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CAPILLARY PRESSURE PROBE FOR SCAL APPLICATIONS

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Abstract

Oil and water relative permeability measurements on reservoir rock plugs are, in general, affected by so-called capillary end effects. These effects are a direct consequence of the finite length of the experimental plugs; in very long plugs or actual reservoirs these end effects are insignificant. Interpretation of the plug data is therefore not straightforward as in fact a superposition of viscous and capillary pressure gradients is measured while only viscous pressure gradients are required for determination of the relative permeabilities. In other words, the viscous and capillary pressures need to be unravelled from the superposed pressure signal for proper relative permeability determination.

To enable a direct measurement of capillary pressures and consequently of viscous pressures gradients, the capillary probe has been proposed in the past. The principle of the proposed methods is the measurement of oil and water pressures via oil- and water-wet filters placed in front of pressure probes. In this paper, a detailed design of a properly functioning probe is presented. The probe is small in size (1 mm^2 active area), can operate at high pressures (300 Bar) and temperatures (120 ^{0}C), is easy to mount and shows reproducible results. Tests of the probe on sandstone and carbonate samples are presented and discussed. Multiple probes along the length of a core plug are used to observe the evolution of capillary pressure during frontal displacement and to demonstrate capillary end effects.

1. Introduction

In dynamic flow experiments, for example steady state and unsteady state experiments, the measured pressure differentials are a superposition of viscous and capillary pressure differentials. To properly determine the viscous pressure gradients either experimental provisions or numerical interpretations are required. An example of an experimental approach is the use of end pieces for suppression of the capillary end effect. Alternatively numerical simulations can be performed to unravel the viscous and capillary pressures from the composite pressure signal. However, the design and implementation of the end pieces is not straightforward and is time consuming and numerical data interpretation is, in general, time consuming and, for some cases, not unique. A direct measurement of capillary and/or viscous pressure differentials would therefore be preferable.

If wetting and non-wetting phase pressures are measured directly, the wetting and non-wetting pressure gradients are known and consequently the phase relative permeabilities can be calculated by simply applying Darcy’s equation. To achieve this, the capillary pressure probes have been developed. The “capillary pressure probe” set-up consists of two pressure probes of which one probe measures the wetting phase pressure and the other the non-wetting phase pressure. The difference of the probe pressures is the capillary pressure. In the following the wetting phase is referred to as water and the non-wetting as oil.

In the past, various experimental set-ups have been proposed that apply oil- and water-wet filters to measure capillary pressures [1, 2, 3, 4]. Two used the porous plate technique to establish saturations and measure capillary pressures [2 and 3]. Labastie [1] and Honarpour [4] measured capillary pressures via pressure probes along the side of a core plug during displacements. In this study, this latter technique is extended and tested for design robustness, ease of operation, and application at high pressure (300 Bar) and temperature (120 ^{0}C).

The principle of the measuring method is given in section 2, the design and construction of the probes are presented in section 3. Details of the tests performed and discussion of the results are in section

4, including results of experiments with three sets of capillary probes, allowing the capillary pressure distribution along the plugs to be resolved.

2. Principle of the Measuring Method

Water and oil pressures can be measured with standard pressure probes for which a water- or an oil-wet filter bas been mounted. By filling the tubes connecting the probes with either oil for the oil probe or water for the water probe, the proper oil and water pressures can be measured. The oil in the oil probe connects via the oil-wet filter with the oil in the sample and therefore only the oil pressure in the sample is measured. Water in the plug is not connected and therefore no water pressure will be measured. For the water pressure probe, the same principle applies. By connecting the oil- and water-filled tubes to a differential pressure gauge, the capillary pressure is measured directly. A schematic of the measuring technique is shown in Fig. 1. Alternatively, when two oil probes are mounted on the plug’s cylindrical surface at different distances from the inlet, the differential pressure between the probes allows the oil pressure gradient in the flow direction to be calculated from the probe reading. Consequently the relative permeability for oil can be calculated directly from Darcy’s equation. The same applies for the water phase. Disturbances in the pressure gradient caused by capillary end effects and the rather cumbersome corrections required to allow for these end effects are thus circumvented.

