ray Technology for Oil & Petrol Exploration

Multiphase flow measurement – core scanners and pipe flow monitors

INTRODUCTION: X-RAYS IN PETROPHYSICAL AND MULTI-PHASE FLOW RESEARCH

Many dynamic processes take place at conditions where they cannot be followed in real-time, either due to they take place internally in an opaque structure, or due to that it is the constituents distribution in a mixture that must be quantified and where other inspection methods are inadequate. The systems offered by InnospeXion are directed towards two areas: The core flow analysis for Enhanced Oil Recovery (EOR) and Quantitative imaging of fast flow in pipe spool systems.

The quantitative assessment of how the oil can be extracted from the reservoir rock is highly relevant for the oil exploration. The amount of oil that can be recovered depends on a large number of inter-dependent factors, such as the rock void structure, the interconnection of voids, the pressure and temperature in the reservoir, the options for pressing the oil from the reservoir rock, and many others. As introduced by Worden et al. (2018; https://sp.lyellcollection.org/content/435/1/1):
"Porosity and permeability (reservoir quality) exert fundamental controls on the economic viability of a petroleum accumulation. They need to be quantified from basin access and exploration, via appraisal and field development through secondary and tertiary recovery in order to minimize cost and maximize return on investment. Consequently, the question of reservoir quality prediction is becoming ever more critical with exploration and production of petroleum in increasingly challenging conditions and from less conventional reservoirs. The porosity of a reservoir affects the volume of oil or gas in place and permeability affects the rate at which oil and gas flow from the reservoir to the wellbore. Measuring porosity and permeability using core analysis techniques ….., is essential for reservoir characterization….."

The above parameters can be quantitatively addressed in the Petrophysical research X-ray laboratory, where Core analysis X-ray is accomplished using a suitable rock as core. The core is placed into a high pressure resistant carbon fiber holder with flanges for oil/gas/water fittings, and subsequently placed in an oven where an X-ray system may scan the core with and without its content, at the P-T regime of the reservoir itself. These X-ray based permeability measurement are fundamental for enhanced oil recovery R&D.

Another important application for oil exploration concerns the real-time flow visualisation in large pipe spool test rigs (Multiphase Flow Measurement). The objective is the dynamic three phase flow quantification and studies of where and how risk of plugs and slugs may arise. Computer models supported by real and large scale tests are needed in order to validate the conditions where catastrophic incidents may occur. The process fluids are typically gas and liquid (oil and/or water), and solid particles, in varying proportions.

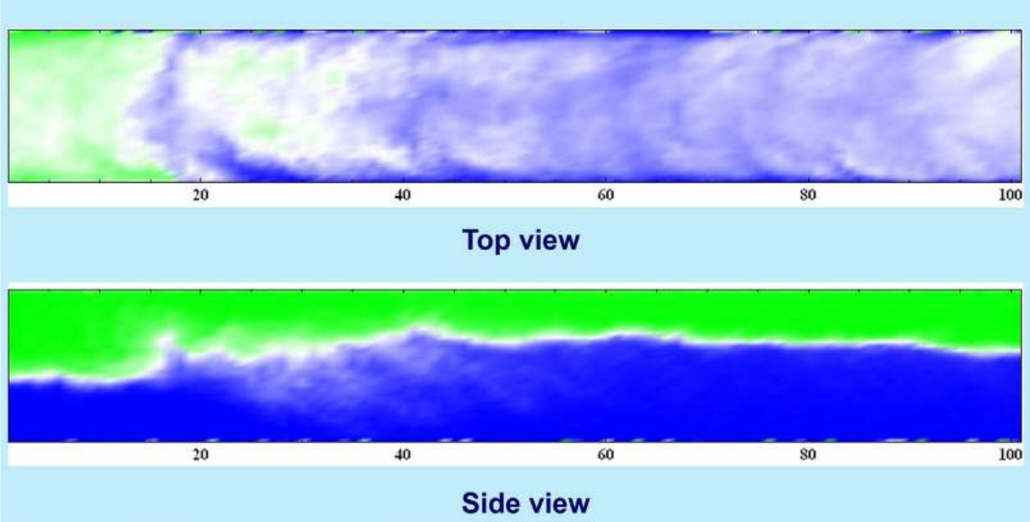

Fig. 1. A high speed X-ray image acquired from two sides of a multiphase flow pipe spool rig, showing mixing of oil and water containing phases at a wave front. Flow approx. 10 m/s.

