LABORATORY STUDIES ABOUT NATURAL CLEANUP OF DAMAGED FORMATIONS

Lopes, F. R. felipe@dep.fem.unicamp.br
Moreno, R. B. Z. L., zanoni@dep.fem.unicamp.br
Faculdade de Eng. Mecânica – DEP - Unicamp

Abstract.

Invasion of drilling fluids and its consequences on petroleum production are well known and it has been intensively discussed by specialists. Moreover, the scientific community has invested a massive effort in understanding the invasion mechanisms and permeability restoration. This study extends previous investigations and includes both invasion and back flow evaluation conditions. Test sample, initially at connate water condition, were submitted to constant pressure displacements. Using a special core holder, saturation and pressure profiles were monitored during overbalance pressure invasion and oil flow back. Monitored data has allowed to observe the formation damage characteristics as well as cleaning dynamics.

Drilling fluid has to enroll many functions and, focusing on that, they can be designed according formation characteristics and operational procedures aiming minimum damage formation. Nevertheless, more than null invasion, natural cleaning during flow back can be a suitable result for overbalance operations.

In this work, polymer injection into the sample at residual water saturation has improved the reservoir representation; however, invasive fluid has displaced both mobile oil and initial immobile water. During the back oil flow, most of the invasive polymeric solution was produced back and saturation distribution was restored close to the original one. Local impairment conditions were calculated using differential pressure along the core and their values were compared with the average global value. Additional insights about dynamic mechanisms were also discussed based on a large quantity of monitored data.

Among many partial contributions, we can highlight the ongoing development of the experimental setup and procedures, the extensions of the previous work and additional insights about dynamic mechanisms.

Keywords*: Oil injection, polymer, saturation, permeability, damage formation.*

1. INTRODUCTION

Drilling fluid or mud is any kind of fluid used in drilling operation. The fluid is circulated and pumped from the surface through the drill and finally returning to the surface through the annular space. Drilling fluids must satisfy many functions, such as those mentioned byDing et al (2004), ie, suspend the cuttings (solids drilling) and remove them from the bottom through the annular space to the surface, controlling the formation's pressure and maintain the stability of the walls in the annular space; seal permeable formations, lubricate and cool the bit; transmitting hydraulic energy, minimize damage to the reservoir, corrosion control, facilitating cementing and completation and others; . The most important drilling fluid function is to decrease the cuttings concentration around the drill bit and carry them out to the surface. As might be expected, the cuttings should be removed from the fluid in order not to reduce the cleaning ability and promote the formation of a thick cake. In order to utilize the drilling fluid again, the cuttings must be removed continuously and efficiently.

Most of the oil and gas wells are drilled using water-based drilling fluids. When there is an overbalanced drilling the drilling fluid invades the reservoir. The inclusion of solid and/or polymer into the formulation of fluid alters the saturation distribution in the porous space. Besides this alteration, reaction between the fine's formation and the fines displaced into the reservoir can result in a reduction of the original permeability.

The problems caused by the invasion of these fluids is well known, however they are not easily predictable. The depth invasion prediction of these fluids and the dynamics of permeability return of the affected region are of great interest to petroleum industry, so losses in production capacity due to reduction of permeability in the region around the well are avoided.

This problem is even more critical in case of horizontal wells because the difference between reservoir and bottom hole pressure is smaler than that for a vertical one. This gradient is extremely important to remove fines and to take the filter cake off the formation interface (well-reservoir). Fields experiments show that in most cases of horizontal wells, production's efficiency is not as expected, partly due to damage formation. In a particular case, only 5-10% of the total length of the well has contributed to the production as reporterd by Jylani et al. (2003).

The reservoir can be damaged in different ways. Physically, the formation can be damage by: (a) invasion of solids from the drilling fluids with blockage of pore throats (B) blockage of capillaries due the retention of polymers and (c) blockage due water, gas or emulsion. Chemically, the formation can be damaged because of reactions between the

filtered and the content of the pore or with the rock. Swelling or clay dispersion and precipitation due to reaction between the mud filtrate and the porous content as well as the dissolution of salts and minerals from the rock are the main factors that cause chemical damage. The formation can still be damage by bacterial colonies and the products precipitated by them, blocking the connecting porous.

In this work will be studied the natural cleaning of the region around the well damaged by the polimeric solution. The goal for this experiment was verify the impact caused by the fluid invasion during the backflow.