3. Design and Construction

The oil and water probes were mounted on the cylindrical sides of the plugs at equal distances from the inflow and outflow ends, although in principle any position is acceptable. The oil and water probes were mounted opposite to each other, although this is not essential as long as the flow path length to the inflow end is equal for both pressure probes. This ensures that there are no viscous pressure gradients between the probes.

The rock plugs were mounted in viton sleeves that enabled pressurisation of the plugs from the outside for sample confinement reasons. The probes must be fed through the viton sleeve in a leak tight way.

3.1. Probes

Figures 2 and 3 show cross-sections of the probes. The probes consist basically of water- or oil-wet filters, filter holders and a connection for tubes leading to pressure gauges. The shape of the filter holders is curved for good connection with the cylindrical plug surface. On the outside of the holders, precautions are taken to provide a leak tight feed through the viton sleeve surrounding the plug.

The ceramic water-wet filter is gently pressed against the plug. To control the force with which the filter is pushed against the plug a gasket construction has been designed (Fig. 2) such that this force is delivered by the compacted gasket and not by the external confinement pressure. The filter selectivity is limited. If the oil pressure exceeds a certain threshold (approximately 10 Bars), the water-wet filter fails and oil is forced through. Once a filter has failed it is damaged and will fail at much lower pressures thereafter. The failure pressure of 10 Bars is considered sufficiently high for the envisaged applications.

The oil-wet filter is made of thin Teflon sheet (0.1 μm) and is very fragile. It is therefore supported by a piece of ‘Victrex’ Peek (Polyetheretherketone) in which small holes (diameter 0.1 mm) are drilled. The Teflon sheet is tightly pulled over the ‘Victrex’ Peek support. The same provisions with respect to the maximum compression force are taken as for the water-wet filter (Fig. 3). The pressures at which the oil-wet filters fail is also approximately 10 Bars.

3.2. Test Set-up and Principle

Fig. 4 shows the schematic of the test set-up. Three oil and three water probes are shown along the cylindrical sides of the plug, although initially only the middle probe combination was used. For the rest of the equipment a set-up similar to the Caprici set-up [2] has been used as in this way saturations and capillary pressures can be set in the plugs in a controlled manner. Therefore an oil-wet and a water-wet filter are mounted on the flat (inflow and outflow) side of the plug. The whole set-up is mounted in a pressure vessel that is pressurised up to 40 Bar during the reported experiments. By injecting oil through the oil wet filter into the plug and knowing that only water can leave the plug through the water wet filter, the oil volume and consequently the average saturation in the plug can be determined accurately. In the set-up of Fig. 4 four pressures (differential) are measured: the three Pc-probe pressures (Pc_top, Pc_mid and Pc_bottom) and the pressure across the total plug (Dp_plug). If injection is sufficiently slow, the saturations are approximately constant over the plug due to capillary smear-out and therefore the pressure required to inject oil (Dp_plug) is equal to the capillary pressure. In the ideal case of infinitely slow injection, the capillary pressure measured along the plug's side by the probes should be equal to the pressure differential measured over the plug (Dp_plug). In the next sections it will be shown that during the experiments the condition of "infinitely" slow injection was not always fulfilled and the capillary pressure profile is not homogeneous over the plug.

4. Experimental Results and Qualitative Interpretation

Figure 5 shows both the pressures measured over a Berea plug (Dp_plug) and the capillary pressure measured by the oil-water probe combination halfway along the plug (Pc_mid). The properties of the plug and fluids are listed in Table 1. The injection rates are chosen to be relatively high; as a result, the condition of "close to zero" injection rates is not fulfilled and the pressures measured over the plug (Dp_plug) are a combination of viscous and capillary pressures. These high rates were selected because the pressure distribution is of more value for test purposes.

