CORE HOLDER TECHNOLOGY FOR STEAM – HEAVY OIL GRAVITY DRAINAGE STUDIES

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ABSTRACT

In the article we describe the development of new innovative core holder technology for the experimental assessment of the gravity drainage potential of heavy oil carbonate bitumen rock. The new core holder permits long duration steam-oil gravity drainage experiments on carbonate bitumen rock at high-pressure and high-temperature in a steam environment. Furthermore the core holder is placed in a medical CT-scanner allowing non-destructive observation of the oil draining from the core as well as the accumulation of produced oil in a fluid collection pan. The pan, which is placed under the core, forms an integral part of the core assembly. We discuss in detail the design considerations and our technical assessment relevant to mechanical, thermal and X-ray criteria. In the paper we present the results of a commissioning experiment on a substitute HVO core including material balance control as well as quantitative CT-image data analysis from such a gravity drainage experiment conducted at 32 bars and 238 ^{0}C. With this core holder technology we have introduced a new generation of core holders for gravity drainage studies under harsh field conditions on the laboratory scale.

INTRODUCTION

Currently substantial effort is undertaken in the E&P industry for increasing the oil recovery from the Heavy oil plays (HVO) such as in the State of Alberta (Canada). Our R&D program aims for the assessment of the drainage potential of heavy oil (HVO) carbonate bitumen reservoir rocks. The EOR process of oil production by thermally induced gravity drainage in principle could be calculated analytically or simulated by numerical reservoir simulators [Hagoort, J. 1978, van Wunnik, J. et al 1992]. This however requires detailed knowledge of the HVO oil properties such as interfacial tension and mass density as a function of temperature and rock properties such as the porosity, permeability and relative permeability. These parameters are very difficult to measure at high-pressure, high-temperature (HPHT) conditions. However by directly observing oil production from the thermally induced steam-oil drainage on a HVO carbonate bitumen core, we can circumvent these difficult measurements. Thus we can directly measure the drainage characteristics under realistic reservoir conditions with the native rock and oil. Similar experiments have been designed with this goal, although at much milder conditions as in our target range [Briggs, P.J. et al 1992, Jafari, M. et al 2008, Summu, M.D. et al 1996]. Our experimental approach has been to put a HVO carbonate bitumen field core in a stationary HPHT steam environment and to observe oil drainage from this core. The resulting material balance data and in-situ saturation data from such a gravity drainage experiment can be used for benchmarking using numerical simulators. Next we describe the development of new core holder technology for the confinement of a carbonate bitumen HVO core and carrying out steam-oil gravity drainage experiments under realistic, harsh, field conditions.

An additional demand is that this core holder should be put in a (medical) X-ray CT-scanner for monitoring of the de-saturation of the core and cumulative production of oil in real time. Additional quantitative image processing of the digital CT-images from the CT-scans should provide data on the cumulative oil recovery and fluid saturations in the core. We discuss coreholder mechanical, thermal, electrical and X-ray design criteria that guided us in the development of this new gravity drainage core holder technology.

EXPERIMENTAL CONDITIONS AND DESIGN PHILOSOPHY

A basic requirement in our experimental program is that the vertical drainage core holder should permit the confinement of a relatively large carbonate bitumen HVO core such that it will produce a reasonably large amount of heavy oil from the core. Other requirements are; the pore pressure in the core and line pressure in flow system should be kept constant to a pressure of 32 bars. Steam at a temperature of 238 ^{0}C should be able to access and imbibe into the core from all sides and oil should drain from the core to a collection unit. The heating-up trajectory for carbonate bitumen core to reach the desired temperature level of 238 ^{0}C should be relative fast in order to avoid premature drainage of oil from the core. In practice this means that the core should be heated with a linear heating rate of 5 ^{0}C/min. After reaching 238 ^{0}C, steam should be introduced to the walls of the carbonate bitumen core to promote oil drainage. The produced oil should be collected for quantitative measurements. The drainage process should be monitored by means of CT-scanning. The experimental system should be sufficiently robust for long periods of operation, as gravity drainage experiments can last for a very long time.