2. MATERIALS

For the development of this work were used saline solution with 150.000ppm of NaI, and mineral oil (Nujol) to simulate the reservoir fluids. To simulate the drilling fluid, was used a polymeric solution with 150.000ppm of NaI and 13.000 ppm of hydrolyzed poliacrilamida (PHPA).

The saline solution concentration was establish according to experimental tests previously performed looking to the acquisition of saturation profiles under different conditions of fluid distribution inside the sample. This value proved to be sufficient to identify differences in sample aqueous phase saturation using X-Rays. The solution was prepared in a kitassato, in which 150 g of NaI were added to one l liter of distilled water. The kitassato was placed in a magnetic stirrer and connected to a vacuum pump to remove any gas from the solution. Polymeric solution was prepared addicting 13 g de PHPA into 1 liter of saline solution. The rheological behavior of polymer solution was obtained using a rheometer Haake Mars III. The measured data and the fit adjusted by Herschel-Bulkley model can be seen in "Figure 1".

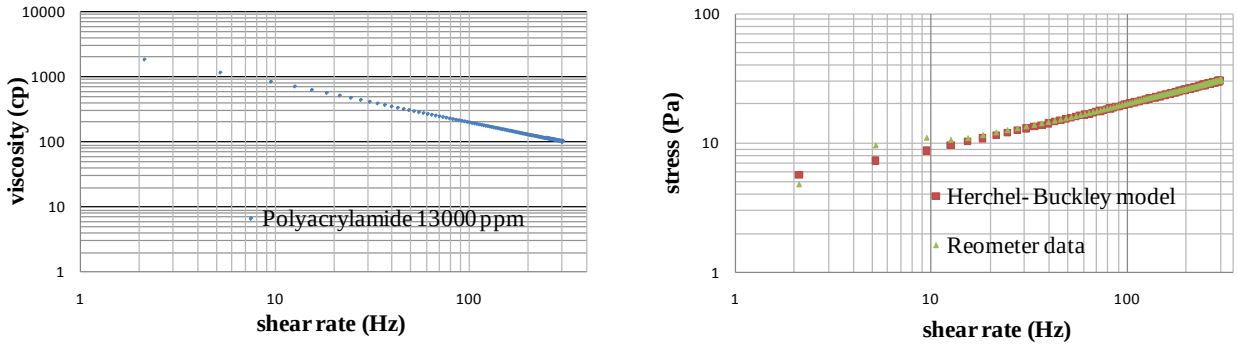

Figure 1: Rheometer records

The oil and saline solution viscosity were measured. The oil viscosity was determined to different temperatures.

To perform the tests presented in this paper was used a sample of Botucatu sandstone. This sample was cut in a shape of cylinder with a diameter of 37.5mm and a length of 44.9cm. The dry sample mass correspond to 1002.2g. The sample porosity was measured and the value was 0.237, with this number was calculated the sample density and it reachs a 2.62g/cm^3. The pure quartz density is around of 2.65g/cm^3, so it was assumed that the porosity was right.

The gas permeability was determined by a gas permeabilimeter (Nitrogen) and the value obtained was 729 mD.

In these experiments was used a special core-holder that allowed the recording of pressures variations inside the sample at many positions as a function of time. The core-holders, usually used in the laboratories, don't have such advantage and only allow to register the pressure drawdown between input and output edges of sample. The special core holder design can be seen in the figure 1 underneath. Validyne pressures transducers with diaphragms were utilized with bottom scale of 320psi and output A/D in the range +/- 5V connected to the data acquisition board.

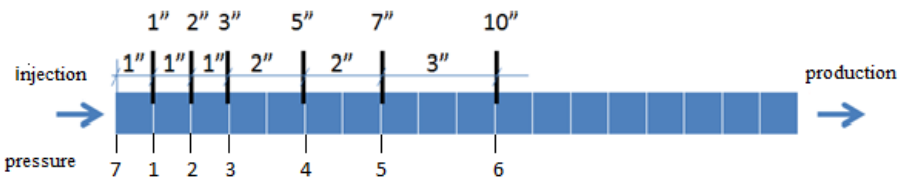

Figure 2: Special core holder design

3. METODOLOGY

The test protocol was divided in 5 steps. (see "Fig. 3")

The first step was the positioning of the sample into a rubber shirt and then inside the core-holder. The annular space was filled with 3000 psi of water for the lateral surface sealing of the rock sample. Measurements were taken for sample porosity and permeability to nitrogen and then the core-holder was placed in the line test, as well as other equipments and devices for measuring pressure, volume and mass. It was performed an X-Ray scanning to verify the homogeneity of the rock sample.