The X-ray technology suitable for oil & petrol reservoir modelling as well as for petroleum exploration research must provide a high imaging speed, a very high contrast to discriminate the constituents, and a high resolution. Climate control of the entire system is needed in order to cope with high (120 deg C) oven temperatures in the lab, and with rough weather conditions in outdoor spool rig applications.

CORE FLOW VISUALISATION AND QUANTIFICATION USING X-RAYS

The InnospeXion core analysis X-ray systems for Petroleum Research are intended for the quantitative assessment of the two- or three-dimensional studies of the multiphase flow of oil, gas or water in porous reservoir rocks, in order to optimize the oil exploration possibilities through detailed X-ray permeability studies.

InnospeXion offers solutions for two and three phase discrimination and quantification, based on:

- Single crystal detectors with multi-channel analyzers to perform linear scans of a cylindrical core in a high P-T core holder, up to 1 m long, with or without rotation stage, horizontal core orientation. Slow scanning speed;
- Single crystal detectors with multi-channel analyzers to perform linear scans of a cylindrical core in a high P-T core holder, up to 1 m long, combined with a high speed, high contrast and high resolution image scanning detector, horizontal core orientation. Fast scanning speed (imaging detector);
- Single crystal detectors with multi-channel analyzers to perform linear scans of a cylindrical core in a high P-low T core holder. A system with multiple cores each up to 20 cm long, vertically oriented in fixed position. The system is configured for automatic repetitive scanning at set intervals. Slow scanning speed;
- (NEW - UPCOMING) multi-energy imaging (scanning) systems to perform linear scans of a cylindrical core in a high P-T core holder, up to 1 m long, with or without rotation stage, horizontal core orientation. Very fast scanning speed;
- Single crystal detectors with multi-channel analyzers to perform linear scans of a reservoir rock slabs (3-5 cm thick, up to 1 x 1 m), combined with a high speed, high contrast and high resolution image scanning detector, horizontal or vertical rock slab orientation. Fast scanning speed (imaging detector);
- (NEW - UPCOMING) multi-energy imaging (scanning) systems to perform linear scans of a reservoir rock slabs (3-5 cm thick, up to 1 x 1 m),, horizontal or vertical rock slab orientation. Fast scanning speed (imaging detector).

All of the above solutions are typically tailored the exact application.

The basis of our systems is the use of in-built calibration steps, stable X-ray emission sources, high stability detectors, and precision mechanics. To this, add our expertise in X-ray safety and know-how on X-ray technology. This is our solution to precise laboratory tests and experiments for 2– and 3-D flow interpretation. Thus, the InnospeXion systems are based on both **high precision X-ray attenuation measurement** AND **real-time high sensitivity imaging**. The flow assessment can be based on simple cylindrical core scanners, or complex three-dimensional rock slab imaging & measurement systems. The three-dimensional X-ray core scanner is based on quantitative attenuation and imaging of up to 1 by 1 m^2 rock slabs, aiming at three phase flow visualization in real time and subsequent quantification of the distribution of phases. To enable modelling based on the orientation of the strata, the entire system can be tilted at any angle from vertical to horizontal.

The new/upcoming approach is the use of multi-energy imaging detectors, to facilitate fast flow discrimination, on the total core / rock slab, in real time and with flow differentiation at pixel level! Please contact us for further details relative to your requirements.

THE ROCK PLATE SCANNER

Two sliding doors give access to the scanning system interior, Fig. 2. The system consists of a heavy duty linear guide set, onto which is mounted another linear guide set. The latter holds an X-ray source on the front linear guide and two detectors (one imaging detector that builds up an image by scanning, and a). The scanning is done over an epoxy covered rock sample that can reach 1000 by 1000 mm^2. The rock sample is mounted into a tray that can be completely extracted when the cabinet is in the horizontal position, also enabling easy fitting of hoses and connectors for fluids. The rock sample holder features areas where calibrations can be performed in order to enable a basis for comparison of scans made in different conditions (different fluids, e.g.).

Fig. 2. The InnospeXion rock slab scanner integrates fast X-ray image scanning and slow (but precise) point measurements with single crystal detector with multi-channel analyzer.

The rock plate scanner is based on a low kV X-ray source that emits a narrow beam of electromagnetic radiation, which is attenuated by the porous rock sample. Attenuation depends on the composition and porosity of the sample. The sample is placed in slide tray, which is made accurately to fit a 1000 x 1000 mm sample. The sample holder provides for an auxiliary system that enables a flow of a liquid through the sample, in a direction normal to the X-ray beam.