Figure 1 shows the principle arrangement of our gravity drainage core holder set-up. The primary philosophy behind this design is that the gravity drainage core holder should be safe to handle. This is achieved by connecting the core holder to existing HVO Steam Core Flooding equipment [Coenen, J.G.C., 2007]. In this way steam can be generated externally by the steam generator and be supplied to the core holder via the tubing at the top flange. In this design a HVO carbonate bitumen core is confined longitudinally between two porous glass plates, mounted atop and below the core. In the radial direction, a coarse sand layer of high permeability surrounds the core. The sand layer is confined by a sleeve. Overburden pressure is maintained by means of an external piston pump and hydraulic oil. Temperature sensors, which enter the core holder by throughputs via the top-cap of the core holder, measure temperature at various positions in the core. The core is electrically heated by means of thin heaters placed around the sleeve. Thermal leakage from the central parts towards the outside of the core holder is minimized by wrapping ceramic wool around the internal core assembly. The ceramic wool prohibits percolation and thermal convection of the mineral oil in the sleeve annulus and reduces the heat leak to thermal conduction only. The core holder and core will be put upright in the CT scanner. Thereby, differently as in normal core flow systems using CT scanning in the radial plane, the X-rays will traverse the core holder from top-to-bottom and vice versa. A CT-image therefore shows a view over the vertical length axis across the core. We decided that the produced oil from the core should be kept inside the core holder to accumulate in a fluid collection pan that will be CT-scanned simultaneously with the core under the same experimental conditions. We selected to place a ceramic material with low thermal conductivity directly under the core to serve as a thermal shield.

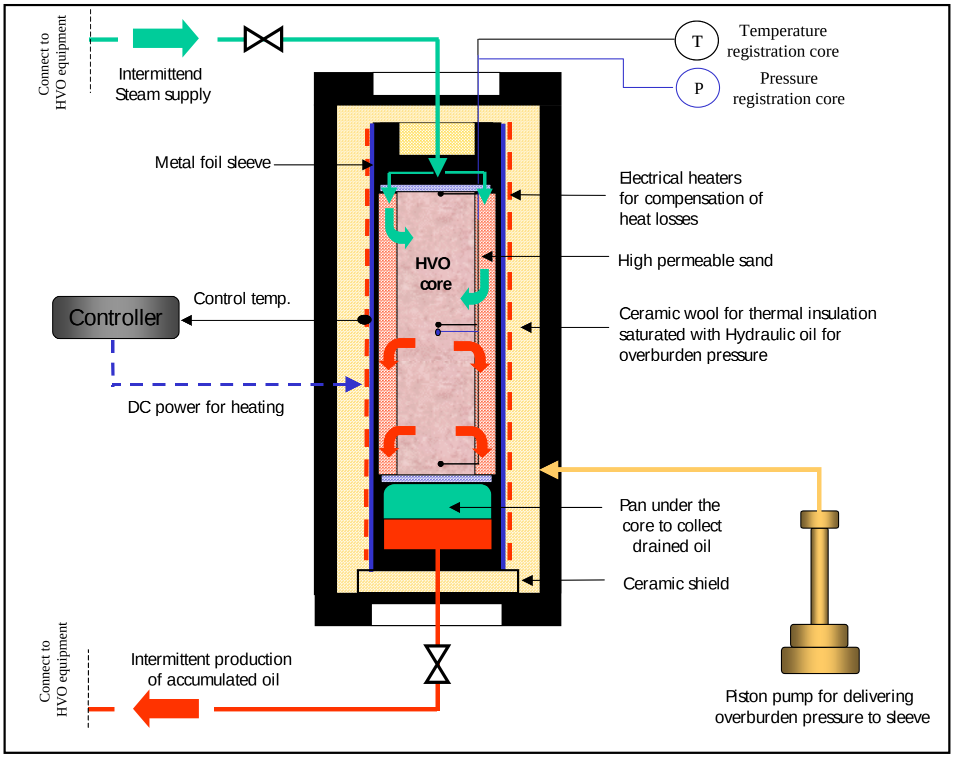

Figure 1: Principle layout of the Steam-Oil Gravity Drainage core holder.

