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CT IMAGING OF TWO PHASE FLOW IN FRACTURED POROUS MEDIA

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ABSTRACT

This paper describes the design, construction, and preliminary results of an experiment that studies imbibition displacement in two fracture blocks. Three core configurations were constructed. The configurations are a compact core, a two-block system with a 1 mm spacer between the blocks, and a two-block system with no spacer. The blocks are sealed in epoxy so that saturation measurements can be made throughout the displacement experiments using a Computed Tomography (CT) scanner.

Preliminary results are presented from a water/air experiment. These results suggest that it is incorrect to assume negligible capillary continuity between matrix blocks as is often done.

INTRODUCTION

The simulation of flow in naturally fractured reservoirs commonly divides the reservoir into two continua – the matrix system and the fracture system. Flow equations are written presuming that the primary flow between grid blocks occurs through the fracture system and that the primary fluid storage is in the matrix system. The dual porosity formulation of the equations assumes that there is no flow between matrix blocks while the dual permeability formulation allows fluid movement between matrix blocks. Since most of the fluid storage is contained in the matrix, recovery is dominated by the transfer of fluid from the matrix to the high conductivity fractures. The physical mechanisms influencing this transfer have been evaluated primarily through numerical studies. Relatively few experimental studies have investigated the transfer mechanisms. Early studies focused on the prediction of reservoir recoveries from the results of scaled experiments on single reservoir blocks. Recent experiments have investigated some of the mechanisms that are dominant in gravity drainage situations and in small block imbibition displacements. Hughes (1995) discusses these experiments in detail. One of the primary drawbacks to many of these experiments is the lack of understanding of the saturation distributions in the rock matrices. Other recent work has emphasized understanding flow through a single fracture with no transfer from the matrix (Persoff, et al (1991), Persoff and Pruess (1993), Fourar, et al (1993), Persoff and Pruess (1995)).

Guzman and Aziz (1993) initiated a study of two-phase flow in fractured porous media. The initial purpose for this work was to attempt to measure relative permeabilities in the fracture. An experiment was designed to measure saturation distribution in two cores of identical material. One core would be a control while the other would be cut in half and propped open with inert material to simulate a fracture. Oil and water would be injected into the cores at varying rates. Saturations would be measured by CT scanning the core at various stages of the injection process. Fine grid simulations would then be used to history match the experimental results.

Fine grid simulations were performed to help in the design of the experimental procedure (Guzman and Aziz, 1992). An experiment was built but, unfortunately, problems developed during single phase injection testing precluded obtaining results. The work reported here is a modification

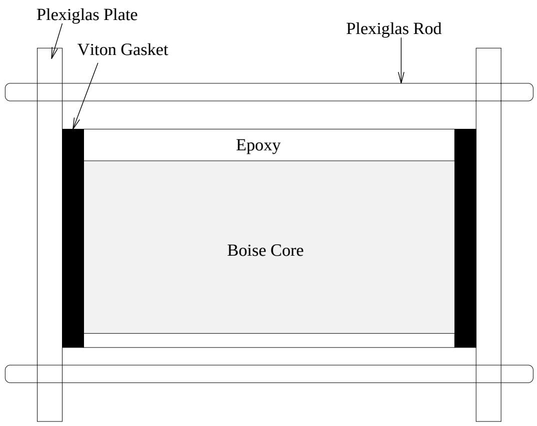


Figure 1: The core holder.

and extension of the Guzman and Aziz (1993) study. The focus will be on obtaining both qualitative and quantitative data on the movement of fluids in fractured blocks.

EXPERIMENTAL APPARATUS

Three rectangular blocks of Boise sandstone were prepared for use in this work. The first is a compact (solid) core measuring 3 1/8 × 3 1/16 × 11 inches. The second and third cores consist of two 2 15/16 × 1 1/2 × 11 inch blocks. The second core system has a 1 mm thick spacer fastened in place with Epoxy 907 to provide a separation between the blocks to simulate a fracture. The third core system is constructed similarly but has no spacer between the blocks.