The scanner incorporates two distinct measurement options: (a) the real-time imaging of the actual attenuation image using a high resolution, high sensitivity linear array that is moved across the sample simultaneously with the X-ray source, and (b) the measurement of attenuation by the rock sample using a NaI scintillation detector which is moved in steps, simultaneously with the X-ray source. The first technique provides an image that may be correlated to an actual flow pattern and flow composition within the sample, whereas the second technique enables the accurate assessment of the actual composition of the flow constituents across the sample.

The scanner has been developed for quantitative studies of the flow of various fluid in the rock plates, i.e., an advanced form of traditional X-ray core analysis. The positional accuracy depends on scanning speed, and the statistical accuracy depends on the rock, the thickness and the integration time. At routine usage, the X-Y position accuracy is about 0.5—1 mm, and the counting accuracy is about 1-2 per cent for an average count rate of 20000 cps.

Better precision is possible at the expense of scan speed. A total scan at 5 mm reolution of a 1 x 1 m^2 rock in counting mode will take about 250^2 to 400^2 seconds, whereas the complete image scan takes about 5– 30 minutes.

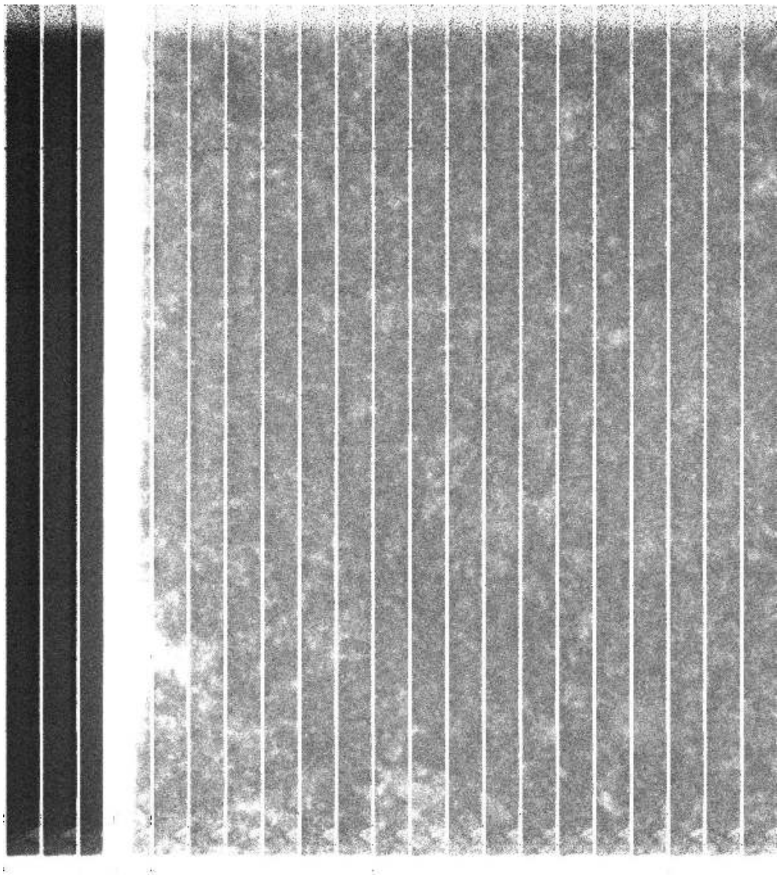

Fig. 3. Image scan of a carbonate reservoir rock sample. The brighter areas are rich in voids. Larger holes are seen as white areas. When a fluid enters the empty sample, the flow front migration can be studied on repetitive scanning. Semi-quantitative assessments can be based on grey level calibrations. Correlation with single point scanning single crystal detector may explain the flow pattern, flow speed and other process related details. Size of scanned rock plate is 1 by 1 meter, resolution 0.1 mm, 16 (12) bit dynamic range.

X-RAY ROCK CORE ANALYSIS SCANNERS

The systems for cylindrical core scanning are typically based on s scintillation detector for precision counting of the sample X-ray attenuation at discrete energy intervals. Through simple calculations, the composition of the fluids may be determined.