The experimental procedure involves supplying steam from the HVO steam generator to the top of the core holder with fixed backpressure. By opening valves at the top as well as at the bottom pan, fluid flow from the cell to the HVO equipment is possible. Next the steam is distributed radialy inside the porous glass plate to the outer rim and subsequently flows in downward direction into the sand layer around the HVO core. Once the whole core holder is fully filled with steam the valves at either end of the core are closed. Hence at normal operational conditions we do have a fully self-contained core surrounded by a steam atmosphere. The core heater has an integrated control thermocouple that is connected to an external controller unit. During the heating-up stage the controller regulates the core temperature to a linear heating rate up to 238 ^{0}C. At steady state the temperatures of the core and pan assembly are regulated to a constant level (steam temperature). Then the supplied heat serves to compensate the heat losses from the core to the external environment. During the steady state phase at 238 ^{0}C steam should imbibe into the core and increase the mobility of the oil. The oil is produced from the core, drains first into the sand pack and subsequently into the pan below the core. At intermittent moments a CT scan is made showing the internal contents of the core and of the pan. For maximal radiation dose utilization and maximal Signal-to-Noise Ratio (SNR) generation in the reconstruction images, we aim to reduce as much as practical, the mass of the metal end-flanges at the level of the CT-scan beam and to have as much useful dose for imaging the internal core holder assembly. When needed the oil can be conveyed away to the external. In that case the composition of drained fluids can as well be analyzed.

STEAM-OIL GRAVITY DRAINAGE CORE HOLDER ASSEMBLY

On basis of the above we have developed a sophisticated core holder that meets the design philosophy. The new core holder has been designed for a maximum working pressure of 45 bars, pore pressure 32 bars and a maximum internal operating temperature of 250 ^{0}C. For reasons of mechanical strength and X-ray friendliness, two options were present in making the core holder; either from carbon fiber composite material or from high-strength aluminum. We decided to manufacture the core holder mantle out of aluminum (see CT-Mockup testing). The top and bottom end flanges as well as the fluid collection pan are made from the same aluminum grade. During operation, for strength integrity, we keep the temperature of the aluminum mantle below 150 ^{0}C (see Cooling). This permits us to maintain an aluminum wall thickness to 8 mm. For maximal CT-scan SNR the new cell has relatively thin end flanges supported by two strong Titanium bars at each end. By this reinforcement we have a thin aluminum end flange leaving minimal absorption mass i.e. an “X-ray window” of 40 mm width in the X-ray beam. The aluminum end-flange possesses several throughputs. At the top end-flange we have a multi-pin connector for the electrical power wires and sensor wires from the internal electrical heater/sensors and a connector for steel capillary for pressure guidance from the core to the external. At the bottom end-flange we have tubing for guiding hydraulic oil from an external piston pump providing overburden pressure to the internal sleeve. The steam inlet tubing enters the core holder at the top and the production tubing exits at the bottom flange. The internal assembly of the steam-oil gravity drainage core holder is shown in Figure 2. This assembly confines a HVO core, 88.9 mm OD, and length 160 mm. The core is mounted on top of a fluid collection pan. Adjacent to the core is a permeable, 6.4 mm wide outer rim filled with loose sand. The sand allows steam to interact with the oil in the core and for oil to drain into the pan. The total diameter of the core and sand pack assembly is 101.8 mm. Mounted on top of the HVO core is an aluminum top-cap that seals the end face of the core with a 6 mm thick porous Borosilicate glass frit mounted below. The steam supply tubing, from an external steam generator, is connected to the top-cap. Aiming for minimal attenuation of the X-ray beam, we removed as much metal mass as practical from the center of the aluminum top cap. We have five connectors for thermo couples and an extra connector for thin steel capillary for measuring the pore pressure in the core. The fluid collection pan is mounted below the core. Unlike the depiction of Figure 1, the pan ‘floats’ in the cell, with sleeve oil pressure acting all around the inner core holder assembly. This was done for minimizing the heat contact of the pan with the bottom flange of the core holder. During gravity drainage, the produced oil drains from the core into the porous sand pack and subsequently through the lower porous glass frit, into the fluid collection pan. The internal metal parts are made from aluminum allowing X-ray transparency.