In the second step, all the air into the sample was removed with a vacuum pump. To do this, the input is closed and a vacuum pump is connected on the output. The sample is pumped for a few hours and with the help of a vacuum gages it's possible to know the right time to admit the solution. In this case, the solution was admitted when pressure inside the sample reached 0.1 mbar. The system rests for several hours to ensure complete saturation of the sample. Once saturated, the water absolute permeability was measured and another X-Ray scanning was performed to verify the uniformity of saturation. The solution volume injected into the sample and the data of X-Ray are the indicatives to verify if the sample was saturated as expected. The most important step at this stage is to determine the water absolute permeability.

In the third step was done the oil injection, until the sample has reached the innate water saturation. This step aimed to increase the representativeness of the sample in relation to an oil reservoir. In the end of this step was performed an X-Ray scanning and determined the oil effective permeability at innate water saturation.

In the fourth stage was performed the polymer solution injection with constant pressure differential of 192 psi. In this part were measured the mass and volumes produced as well as pressure from the transducers placed along the test sample. Two X-Ray scannings were performed for different times and injected porous volume (IPV). The first scan was performed at 1150 seconds and 0.106 IPV, and the second after 0.244 IPV (in the end of the test).

Finally, in step 5 was performed oil backflow through the sample with a constant differential pressure of 185 psi. To do this acquisition, the transducer that was in the input position was changed to the output one to allow the pressure control.

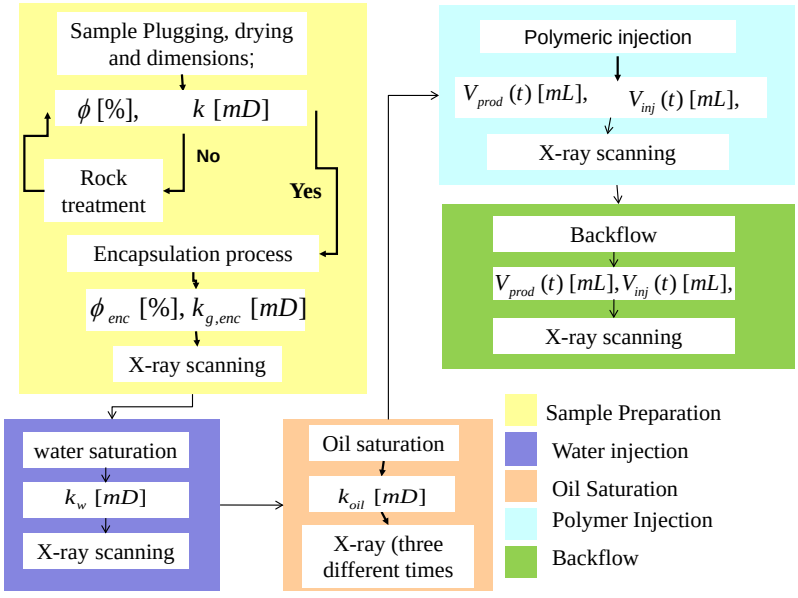

Figure 3 : Test protocol

The produced mass during the tests was measured using a precision scale. This data is very important to monitor the injected and produced volumes accurately, because it also allows to determine the volume in relation to time once the fluids' density can be measured with a proper device. There is an acquisition system that stores all the data from the balance and from the pressure transducers in intervals of 50 seconds. With this data it is possible to do a well-founded description of the damage formation and removal dynamics caused by the polymer solution.

4. RESULTS

The table 2 shows the measured and calculated parameters at each stage of the experiment.

In the first stage of the test, effective porosity of the sample, so the connected pores volume, and gas permeability were measured. The determined values were respectively 23.7% and 729.1mD.

In the second step was measured water absolute permeability value. For this was measured the output flow due to water column hydrostatic pressure connected to the input, which was 0.092 atm for two intervals of time, 2 and 4 minutes. With these values was made an average flow rate during this interval and by Darcy's Law, was found the water absolute permeability value. The viscosity measurement for the saline solution was approximately 1 cp, and hence the value of water permeability was found 727.98 mD.

In the table below there are the values necessary for this calculation.