Fig. 4. Linear core analysis X-ray scanner for cylindrical core, up to 1 m long. The system is based on a high stability X-ray source and a scintillation detector positioned on a linear guide. Based on references placed at the end of the core holder, the 2 or 3-phase composition is calculated following each scan. Scan time for a core of 60 cm is about 3-10 minutes, depending on detector aperture and integration time at each measurement point. The system integrates a control PC with acquisition and processing hard- and software, coolers and air-condition unit.

Fig. 5. Cyclic linear X-ray core analysis scanner for short (200 mm) vertically positioned cylindrical cores (up to 48 in total). The system is based on a high stability X-ray source and a scintillation detector positioned on a linear guide. Based on references placed at the end of the core holder, the 2 or 3-phase composition is calculated following each scan. Scan time 0.5-2 minutes per core, depending on detector aperture and integration time at each measurement point. The system is PLC controlled and allows multiple, repetitive measurements over long time.

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Fig. 6. Linear core analysis X-ray scanner for horizontal cylindrical core, up to 1 m long, placed in a high stability oven (100-120 deg C) . The system is based on a high stability X-ray source, a scintillation detector, and a high sensitivity high speed X-ray image detector, all positioned on a linear guide. Based on references placed at the end of the core holder, the 2 or 3-phase composition is calculated following each scan. Scan time for a core of 60 cm is about 3-10 minutes, depending on detector aperture and integration time at each measurement point. Flow imaging across the entire core can be performed in 10 s. The system integrates a control PC with acquisition and processing hard- and software, coolers and air-condition unit. Automatic ventilation for CH fume extraction

X-RAY IMAGING SYSTEMS FOR MULTIPHASE FLOW MEASUREMENT

Real-time flow visualization in large pipe spool test rigs (Multiphase Flow Measurement) aims at the dynamic three phase flow quantification to predict risk of plug and slug formation. The process fluids are typically gas and liquid (oil and/or water), and solid particles, in varying proportions.
X-ray technology suitable for Multiphase Flow Measurement must enable a very fast image acquisition, and the images must have a high resolution. The challenge is to secure sufficient signal-to-noise ratio (SNR) at the fast recording speed. A low SNR results in a low contrast, and hence inability to discriminate the phases present. Therefore, the detection technology must provide the best possible sensitivity (highest possible detection quantum efficiency, DQE).