Due to the rectangular shape and the desire to measure in-situ saturations through the use of the CT scanner, conventional core holders could not be used. A core holder similar to the original design by Guzman and Aziz (1993) was developed for each of the cores. It consists of an epoxy resin surrounding the core. The resin system used was Tap Plastics Marine Grade Resin #314 with Tap Plastics #143 Hardener. Plexiglas end plates were constructed for the core holders with a piece of 3/8 inch Viton acting as a gasket between the core and the Plexiglas end plates. The Viton gaskets were held in place with automotive gasket material and Plexiglas rods as shown in Figure 1.

The original design had six pressure taps all on the top of the core holder. The new design has two pressure taps on the top and two on the bottom. In addition, a Plexiglas plate that was epoxied to the top surface of the core was removed in the new design. The plate was found to be unnecessary and a potential source for leaks.

Several different epoxy systems were tested in addition to the system chosen. Among these were Tap Plastics 'One to One' General Purpose Epoxy, Tap Plastics 'Super Hard' Four to One Epoxy, and Evercoat Laminating Resin. All of these epoxies were extremely exothermic when reacting to become solid. The Tap Plastics Marine Grade Epoxy system selected uses the #314 resin in combination with various hardeners to provide different cure times with similar chemical resistances and strengths. The #143 Hardener was chosen because it provides a slower cure, yet retains its chemical resistance properties. This system is slightly less viscous so penetration is a bit deeper into the core than it was for some of the other systems we observed; however, for this experiment the added control the slow cure time provided was deemed to be a more important issue than penetration depth.

In addition to using a slower curing epoxy system, an aluminum mold was constructed to allow better heat dissipation. The mold was built so that there would be a 1/2 inch border of epoxy around the bottom and sides of the core. It had an open top with sides which were six inches taller than the estimated top of the epoxy. This allowed the heat to radiate out of the mold and helped to prevent cracking of the epoxy.

To construct the core holders, Plexiglas end plates were attached to both ends of a 12 inch long core with GE White RTV 102 Silicon Rubber Adhesive Sealant and held in place with clamps. Epoxy was layered on with a paintbrush and allowed to set for one hour. The core was then placed into the mold. The mold was tilted at a 45 degree angle and the epoxy was poured in. Tilting the mold reduced the number of air bubbles which can form along the bottom of the core. Once the liquid resin covered the core, the mold was returned to horizontal and additional resin was added to reach the desired height. During the construction of the compact core holder, heat expansion of the air inside the core caused air bubbles to form and rise to the surface of the epoxy at one of the ends. For the two subsequent cores, holes were drilled in the Plexiglas end plates. This action alleviated the problem. Figure 2 shows an oblique view of the core holder after the epoxy has cured.

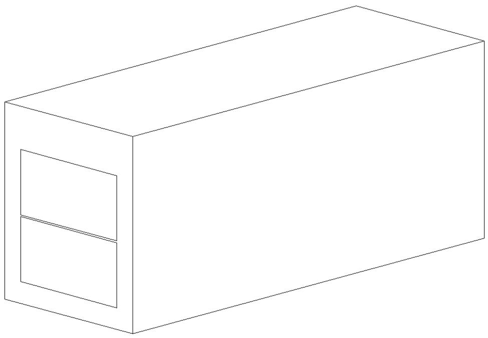


Figure 2: The core holder after curing.

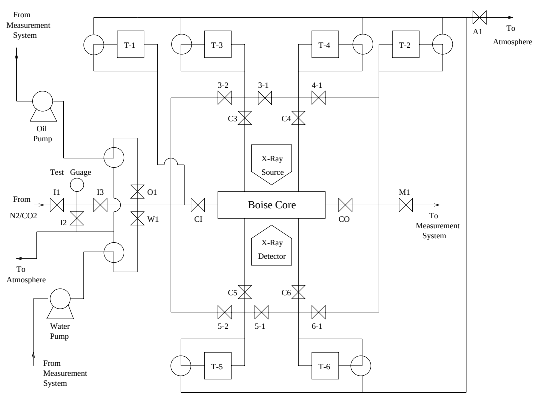


Figure 3: Experimental flow schematic.