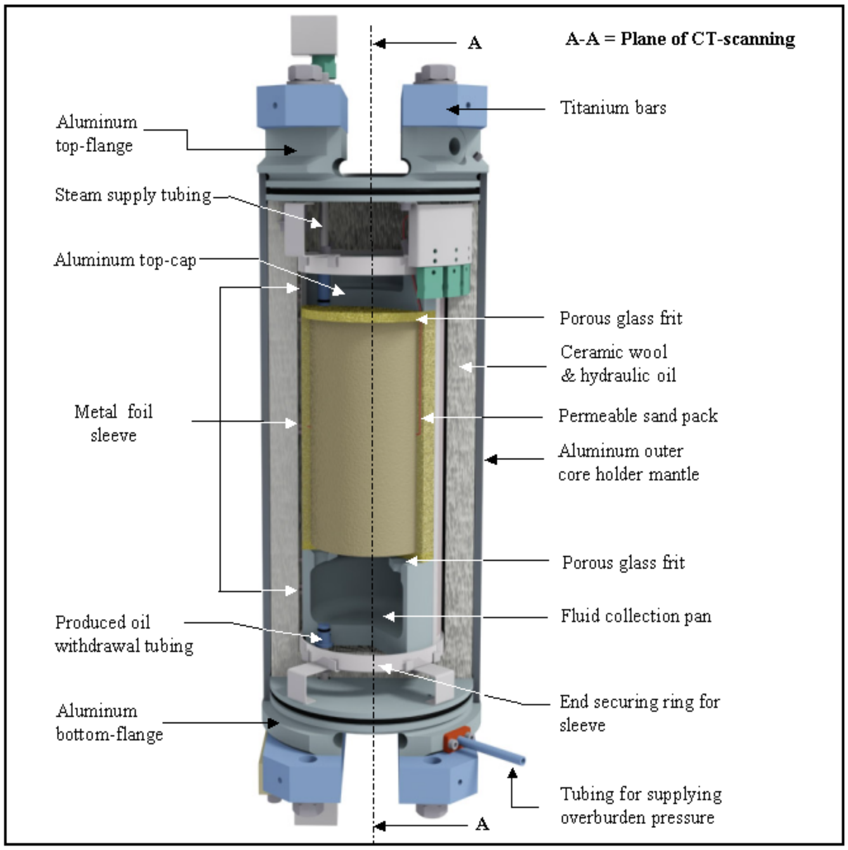

Figure 2: Illustration of the internal arrangement of the steam-oil gravity drainage core holder.

We nickel-plated these aluminum parts for corrosion resistance. Note that this nickel coating is very thin and any scratch might result in corrosion. As a safety check before every experiment, all parts of the cell are visually inspected. Our choice for the inner sleeve confining the HVO carbonate bitumen core was to use a thin metal foil. The sleeve is robust against puncturing by sand particles. The sleeve is sealed at either end of the core assembly a rubber O-ring. The sleeve extends from the bottom pan all the way up to the end of the top-cap.

We decided to arrange three heating zones along core. The main heating element for the HVO core is placed in the center of the core holder. A second zone heater is placed adjacent to the top-cap. A third zone heater is placed adjacent to the fluid collection bottom-pan. We choose thin thermo foil heaters with transparency for X-rays allowing CT-imaging of the internals of the core holder. The power ratings are 60 Watt for the top heater, 242 Watt for the core section and 100 Watt for the bottom pan. Each zone heater can independently be power-regulated. The heater in turn is kept in-place by an outer single layer of stainless steel foil viz. the “corset sleeve.” We have as well mounted MICA-based cylindrical heaters, with 135 Watt power each, to the top-cap and on the bottom pan. For the hydraulic oil providing overburden pressure to the sleeve and core we have selected Thermia-B mineral oil with an exceptionally good thermal stability at bulk oil temperatures up to 320 ^{0}C.

Sensors

An important feature during a steam-oil gravity drainage process is to verify whether there is temperature homogeneity in the core during the linear heating-up stage and during the drainage stage. To accomplish this, we mounted five ultra slim thermocouple sensors distributed in the core. These sensors do not create CT- artifacts when they interfere with the CT scanner's X-ray beam. For measuring the pore pressure in the core we mounted stainless steel capillary tubing, filled with hydraulic oil, guiding the pressure from the centre of the core to a pressure gauge mounted at the outside of the core holder.