Table 2: Summary of tests

Sample data - Steps 1 and 2				
Lengh(cm)	diameter (cm)	porosity	Area(cm)	Volume(cc)
44.9	37.5	0.237	11.04	495.9
Porous Volume (cc)	k (Nitrogen)mD	kabs (water)mD	Mass (g)	sample density (g/cc)
117.9	729.1	728.0	1002.2	2.65
Oil Injection - Step 3				
$S_{w\ inicial}$	$S_{o\ inicial}$	$V_{prod.}$ de água (cc)	V_{inj} de óleo (cc)	$k_o@S_{wi}$ (mD)
1	0	88.5	320	556.95
Oil injection rate(cc/min)	$S_{w\ final}$	$S_{o\ final}$	Total dead volume(cc)	input dead volume (cc)
0.25	0.25	0.75	5.5	1.3
output dad volume (cc)	Oil viscosity - cp (T=20°C)	Oil viscosity - cp (T=25°C)	Nujol density (g/cc)	water density with NaI(cp)
4.2	142	105	0.865	1.0
Polymer Injection - Step 4				
Injected volume in the sample (cc)	Output Volume (test tube -mL)	Output dead Volume	Input dead volume(cc)	Percentage of injected porous volume
28.7	30	0	1.3	0.24
Percentage in relation to oil in place	Distance reached by polymer (cm)	Avarage saturation before the advancedd front.	Polymer vuiscosity	
0.32	≈25.4	0.43	See figure 1	
Oil Backflow - Step 5				
Backflow injected volume (cc)	Polymer producted volume (cc)	Effective produced volume	Percentage of polymer producted	Volume withheld inside the sample (cc)
290.0	18.0	15.1	0.53	13.6

In the third stage (oil saturation), it was used a scale at the input to monitor the injected volume and mass of oil in the sample, and a scale in the output to monitor the produced volumes of water before and after the oil breakthrough.

As oil viscosity is too higher relative to water viscosity the mobility ratio is very low, to around 0.006, and because of this, displacement is like-piston. To facilitate interpretation, the saturation before the advancing front was considered as constant and equal to the residual saturation.

Records of mass variation in the injection (input) and production (output) are shown in "Figure 4". The produced fluids were collected in test tubes and their volumes were recorded manually. The oil breakthrought occurred after 6 hours corresponding to 0.77 IPV. Figure 4 shows the cumulative produced water volume, relative to the injected porous volume. When the water production rate approached to zero, the injection was stopped. Thus it was possible to find the oil effective permeability at innate water saturation, which in this case was 548 mD. In the end of the oil injection, the

water produced at the sample output was 88.5mL or 75% of the porous volume. Thus, innate water saturation after oil injection was 25%. In the Figure 4 can be seen that after oil breakthrought amount of produced water was very small, indicating that the oil displacement was like piston and the saturation behind the advancing front was near to innate water saturation.

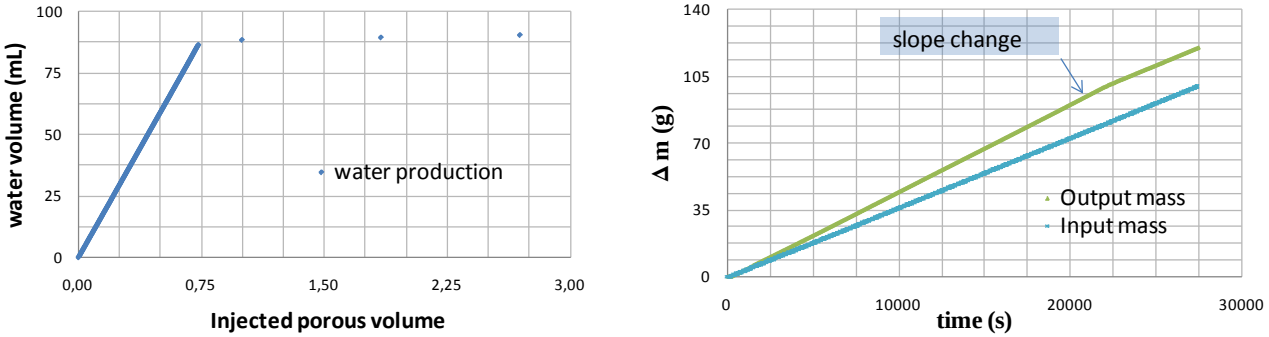

Figure 4: Water injection records

The testing apparatus allowed the study of the oil saturation front advanced in three ways. The first way allowed to estimate the speed of the oil saturation front considering a constant saturation behind the front. Another way was to follow it thought the X-Ray scan, and finally, monitor the advancing front through the pressures transducers. The pressure transducer recorded a change when the advanced front reaches each of them. (See Figure 5)