Once the epoxy had cured, the cores were removed from the mold and the ends were trimmed with a water-cooled diamond circular saw to provide an 11 inch length. A piece of 3/8 inch Viton was then cut for each end face of the core holder. A hole was cut in the Viton so that the core face would be exposed. Automotive gasket material was then used to glue the Viton to the epoxy and the Viton to the Plexiglas end plates. Plexiglas rods were bolted into place through holes that had been drilled into each end plate. This provided added support and also allowed the gasket material/Viton to be compressed to eliminate leaks.

Figure 3 shows the flow schematic for this work. The injection system consists of two LDC Analytical, Inc. model constaMetric 3200 pumps. Each pump has the capability to deliver 0.01 to 9.99 cm^3/min in 0.01 cm^3/min increments. The pumps use a dual plunger system that has been designed to provide constant fluid discharge rates at outlet pressures from 100-6000 psi. To use the pumps the

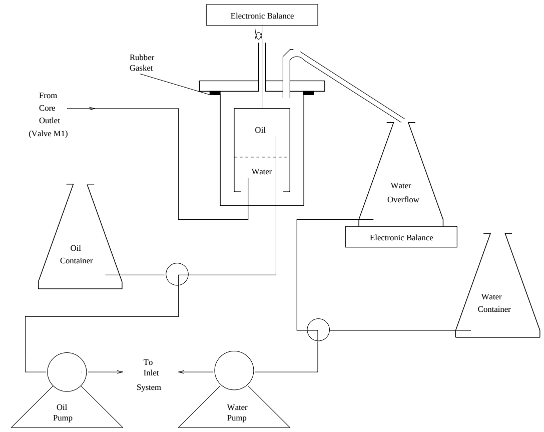


Figure 4: The production measurement system.

user sets the desired discharge rate, the minimum allowable pressure, and the maximum allowable pressure. Plumbing downstream of the pumps allows mixing of the fluids being discharged by each pump. This setup allows injection pressure to be monitored with a test gauge and recirculation to measure pump output rates. This configuration also is a convenient way to use nitrogen in the calibration of the pressure transducers, or to use CO_2 to help in the saturation of the core. Pump inlet can be from an extra "make up" container or from the measured fluids being discharged from the core.

All piping used for the experiment was Paraflex 1/8 inch diameter, 500 psi working pressure plastic tubing with stainless steel Swagelok fittings. The distribution of fluids throughout the experiment is controlled by Whitey B-43F2 ball valves. This system allows fluids to be directed to any port or combination of ports in the experiment. It can be directed to test the calibration of the pressure transducers, inject from one end and produce from the opposite end (the primary configuration), inject into one or more of the ports on the top and bottom of the core holder (which are normally used for monitoring pressures), or to bypass the core holder completely. The ability to direct fluids to any port in the experiment allows charging the core with fluids readily, testing various flow configurations, and cleaning the core more easily.

The production measurement system is an adaptation of a design first proposed by engineers at Conoco, Inc that was built by Ameri and Wang (1985) and modified by Qadeer (1994). Figure 4 shows the system.

The key element of the measurement system is the separator. It consists of two glass vessels, one inside the other. The inner vessel has an open bottom and a closed top. It hangs inside the outer vessel, suspended from an electronic balance by a hooked wire. Produced fluids enter this inner vessel and separate due to density differences. The lighter fluid (in this case, oil) rises and collects at the top of the inner vessel and the more dense fluid (water) exits from the bottom. The outer vessel is initially filled with water. When production begins, water from the inner vessel is displaced into the outer vessel and in turn, displaces water from the outer vessel through the glass tube at the top. The glass tube has a hole in the top to break any siphon effect. Total liquid production is calculated by the amount of water that is collected in a beaker which sits on an electronic balance. The electronic balance attached to the inner vessel measures the buoyant weight of the vessel. From the weight change measured on this balance, oil production is calculated.