4.1. Drainage Experiment

During the first 23 hours of the experiment shown in figure 5, oil was injected through the oil-wet filter (drainage experiment), thereafter (23 to 90 hours) water was injected through the water-wet filter (imbibition experiment). At start of oil injection a displacement front was established which moved through the plug. This is noticeable in the response of the capillary pressure probes that show no signal for the first three hours as apparently the oil front has not reached the location of the probes. After three hours, a signal is measured that is equal to the pressure differential over the plug. Once the front arrives at the outflow end the oil starts accumulating in front of the water-wet filter as oil cannot leave the plug through the water-wet filter. As a result the oil saturation at the outflow end increases more rapidly than over the rest of the plug and the water relative permeability at the outflow end decreases quickly. Effectively a flow barrier at the outflow end builds up and the pressure over the plug increases rapidly as a result of this flow barrier. Reducing or stopping flow enables capillary forces to smear out the saturation over the plug and to dissipate the flow barrier. When restarting injection at a lower rate the same build-up phenomena will occur again at a somewhat higher average saturation. The described pattern can be observed in Figure 5. The pressure over the plug builds up initially to a value close to the capillary entry pressure and steeply rises after some time (approx. 15 hours). Reduction of the flow rate reduces this pressure but a repetition of the steep pressure increase occurs at a later time (approx. 21 hours). According to this qualitative model the steep rise is mainly a result of the viscous pressure drop over the saturation barrier at the end of the plug. The capillary pressure probes mounted halfway along the cylindrical sides of the plugs should therefore not be sensitive to these viscous drops. This can indeed be seen in Fig. 5 where a much more gradual increase of pressure is observed on the probes than in the pressure over the plug. Also it can be seen that after ceasing injection, the pressure over the plug approaches the pressure on the probes as should be (capillary equilibrium). Note that the little dip in the probe pressure at 10 hours is an experimental artefact as a result of ambient temperature variations. Similar temperature effects are seen at 45 hours and 83 hours.

4.2. Imbibition Experiment

After 23 hours the flow was reversed and water was injected through the water-wet filter while oil is expelled through the oil wet filter. Figure 5 shows that the pressure over the plug rapidly drops to low values while the pressure on the probes continues to increase, the pressure only starts to decrease after 27 hours. The reason for the (temporary) continued increase is the mound of oil in front of the water-wet filter. This mound is displaced towards the oil-wet filter by the injected water and consequently the oil saturation at the probes increases and so also the capillary pressure until the oil mound is displaced past the probes.

After some 65 hours water accumulation occurs now at the oil-wet filter and again a pinch-off of the flow occurs and a steep decrease of pressure is seen over the plug. Despite this negative pressure, the pressure on the probes is still positive and is not influenced by the pressure drop at the oil-wet filter. After ceasing injection the pressure over the plug is restored (although relatively slowly) to a pressure close to zero. A small difference with the probe pressure remains, which might result from an inhomogeneous saturation distribution due to an incomplete capillary smearing out after injection ceased.

A similar experiment to that shown in Fig. 5 is shown in Fig. 6, although here the injection rate was chosen to be a factor 1.75 higher. The same phenomena as in Fig. 5 are observed although the pressure response is more pronounced. According to the proposed model the height of the mound as measured on the capillary pressure probes once the flow is reversed and water is injected, should be dependent on the rate at which the water is injected. At a relatively low water injection rate the oil mound spreads, as a result of capillary forces, during displacement towards the oil-wet filter. For a high rate the spread is less and a more pronounced mound is displaced through the plug, resulting in higher pressures on the probe. This can indeed be observed in Fig. 6.

Note that the time period of injection interruption was not long enough and pressures over and along the plug did not reach equilibrium, i.e. the same value.

4.3. Three Probes Measurements

To further test the principle of the probes, the bottom and top probes were connected (Fig. 4), with the bottom-probe situated close to the water inlet and the top-probe close to the oil inlet.