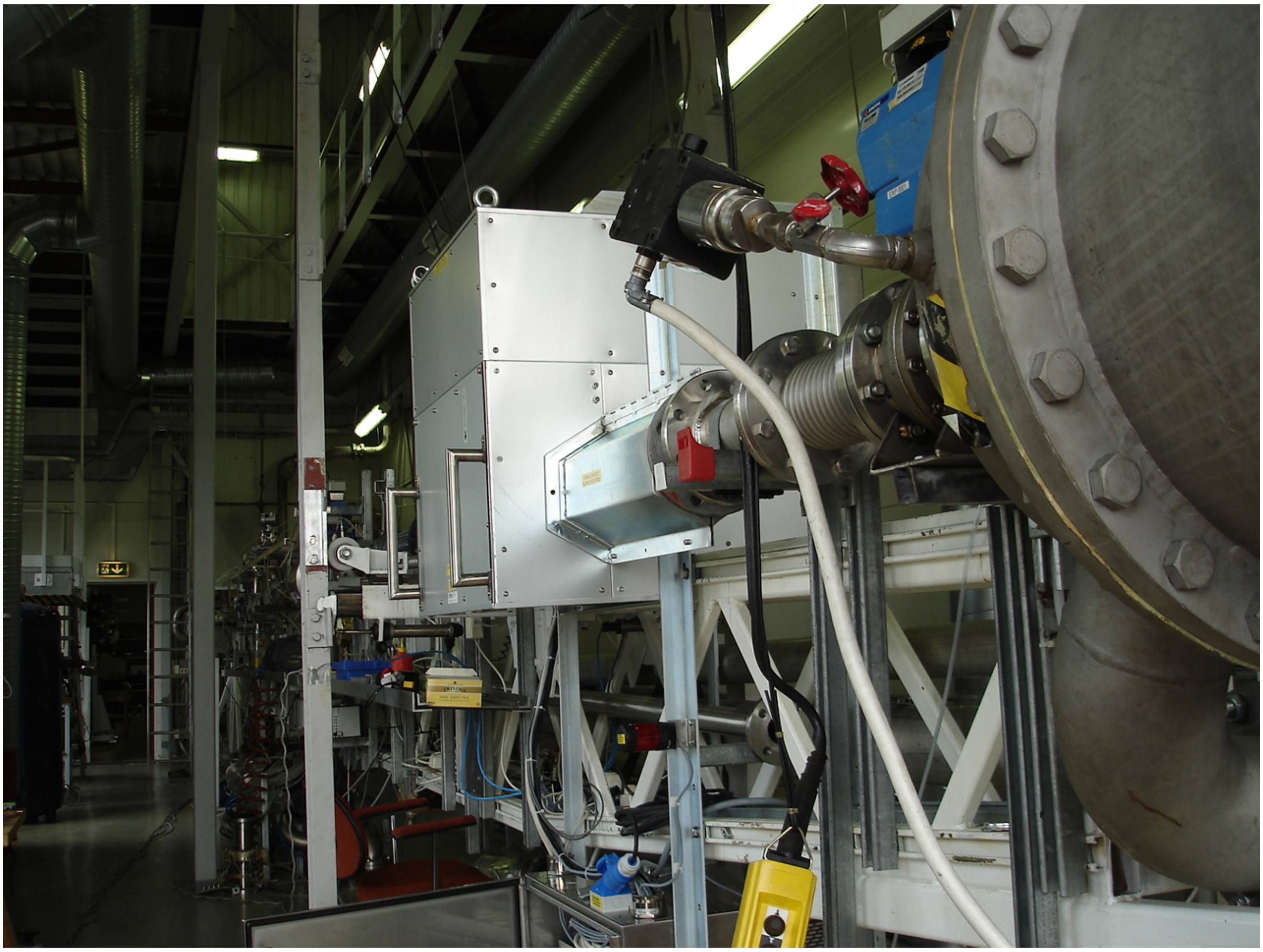

Fig. 7. X-ray system for Multiphase Flow Measurement mounted on pipe spool rig (20 m) in laboratory, for positioning between horizontal and vertical. Dual source-detector configuration (at 90 degrees). Remote control and image capture station. 110 mm diameter pipe.

Systems for Multiphase Flow Measurement on pipe spool rigs are invariably tailored to varying degree. They are fitted with the number of X-ray source-detector sets needed to enable the required spatial resolution and the precision of the assessment of the flow. Systems thus range from 1 projection to 6 projections, the latter forming a real-time CT system with sufficient quality cross section images at flow speed over 10 m/s.

Fig. 8. Detail of a 2-projection imaging system at a 110 mm pipe for Multiphase Flow Measurement. The pipework is stainless steel, but the X-ray imaging window is typically plastic or CFRP. X-ray imaging can take place at flow speed over 10 m/s.

Fig. 9, below. Multiphase Flow Measurement Pipe spool rig X-ray imaging system, single view. The system is fitted with heaters and air conditioning system for outdoor placement. Pipe diameter 250 mm.

The results from the multiphase pipe flow measurements differ relative to the actual scope of the work. At IFE (Institute for Energy Research, Kjeller, Lillestroem, Norway), a large R&D team works on various flow topics, including pipe spool systems, plug effects, and many others. To visualize and quantify the flow, IFE apply a number of advanced and specially designed X-ray systems. Some of these have multiple X-ray source-detector combinations to enable fast (real-time) tomographical imaging.