Pressure measurement for the experiment is accomplished through the use of six Celesco DP31 differential pressure transducers. Two of the transducers are connected to ports on the top of the core holder and two on the bottom. The ports are approximately 8 cm from each end. Two other transducers are connected to the inlet and outlet ends of the core holder. The negative side of each transducer is open to the atmosphere. This differs from the original work by Guzman and Aziz (1993). In their study, only the outlet end port had the negative side of the transducer open to the atmosphere. The remaining ports had their negative sides connected to the core outlet end. All the stainless steel diaphragms for the transducers are the 5 psi type. The Celesco transducers work in combination with carrier demodulators, either Celesco model CD10A, CD10D, or CD25A demodulators. The demodulators take the output from the transducers and produce a DC signal in the range -10 to +10 volts.

Output signals for the carrier demodulators can be collected by a set of Soltec Transducer Products, Inc. 1243 Chart Recorders, or the signals can be fed into an HP3497A data logger. If the data logger is used, the digital signal from the data logger is sent to an IBM compatible personal computer (PC) through a HP-IB interface card in the PC. Output signals from the two electronic balances are sent directly to serial communication ports in the PC.

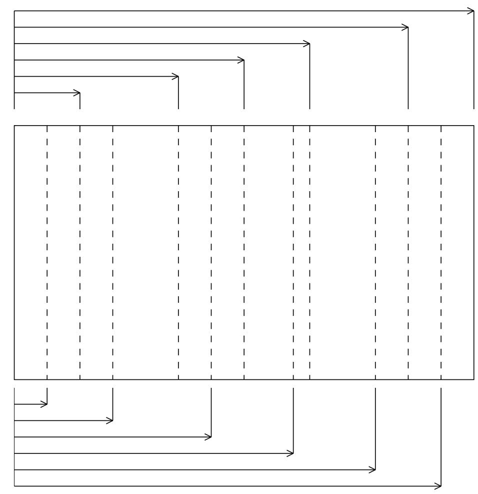


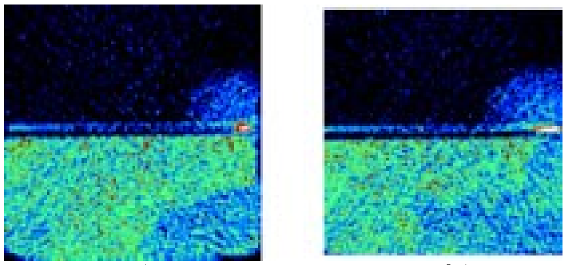
Figure 5: CT scan locations.

Saturation measurement for this experiment is through the use of a Picker 1200SX Dual Energy CT Scanner. This scanner is a fourth generation medical scanner that has been modified for laboratory use. The interested reader is referred to the Picker 1200SX Operators Guide (1983) for further specifications on the system.

PRELIMINARY RESULTS

Once the experiment had been designed and constructed, the equipment needed to be tested and evaluated for its ability to obtain meaningful results. Guzman and Aziz (1993) presented a figure in their work which showed how the CT scanner can indicate unsaturated conditions within the rock matrix.

For this study it was decided to evaluate how water imbibed into an unsaturated core. The first core that was used had the 1 mm fracture. Figure 5 shows the locations that were chosen for the CT scans. Two items prevented a regular sequence of scan locations. The first was that stainless steel fittings were used for the ports on the top and bottom of the core holder. These fittings caused artifacts and prevented scan locations from 70 mm to 85 mm and from 190 mm to 205 mm. These are distances measured from the inlet face. The second item that caused an irregular spacing of the scan locations was a large vug located 170 mm from the inlet face which we wanted to monitor throughout the experiment.



a.) b.)

Figure 6: CT scan at a.)+40 mm and b.)+60 mm from the inlet end at 0.09 PV injected. Lighter shades indicate higher water saturation.