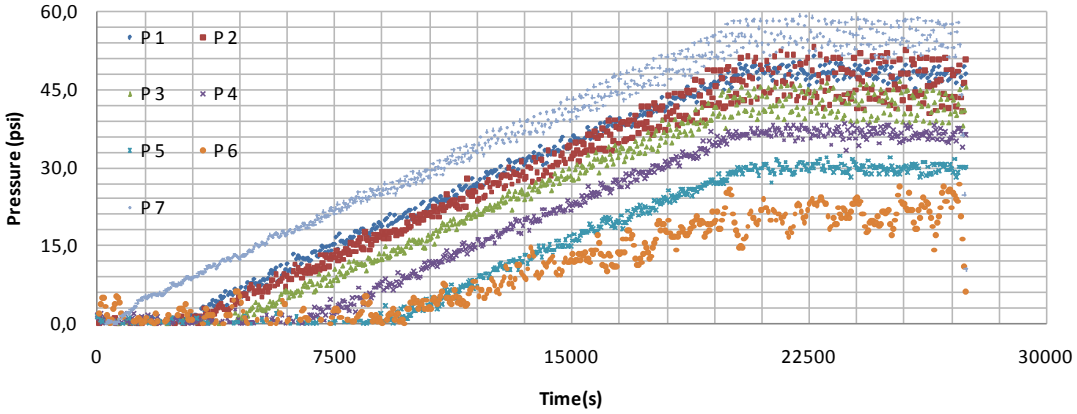

Figure 5: Pressure records during the oil injection

The first X-Ray scan was performed after 0.13 injected porous volume and 65 minutes. The distance covered by the mass balance was 5.94 cm and X- ray analysis indicated a change of saturation around 6 cm from the sample inlet face. Using the X-Ray time as a reference, it was possible compare the position of the advanced front through the pressure transducer and analyzing figure 5 it can be concluded that the advanced front was between the transducers 2 and 3 (5.08cm – 6.35cm).(check out the position in figure 2).

The second X-Ray scan occurred after 0.26 injected porous volume and 122 minutes and 50 seconds. The distance determined by the mass balance was 15.32 cm, the X-Ray data showed a saturation change next to position of the 14 cm from the sample inlet face. Using the X-Ray time as a reference, it can be concluded that the advanced front was between the transducer 4 and 5 (12.7cm – 17.78cm).

The third X-Ray scan occurred after o.46 injected porous volume and 215 minutes. The distanced determined by the mass balance was 27.33 cm, the X-Ray data showed a saturation change around the position 30 cm from the sample input. Using the X-Ray time as a reference it can be concluded that the advanced front was after the last transducer placed at 25.40 cm (P6). The saturation profiles obtained using X-Ray scans are shown in figure 6.