Cooling of the Core holder Assembly

We choose to cool the outer core holder mantle such that its temperature stays at all times well below 150^0C. Our solution is to use air convection cooling to the outside core holder mantle. We designed a casing or conduit to ensure cooling airflow around the cell circumference, rather than from one side. A fan blower provides cooling air to all external parts of the core holder and by means of a controller keeps the external temperature at 130^0C.

CT Mock-Up Studies

During the design stage of the gravity drainage core holder it was unclear upfront how mechanical design options might affect CT scanning properties. This was especially relevant for the choice between a full aluminum core holder and a (partial) carbon fiber-composite core holder. A simple test was arranged to shed light in this domain. This "CT Mock-up" model test involves manufacturing of a simple 2-D substitute model in the same shape as the cross-section in the scanning plane of the real 3-D gravity drainage cell that will be intercepted by the CT X-ray beam. The main conclusion from these mock-up tests is that a carbon fiber cell would offer only minimal SNR benefits as compared to a full aluminum cell. Furthermore fluid levels in the pan can easily be measured. However due to the rectangular geometry and material sequences inside the core holder the CT-pixel values in the core are so noisy that saturation measurements can only be carried out on a region-of-interest (ROI) averaged basis.

Connection to HVO Equipment

We have integrated the new gravity drainage core holder technology with the existing Heavy Oil Steam core flooding equipment [Coenen, J.G.C., 2007]. Tubing mounted to the top of the core is for steam supply. Tubing to the bottom of the core is for withdrawal of fluids and guiding the fluids to a steam condenser and backpressure regulator. Both tubes are heat-traced and thermally insulated. We can take full advantage of the high level of automation and safety provided by the HVO steam core flooding equipment. Fail safe operation is warranted by implementing a safety sensor circuit that consists of 4 gas sensors, to detect any eventual release of small amounts of trace gasses, as well as a gauge for monitoring the sleeve confinement pressure and sensors for monitoring temperatures of the thermo foil heaters.

COMMISSIONING EXPERIMENT

The new HVO steam-oil gravity drainage core holder was tested by means of a commissioning experiment. In this experiment we used a random carbonate bitumen core drilled from Canadian outcrop material as substitute HVO core.

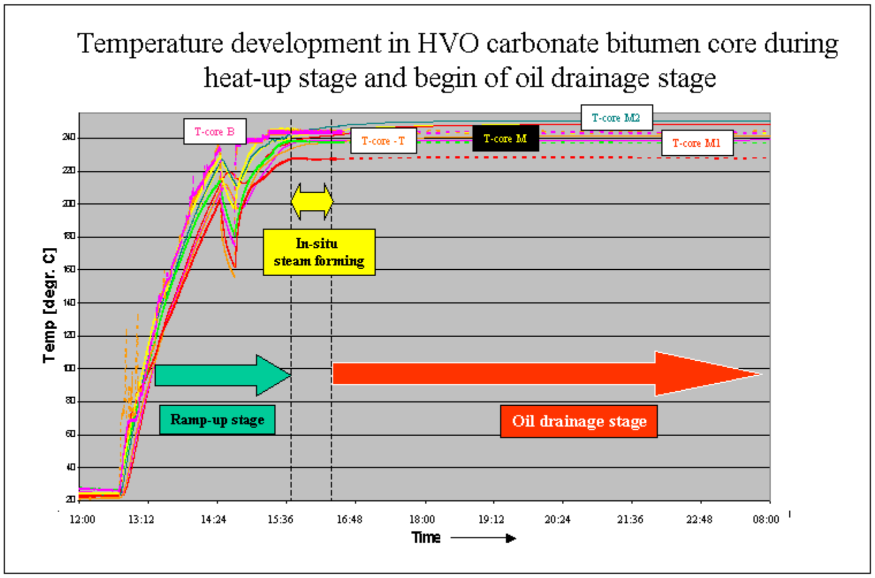

Figure 3: Temperature development during the commissioning experiment.