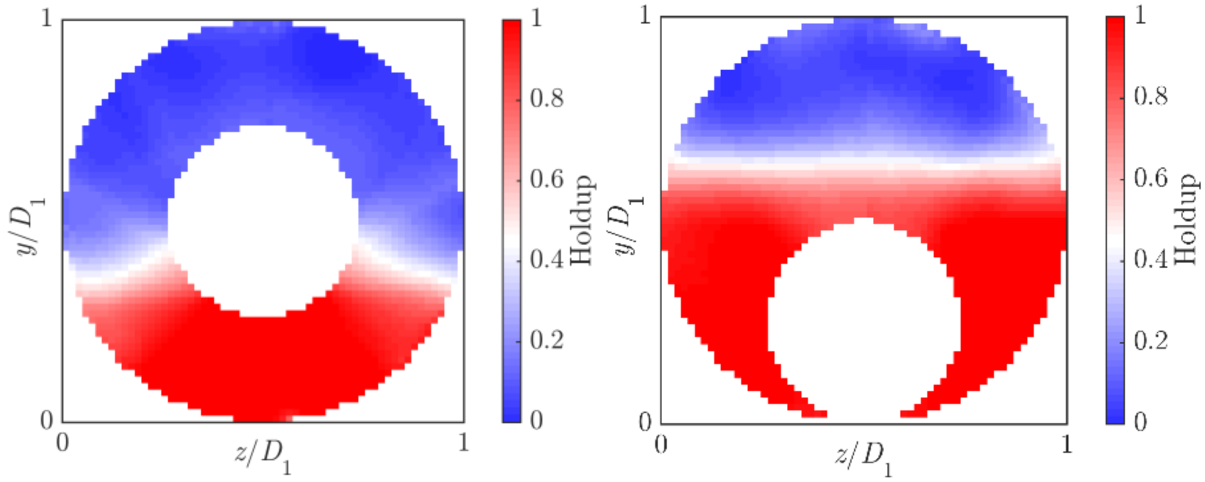

Fig. 10 a and b. X-ray CT of an annular flow with a small massive pipe (white) within a dual phase flow regime. Courtesy of Institut for Energiteknik (IFE) (Roberto Ibarra-Hernandez).

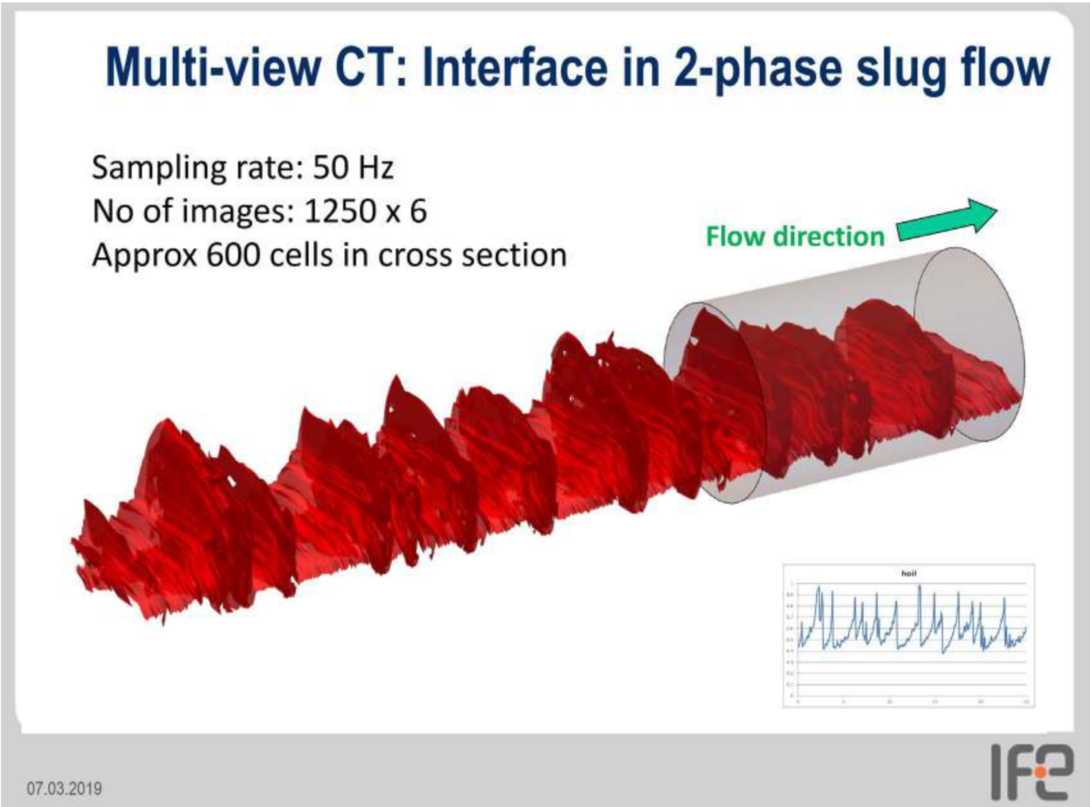

Fig. 11. Multi-view X-ray CT showing the Multiphase Flow Measurement interface in a dual phase slug flow at 50 Hz acquisition rate. Courtesy of Institut for Energiteknik (IFE), Olaf Skjæråsen.

MULTI-SPECTRAL X-RAY IMAGING TECHNOLOGY

NOVEL TECHNOLOGY FOR REAL-TIME MULTIPHASE DISCRIMINATION OF OIL, GAS AND WATER IN CORES AND PIPES

Novel X-ray technology using multispectral imaging has the capability of providing the information on the radiation attenuation spectrum at pixel level, in real time. This gives the huge advantage of quantifying the flow front composition in real time, thus forming a much improved basis for the understanding and interpretation of the flow processes in the different rocks, at different PT regimes, and with different gasses and agents for oil recovery.