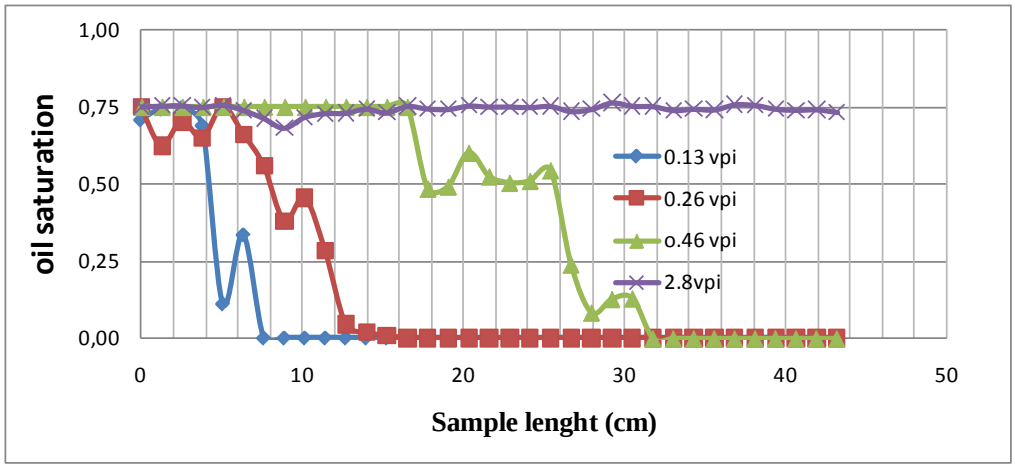

Figure 6: Saturation profile made from X-ray scan during the oil injection

The drilling fluid invasion process was simulated in step 4 of the test. Almost 25% porous volume of polymer solution was injected with a differential pressure around 192 psi. To adjust the injection pressure, it was used a transducer placed before the sample input. After setting the value to 200 psi in this transducer, the valve was opened and the pressure falls slightly. The polymer solution injection was stopped when oil production reached at 30 mL in the test tube. The polymer volume injected in the sample was 28.77 mL, because there is 1.23 of input dead volume. In this case was considered only the input dead volume because there was no output polymer production. The output volume helped control the polymer damage volume injected into the sample at this stage, once the injection was performed at constant pressure and there wasn't input mass control.

To check the invasion depth of this solution, X-Ray scans were run again, as well as observation from pressure records by the transducers. Analyzing pressure records it's possible to see that there is a correlation between the local minimum point in each transducer and the advanced front speed (see figure 7). This effect was noted with the help of mass balance done before. Thus looking at those points, it's possible to follow the advanced front inside the sample.

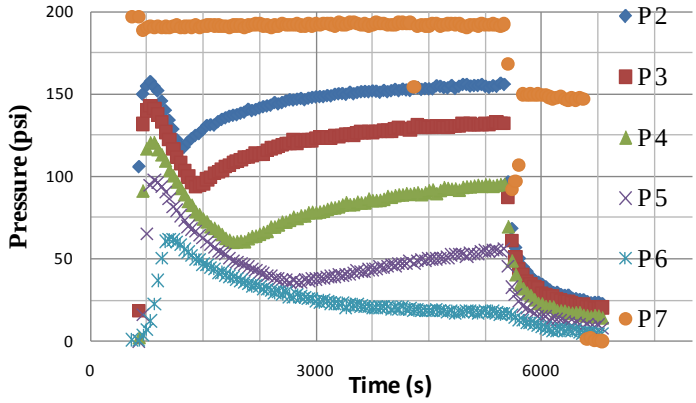

Figure 7: Pressure records during the polymer injection.

The pressure values highlight in the table below refer to the pressure behind the front in advance. These measures were obtained taking the pressure at the time that each curve reaches the minimal point.

Table 3: Pressures in the minimal points

time (s)\ transdutores	input	P2 (psi)	P3 (psi)	P4 (psi)	P5 (psi)
1200	190	119	108	93	76
1350	191	123	96	83	68
1900	191	137	108	60	49
2650	192	146	120	73	36

Using all possible combinations behind the advancing front for each time step, the polymer's effective mobility was calculated. So, to transducer 3 for example, the polymer mobility was calculated using the difference between the input

pressure and transducer 2, input pressure and transducer 3 and finally between the transducer 2 and 3. After these calculations, the average was done for each time. These values can be seen in the table below.

Table 4 : Average Mobility behind the advanced front.

times (seg)	1200	1350	1900	2650
average mobility (mD/cp)	1,06	1,14	1,06	0,87
Saturation behind the advanced front	0,52	0,43	0,40	0,40

Looking the pressure records with the X-Ray data is possible to conclude that the polymer reached the region between transducers 5 and 6. For this reasons the transducer 6 was not included in the above estimates.

With the position data of the advanced front at different times, it's possible to calculate the average saturation behind the advanced front as it was measured the output volume that in turn is equal to the injected volume.

The higher is the distance between transducer and the inlet face of the sample, more difficult is to determine the time when the front reaches that point, because the pressure record by these transducers have a lower change in their slopes as show in Figure 8.

The behavior of the average saturation behind the advanced front indicates that the displacement of the polymers not an ideal piston, but doesn't refers to an unstable flow (presence of fingers) either, since the fall of average saturation behind the front was not occurring in a brusque manner.

Analysis of the variation on the polymer mobility can be done as injection occurs, similarly to that performed for oil injection. During the polymer injection, cumulative produced oil was recorded and the data are showed in the figure 9. The slope of this curve indicates the production flow rate and it's very easy to note that the slope is decreasing.