Although we have very limited knowledge on the properties of this core (e.g. porosity and So_i) this was not important since the primary aim of this test was to check the functionality and endurance of the equipment. Additionally we aimed for material balance data and to develop a method for CT-image data analysis. To enhance the control and safe operation of the experiment we applied a “wet start” which means that water was introduced in the pan and in the sand pack around the core. During the test CT-scans were taken at a fixed location over the center axis of the core holder. We employed 130 KV, maximal X-ray dose and a beam width of 10 mm. Next we increased both the sleeve pressure and pore pressure in the core in a synchronized manner while maintaining 10 bars net confining pressure. Finally we conditioned the HVO carbonate bitumen core to 32 bars pore pressure (set point of the backpressure controller) and 45 bars over burden pressure at ambient temperature. (Note that the steam temperature at 32 bars is 238 ^{0}C.) Initial CT-scans were made from the core holder at the beginning of the gravity drainage experiment. First step in the gravity drainage experiment was to ramp the temperature of the inner core holder assembly from ambient up to 238 ^{0}C.

Figure 3 shows a graph of the temperature development inside the HVO carbonate bitumen core versus time during the heating-up stage. The linear ramp-up went fine except for a small operational error, which interrupted the power supply to the heaters at around 220 ^{0}C. After a quick repair the linear heating was resumed and after 3 hours the HVO core reached an average temperature level of 238 ^{0}C.

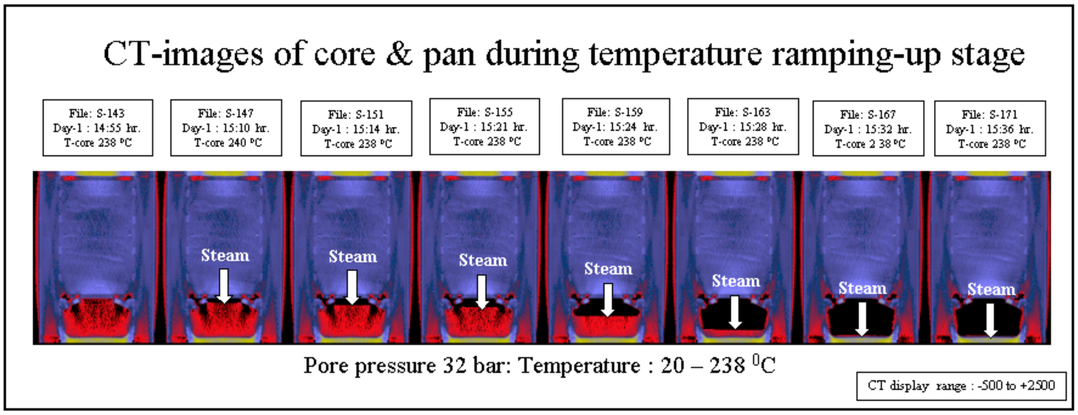

Figure 4: Note that these events play within 1 day.

Figure 4 shows a series of CT images from the core and fluid collection pan during the heating-up stage. Surprisingly, soon after reaching a core temperature of 238 ^{0}C, we observed a spontaneous in-situ generation of steam. Owing to the active backpressure control, maintaining 32 bars line pressure, water was retrieved from the pan. The steam front expanded from the top of the coarse sand pack, adjacent to the HVO core, vertically downward towards the bottom of the pan. After the steam formation phase the pan was empty since all water was driven from the pan. Both valves at each side of the gravity drainage cell were closed and the gravity drainage process commenced.

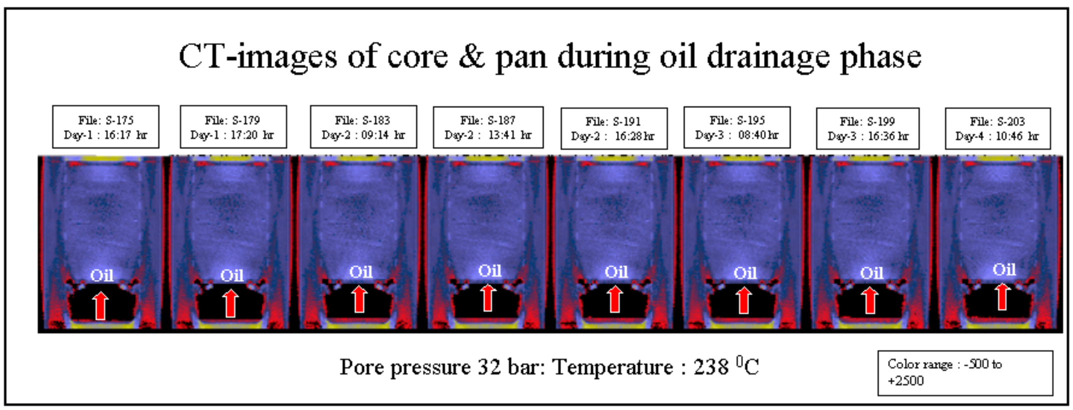

Figure 5: Note that the CT-image history goes over 4 days and longer.