4.3.1. Sandstone Plugs

An experiment similar to the one probe experiment has been performed: first oil was injected through the oil-wet filter in a water saturated plug (drainage) and subsequently water was injected through the water-wet filter (imbibition). A more permeable (1560 mD) Bentheim plug has been used; as a result the capillary pressure effects are of a smaller magnitude than in the previous Berea plug data (620 mD). The results of the experiment are shown in Fig. 7. In the presentation the focus is on the pressure effects which occur at the transition from drainage to imbibition. Starting at 70 hours we see that the pressure over the plug (Dp_plug) is increasing due to build up of the oil mound in front of the water-wet outflow filter. The capillary pressures along the plug show this mound as the probe closest to the water outflow end (bottom) measures the highest capillary pressures and the one at the inflow end the lowest pressures. Due to the high permeability of the plug the absolute differences are only small but the trend is clearly visible. Also note that the scale for Dp_plug is 5 times compressed. The oil mound in front of the water-wet filter is very compressed as the bottom probe that is close to the water-wet filter does not measure a capillary pressure value that is anywhere near the pressure differential over the plug.

At 75 hours the oil injection at the top was stopped and water was injected at the bottom. The figure shows that the pressure over the plug (Dp_plug) became slightly negative while the capillary pressures stayed positive. The slight negative pressure is likely to be due to the viscous pressure gradients over the plug. At flow reversal all three probe responses show a slight (unexpected) response, cross lamination in the plug and slight alignment mismatch of the probes along the plug, resulting in a viscous component measured on the capillary probes, might be the cause.

Considering the probe responses individually shows that the capillary pressure at the bottom probe decreases first which is the result of the injected water reaching this probe first. The other probes, which are further away from the injection face (Pc_mid and Pc_top), at first measure an increase in capillary pressure as they are still affected by the spreading oil mound which is pushed through the plug by the injected water. The reason that the mound is detected by the mid and the top probes at approximately the same time might be a result of capillary pressure heterogeneities along the plug. Nevertheless the mid-probe pressure approaches the bottom value faster than the top probe and that is consistent with the proposed model.

4.3.2. Carbonate Plug

In the previous experiment the pressure readings of the probes showed small values due to the high permeabilities and consequently low capillary pressures. The last example that will be presented is for a "low" permeability carbonate sample (1.6 mD) for which capillary pressure effects are more pronounced. The same "three probe" set-up as previously used was applied. The experiments start with a water-saturated plug. In this experiment only oil injection was performed, i.e. the experiment was stopped after the first drainage.

Due to oil injection the pressure over the plug (Dp_plug) builds quickly up to the capillary entry pressure 60 – 70 kPa (see Fig. 8). The probe reading closest to the inflow end follows this response very closely, while the other two probes are still in the completely water filled part of the plug and therefore show an erratic and undefined response. The oil pressure is here undefined due to the absence of oil. Only after 55 hours when the oil front has reached the mid-probe and capillary contact has been established with the oil in the probe and oil in the plug a meaningful signal is recorded. After 58 hours the front reaches the bottom-probe and only after this time is the reading of this probe meaningful. The small time difference of the response between the mid and the bottom probe (3 hours) compared to the relatively long time for the front to reach the mid-probe (55 hours) is unexpected and might indicate that the displacement front had developed a fast running tip during the displacement. Difficulty in establishing capillary contact of the oil in the mid and bottom probes with the oil in the plug might be another reason. If so, a tiny amount of oil injection through the oil probes into the plug at the start of the experiment might resolve this problem.

After 65 hours the bypass valves in the system were opened and spontaneous imbibition of water into the system occurred; the measured pressure differentials in the system became zero. Thereafter oil injection resumed and the pressures over the plug (Dp_plug) and the pressure at the top (Pc_top) and bottom probe (Pc_bottom) were restored to the previous values. The pressure at the mid-probe (Pc_mid) did not completely return to the pressure before the interruption., The reason for the slight difference is not understood. Increase of the flow rate with a factor 5 (between 80 and 100 hours) only shows a very small response in Dp_plug and none in the probe responses, indicating that viscous pressure drops are insignificant during this experiment. Note that the pressure data storage system failed between 90 to 110 hours but could be re-vitalised after that time.