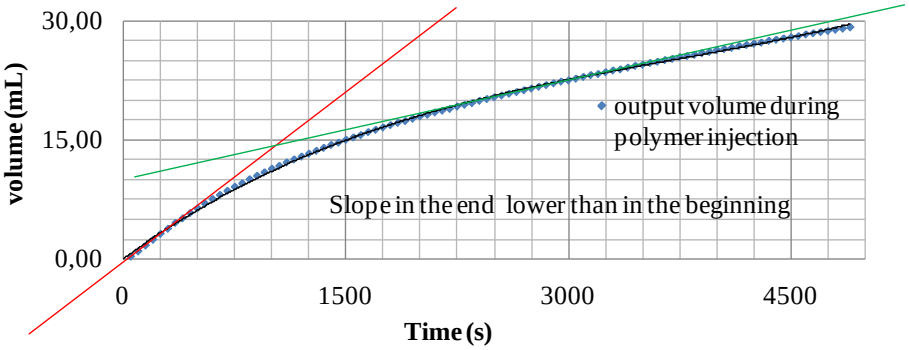

Figure 8: Output volume during polymer injection

The estimation of the position of advanced front made from the pressure records was satisfactory in comparison to the X-ray scans and mass balance.

The last stage consisted to perform the backflow. For this step, the input transducer was placed at the output, where a bottle with oil (Nujol) was connected At this stage, oil was injected with a differential pressure of approximately 185psi, at the output face, ie, through the reverse direction of the core-holder,, reversing the whole system. It was taken care to leave all conduits always filled to facilitate analysis of the produced and injected volumes.

At the end of the test, it had been injected an amount of oil equal to 292 mL, about 2.47 porous volumes. The cumulative production of oil was 18 mL but there was 2.83 mL of input dead volume that needed to be discounted. So the real volume produced was 15.16 mL. During the backflow, the percentage of polymer solution produced was 52.7%.

The interest of this backflow is to observe the permeability return of the region invaded by the polymer, in a natural way, without any intervention but the flow of reservoir fluids into the well according to the difference between reservoir pressure and bottom hole pressure.

To observe this fact a cumulative production curve was plotted ("Figure 9"). In this curve can be seen an upward concavity indicating that the flow rate is getting up over time. To verify this, a plot of flow rate as function of the time was done ("figure 9b"). It's easy to see an increasing flow rate. In the end of the test the flow rate was the double of the initial one.

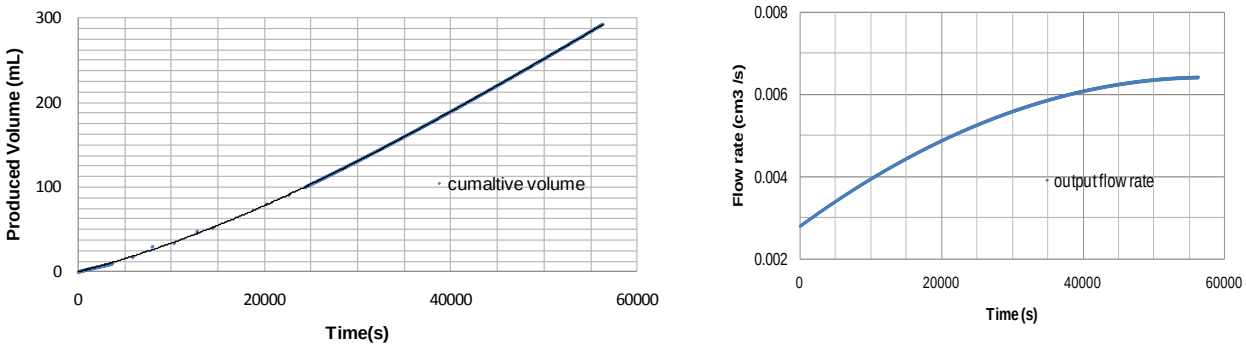

Figure 9 : Volume produced during backflow

A qualitative analysis is show in Figure 10 because it does not take into account the displacement of the aqueous phase inside the porous medium. A curve of calculated permeability from the Darcy's law indicates that the polymer has reached into the position between transducer 5 and 6. It's possible to conclude this by observing the next graphic. When the curve is traced using just the transducers 6 and 7 (now in the sample output) the value of the oil effective permeability is close to the calculated permeability at the end of the stage 3 (see table 2). The result would be expected between transducers 5 and 6 , but this doesn't happened, actually there is a good decrease. The situation worsens as the closest is the region to the considered output face. As a qualitative result, this region is becoming more permeable to the oil as production goes on.