Figure 5 basically shows the sequence “CT-snap shots” of the core and pan from the oil drainage stage. The oil drainage happened relatively fast after steam was formed. These CT-images show accumulation of oil at the bottom of the fluid pan. From Figure 5 it is deduced that an oil layer accumulated quickly at the bottom of the pan. The full experiment lasted an unprecedented 120 hours of operation. We observed that the temperature at the bottom of the core is 10 degrees C lower than of the centre of the core. Remarkably the pressure in the core increased slightly over time. We could trace back the cause of this pressure increase to a small leakage of hydraulic oil from the sleeve annulus into the coarse sand adjacent to the HVO core. Therefore occasionally we corrected the pore pressure in the system. Finally the experiment was terminated. This first experiment with the new gravity drainage core holder equipment has shown that indeed we are able to study gravity drainage using a HPHT steam atmosphere.

Thereby we did not need to inject steam into the core holder because the heating capacity was good enough for in-situ steam generation. Thus the gravity drainage core holder can be kept fully confined. The events during the drainage phase can be explained on basis of the in-situ pressure and temperatures combined with the CT information.

RESULTS

The data analysis concentrated on two issues; material balance control and CT-image analysis both of the fluids in the pan and the de-saturation of the core. First we established the average amount of produced oil from the core from weight change of the carbonate bitumen core after the experiment as compared to the initial pre-test weight. From the mass difference we deduce that the produced amount of oil is 43 gram. Secondly we verified the cumulative produced amount of oil and water in the pan by measuring the mass of the fluid collection pan before and after the experiment. By this technique we measured a total amount of produced heavy oil to 69 gram. Next we used digital image analysis to derive quantitative information on the change in liquid levels in the pan as a function of time.

To this aim we developed an algorithm based on a rolling ROI averaging procedure to obtain a more accurate profile. In fact this procedure produces the statistical mean for the CT pixel values in a rectangular ROI (205 pixels width, 4 pixels height). The shift in subsequent ROI-positions is 1 pixel. In this way a smoothed vertical density profile is obtained starting at the bottom of the CT image of the pan and moving to the top. The CT density profiles in Figure 6 clearly show the transition from the bottom of the metal pan, to oil and subsequently to steam by a sharp decrease or bend in CT-density. The shifting plateau shows a growth of the liquid volume in the pan over time. Our aim was to derive quantitative information on the produced volume in time. This is done on hand of CT calibration scans made on the fluid collection pan with accurately known fluid volumes in the pan taken prior to the drainage experiment. By correlation of both the data sets we have established the volumes of produced oil during the experiment. The so obtained drained heavy oil volume in the fluid collection pan was measured to 52 ml, or approximately 52 gram. We could indeed construct an oil recovery curve versus time from these data. Obviously we now have a paradox whereby the material balance shows different results than the liquid level read out from the CT-scan information. Further effort will be devoted to improve accuracies.