The core holder had a gap corresponding to the width of the Viton gasket at both the inlet and outlet face of the core. At an injection rate of 1 cm^3/min, the injected water simply dribbled down the inside of the Plexiglas inlet face plate and was imbibed into the bottom block. As the experiment progressed, the water began filling the gap between the Plexiglas plate and the core; however, it was very late in the experiment before the injection water got above the level of the fracture. The outlet condition was initially open to the atmosphere. After approximately 1.75 PV had been injected, the outlet was directed to the separation system and the injection rate was increased. Outlet pressure was 0.51 psi, while inlet pressure was 0.75 psi, at a flow rate of approximately 2 cm^3/min.

Migration of the water was monitored with the CT scanner. Initially, all water moved through the lower block only. When approximately 0.06 pore volumes (PV) had been injected, a slight amount of water was seen crossing the fracture to the top block at both the 40 mm location and the 60 mm location. Figure 6 shows CT scans taken at 40 mm and 60 mm from the inlet end when approximately 0.09 PV of water had been injected. These scans were chosen since they clearly show the water in the upper block. There appears to be at least one continuity across the fracture on the right edge of the blocks near these locations. The conclusion drawn from these and other CT scans is that the water crosses at these locations and then migrates towards the outlet face in the top and bottom blocks. The water also imbibes back towards the inlet face in the top block. Note also that water appears to be along the entire width of the fracture face on the top block in both scan locations, but that the fracture seems to be filled with air (except on the right edge as noted above).

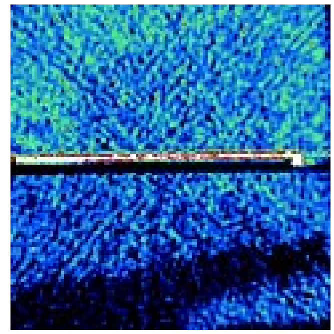
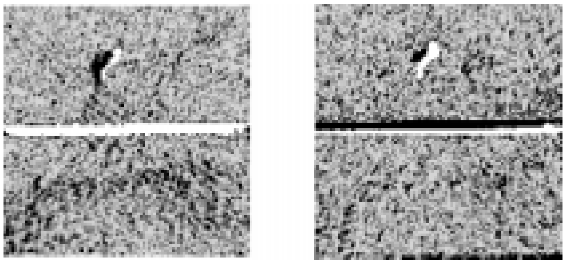


Figure 7: CT scan at +260 mm from the inlet end at breakthrough. Lighter shades indicate higher water saturation.

As the injection process continues, water advances towards the outlet end in both the upper and lower blocks; however, since there is no water between the inlet face and where the water crosses the fracture, the advance in the upper block appears to lag behind that in the lower block. Once this space has been filled, water advance in the top block overtakes the advance in the bottom block.

Water breaks through and begins collecting on the bottom of the outlet face plate at approximately 0.47 PV injected. Figure 7 is the scan at 260 mm from the inlet face at the time of water breakthrough. It clearly shows areas in the bottom block where water has not contacted the rock pores. It also shows that the top block has a more uniform saturation distribution. Despite the fact that water was being injected only into the bottom block, capillary imbibition pulls the water across the continuity and through the top block such that the top block actually breaks through before the bottom block.

The experiment was run over the course of four days. Approximately 4.26 PV of water passed through the core. Once the experiment was terminated, the valves leading to the core were closed and the core was allowed to sit for three months. The core was then scanned again. The changes that occur between the scans at the end of injection and those three months later are most noticeable along the edges of blocks and the edges of the vug. These alterations could possibly be caused by positioning errors, since the core holder was removed from the scanning table during the three month wait. Figure 8 shows scans 170 mm from the inlet. Figure 8b has an increased saturation and appears more uniform than Figure 8a. The



a.) b.)

Figure 8: CT scans at +170 mm from the inlet end a.) at the end of the displacement and b.) after a 3 month wait. Lighter shades indicate higher water saturation.

entire scan area has added water and a pocket of air has formed on the top of the fracture adjacent to the top block. Note that the vug has filled considerably with water but that there continues to be a small area in the upper left side of the vug that contains air. These results would suggest that, at least some of the changes seen are real, and are not positioning differences. This figure also emphasizes the slow nature of the approach to equilibrium in porous media.