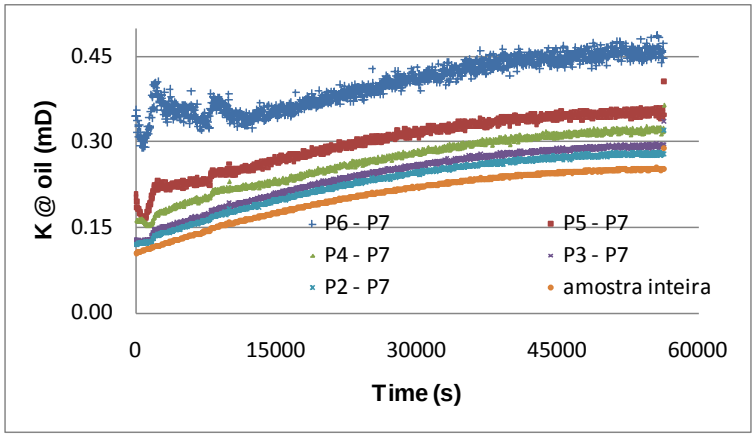

Figure 10: Qualitative analysis of permeability

At the end of the test, the permeability variation to the oil had changed.

At the end of the experiment, it was possible estimate the average permeability variation to oil in both zones, ie, invaded zone by polymer and not invaded zone. Invaded region was placed between output face and the transducer 5 and the clean zone corresponds to the region between input face, for oil flow back, and transducer 6. In the damage zone the oil permeability has changed from 60mD to 200mD and in the other region permeability has changed from 345mD to 530mD .

5. CONCLUSION

In this work it was possible to verify the operation of a core holder with pressure measurements along the sample. These data has allowed the calculation of permeability in portions of the sample. It was then possible to quantify the damage caused due to polymer injection in different areas of the rock. The used method to verify the position of the saturation front has proved to be very satisfactory, since analysis considering pressure data, material balance and X-Ray scans have agreed.

During the backflow, it was possible to measure the permeability return due only to oil production (reverse injection).

The sample's permeability restoration could have been improved, if more fluid had been allowed to flow during the backflow because, as can be seen in Figures 09 and 10, the flow rate was still increasing.

The transducers allowed monitoring the advance of the front of saturation for the oil and polymer injection.

6. ACKNOWLEDGEMENTS

The authors of this paper would like to thank Petrobras for the financial support to this project and to Luiz B. Pompeu Netto and to Leandro A. Fernandes for their great assistance with the experiments.

7. REFERENCES

CIVAN, FARUK. Gulf publishing Company, Houston Texas, 2000.

Y. Ding, D. Longeron, G. Renard, and A.Audibert, Modeling of Both Near-Wellbore Damage and Natural Cleanup of Horizontal Wells Drilled With Water-Based Drilling Fluids. SPE 88807 , 2004.

Jilani, Syed Zeeshan: "Experimental study of formation damage in horizontal wells" King Fahd University of Petroleum & Minerals, cap 1, 2, 3. A thesis presented to the deanship of graduate studies-king Fahd University of Petroleum & Minerals, Dhahran, Saudi Moreno,

R.B.Z.L; Bonet, E.J.. Experimental and Numerical Calculation of Polymer Base Mud without Solids Invasion In a Porous Media. IN: SPE EUROPEC/EAGE Annual Conference and exhibition held in Barcelona, Spain, 14-17June 2010, SPE 131628, 13pp.

Annie Audibert, Jean-François Argillier, Hemant K. J. Ladva, Paul W Way, Arvid O. Hove, Hole of Polymer on Formation Damage. European Formation Damage Conference held in The Hague, 31May – 1June1999, SPE 54767.

Ryen Caenn[a], George V. Chillingar[b]. Drilling fluids: State of the art. Journal of Petroleum Science and Enginnerning 14 (1996) 221-230.

A.T.A. Waldmann, R.A.F. Leal, I.J. Pires Jr., R.F.T. Lomba, A.F.L. Aragão, and A.L.Martins. Minimizing Drilling-Fluid Invasion in Coring Operations – SPE Europan Formation Damage Conference held in Scheveningen, the Netherlands, 30 May-1 June 2007, SPE 107618.

V.C. Keçessidis, R. Maglione, C. Tsamantaki, Y. Aspirtakis. Optimal determination of rheological parameters for Herschel-Buckley drilling fluids and impact on pressure drop, velocity profiles and penetrations rates during drilling fluids, Journal of Petroleum Science and Enginnerning 53 (2006) 203-224.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.