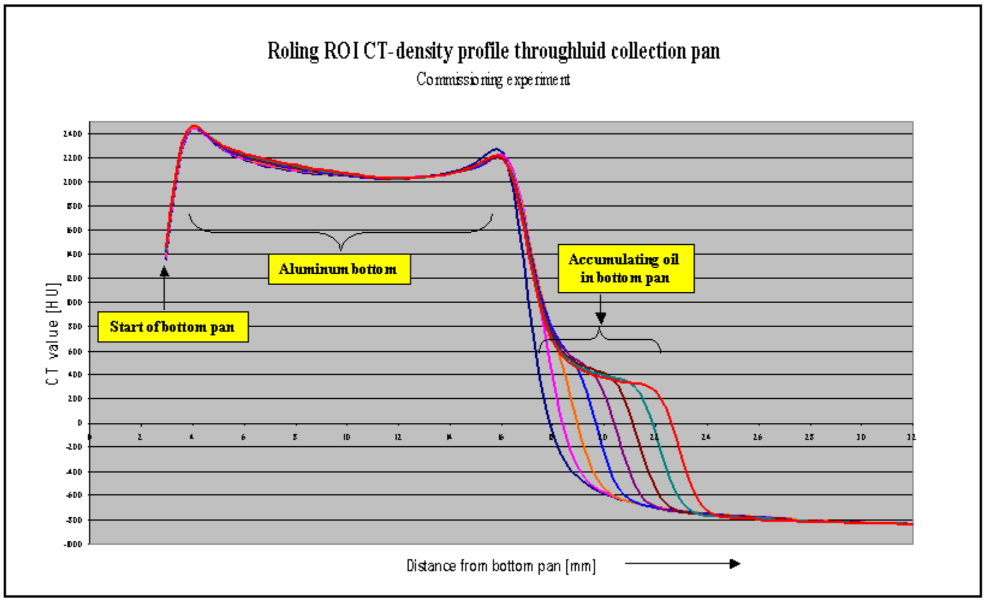

Figure 6 : CT-density profiles through the fluid collection pan during the commissioning experiment.

The CT-images of the carbonate bitumen core are processed in order to detect de-saturation of the core from heavy oil. We have compared on a pixel-by-pixel basis the CT-images of the core. The resulting pseudo saturation images are too noisy to reveal any zone of oil de-saturation in the core. We processed the CT images using the rolling ROI procedure assuming that saturations in the width of the core are more or less uniform. Statistical averaging over an ROI of 820 pixels size produces more accurate results than on a pixel-by-pixel basis (see CT Mock-Up studies). The resulting smoothed density profiles are compared to the density profile at the start of the experiment. The result is that we observed heavy oil de-saturation to happen in a zone close to the bottom of the core. This is an atypical observation since de-saturation of oil in a homogeneously heated core, fully surrounded by steam, usually starts at the top of the core (Hagoort, J. 1978). Further efforts will be devoted to underpin this finding.

CONCLUSIONS

We have described the steps in a core holder technology development program for the study of steam – heavy oil gravity drainage at realistic field conditions while using CT-scanning. The new core holder has been designed for a maximum working pressure of 45 bars, pore pressure 32 bars and a maximum internal operating temperature of 250 ^{0}C. The core holder allows the experimental assessment and monitoring of (1) the de-saturation process of heavy oil draining from a carbonate bitumen core as well as (2) the accumulation of produced oil in a fluid collection pan, placed under the core, forming an integral part of the core assembly. Most parts are made from aluminum to obtain a better signal-to-noise ratio for the CT X-ray beam. The internal parts are coated by a thin Nickel layer for corrosive protection. The thermal housekeeping of the new gravity drainage core holder is based on heating the internal core assembly by X-ray transparent electric thermo foil heaters and keeping the outer core holder to a temperature below 150 ^{0}C. The installed heating power is 195 Watt at the top-cap, 242 Watt at the core section and 235 Watt at the bottom pan. For minimal heat leak the annulus in between the internal core assembly and the outer core holder mantle is filled with ceramic wool saturated with hydraulic oil. The CT-imaging quality of the new gravity drainage core holder was screened upfront in the design process by a relative simple Mock-up model test. We have carried out a commissioning experiment with this core holder at 32 bars and 238 ^{0}C. We observed that the SNR quality for the individual CT-pixels in the core is too poor for detailed analysis on a pixel-by-pixel basis. The large noise is mainly due to the rectangular aspect ratio of the core holder cross-section. Also the presence of hydraulic oil in the core holder sleeve annulus considerably deteriorates the quality of the CT-images. However we can improve on the quality for the CT data analysis in the core when statistical averaging is applied over a region of interest (ROI) moving over the core. The SNR quality and CT-contrast between the fluids in the fluid collection pan is good enough to carry out accurate liquid level detection for the produced oil. With the design of this core holder we are proud to have introduced a new generation of core holders in the industry for gravity drainage studies at realistic harsh field conditions on laboratory scale.

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