One additional item on these experimental results is noteworthy. Withjack (1988) has shown that porosity can be calculated from the matrix of CT numbers obtained when scanning by using the equation:

$$\phi = \frac{CT_{cw} - CT_{cd}}{CT_w - CT_a} \quad (1)$$

where: CT_{cw} is the CT number for a water saturated core at a matrix location, CT_{cd} is the CT number for a dry core at a matrix location, CT_w is the CT number for water, and CT_a is the CT number for air. The CT number for water is 0, while the CT number for air is -1000.

Despite passing more than 4 PV of water through the core, the average value for "porosity" calculated from the scans at the end of the displacement experiment using Eq. 1 was 14.35%. This differs from the average porosity measurements of 25.4% obtained by Guzman and Aziz (1993) and 29.3% obtained by Sumnu (1995) for rock samples obtained from the same part of the quarry that the samples used in this study were from. Sanyal (1971) also worked with Boise sandstone in his studies and obtained an average porosity value of 32% for his samples.

Attempts to saturate the core by the addition of CO_2 and injecting water into the pressure measurement ports raised the value calculated to an average of 20%. There continue to be areas (mainly in the lower block) that either have lower porosity or that have difficulty being saturated at the rates and pressures used in the experiment.

SUMMARY

The experiments conducted thus far have shown that the constructed system can obtain meaningful results in the effort to understand the physics of flow in fractured media. Flow in the experiment is across the blocks with gravity segregation possible at low rates. Thus, experiments can be run which mimic flow between wells (across the block) with water rising from below on one side. The flow configuration can be easily altered to accommodate other possible boundary conditions. Filter paper or fine grained sand could be used to fill the space between the Plexiglas plate and the core if a more even distribution inlet or outlet condition is desired. A tubing configuration could be devised similar to that described in a study by Kazemi and Merrill (1979) if injection is to be limited to the fracture space. Experimental pressures have been as high as 16 psi and flow rates up to 10 cm^3/min have been recorded. The preliminary experiments have also shown areas in the rock which have lower permeability. These areas will need special attention when charging the core with oil, during displacement experiments, and also during cleaning operations. We would not have been aware of these problems if we had not had the useful additional information provided by the CT scanner.

To use the CT scanner to monitor the migration of fluids when the core is being charged with oil, or when the core is being cleaned, the stainless steel Swagelok fittings should be replaced with equivalent plastic fittings. Artifacts in the CT numbers will still occur due to the fittings, but these would be minor and would allow observation of saturation changes near the injection ports. Such observations are not possible with stainless steel fittings.

Several authors (Kazemi and Merrill (1979), Beckner (1990), Gilman, et al (1994)) have assumed that fracture capillary pressures are negligible. Others have shown experimentally that capillary continuity becomes important when gravity provides a driving force (Horie et al (1988), Firoozabadi and Hauge (1990), Labastie (1990), Firoozabadi and Markeset (1992a, 1992b)). Kazemi (1990) states his belief that capillary continuity is prevalent in the vertical direction and has suggested that, to reduce the number of equations to solve, fractured reservoir simulations should use the dual permeability formulation for the z direction, and the dual porosity formulation for the x and y directions.

The CT scans shown in this report confirm that capillary continuity can occur in the vertical direction. This continuity pulls fluid in the opposite direction of gravity. The continuity works in any direction depending on the relative strengths of the capillary and Darcy terms in the flow equations. Thus, the simulation engineer should evaluate the forces present in the system being simulated to decide which directions should be evaluated by dual permeability equations and which by dual porosity.

It should be noted that it remains unclear as to what has caused the continuity between blocks in this experiment. The most likely explanation is that fine grained material from cutting the end pieces may not have been thoroughly cleaned from the fracture. Some fine grained material was observed in the space between the rock and the Plexiglas end plates once the core had been filled with water. A repeat of this experiment should reveal whether this material caused the continuity across the fracture, or if there is some other mechanism.

ACKNOWLEDGEMENTS

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