The example below shows a multispectrum X-ray image of samples of oil, water, oil-water, steel, copper, lead, plastic and aluminum. Based on the acquired image, the X-ray spectrum of each material is compiled. From this, it can be seen that the methodology can separate materials based on their spectrum peaks. These measurements can be accomplished in real-time and is thus adequate as a tool for sorting of mixtures of materials, e.g. for core analysis and permeability studies, or for Multiphase Flow Measurement.

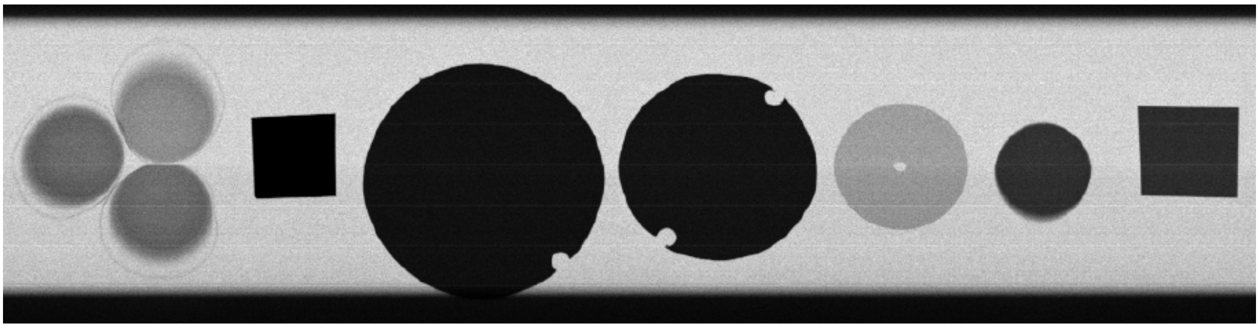

Fig 12. The X-ray image of the samples used in the tests. From left to right: Oil, water, oil-water, lead, steel, steel, aluminum, Teflon, copper. The spectrum for each material is depicted in Fig. 13.

From the X-ray image above, the regions are separated from the background and the X-ray spectra for the different regions is validated. Fig. 13 displays the associated spectral curves for each region covered by the different materials. As can be seen, computational methods can be applied to achieve a quantitative estimation of the proportion of various natural elements.

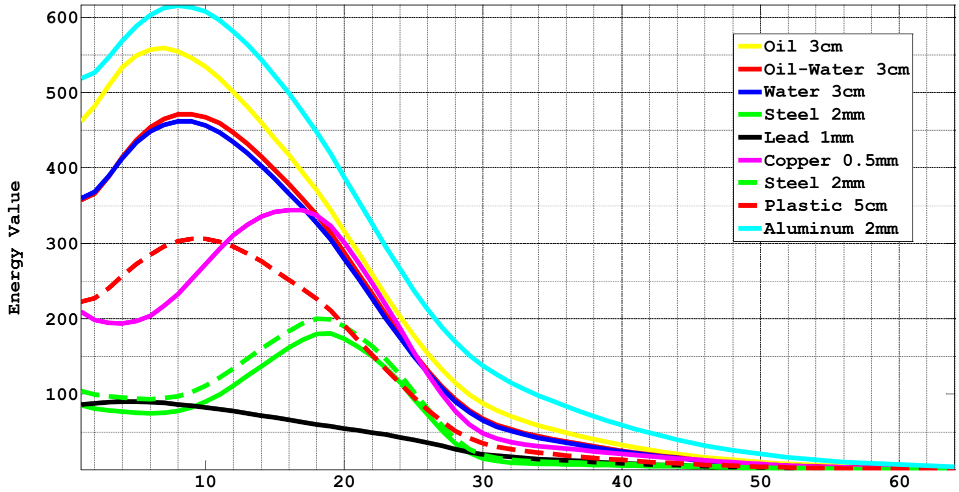

Fig 13. X-ray absorption spectra (represented by energy bins or channels) for the various materials imaged in Fig. 12.

The multi-energy imaging technology is very well suited for the oil and petrol exploration laboratory assessments. However, to enable the quantitative assessment, R&D work must be conducted towards correcting the acquired spectrum relative to inherent artefacts. This work is under development.