After 120 hours into the experiment Pc_bottom clearly starts approaching Dp_plug indicating that an oil mound is building up in front of the exit water-wet filter. In addition Pc_top is not following anymore Dp_plug, another indication that the mound at the outflow is dominating the pressure differential over the plug. The experiment was stopped after 135 hours.

5. Conclusions

1. Capillary pressure probes work well and enable a direct measurement of capillary pressures.
2. The probes allows for the experimental unravelling of viscous and capillary pressure gradients and can therefore be used to circumvent disturbing influences by capillary end effects.
3. Application of the capillary pressure probes in steady state and unsteady state experiments enables an unambiguous and analytical interpretation of experimental results.
4. Oil- or water-wet filters in the main flow stream can cause accumulation of oil or water. This phenomenon needs attention during data interpretation.

References

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2. Kokkedee, J.A. and Boutkan, V.K.: “Towards measurement of capillary pressure and relative permeability at representative wettability”, Geological Society Special Publication No. 84, 43-50.
3. Longeron, D., Hammervold, L. and Skjaeveland, S. M.: “Water-Oil capillary pressure and wettability measurements using micropore membrane technique”, SCA-9426.
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Table 1 Fluid and core plug properties used in the experiments

	viscosity in cP @ 21 deg. C.	**density in g/ml @ 21 deg. C.**	**Length (cm)**	**Diameter (cm)**	**porosity (%Vb)**	**K_brine (mD)**
kerosene	0.88	0.781				
brine	1.02	1.015				
Berea			4.99	3.78	24.2	620
Bentheim			4.98	3.82	22.5	1560
Carbonate			5.06	3.78	23.4	1.6

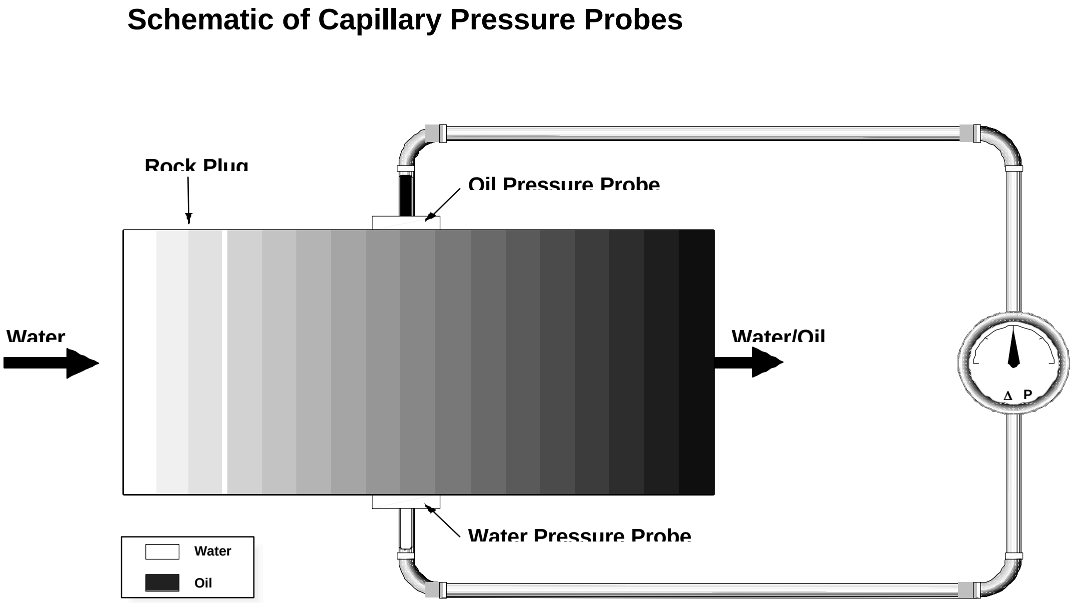


Figure 1: Schematic of the Pc probe measuring technique

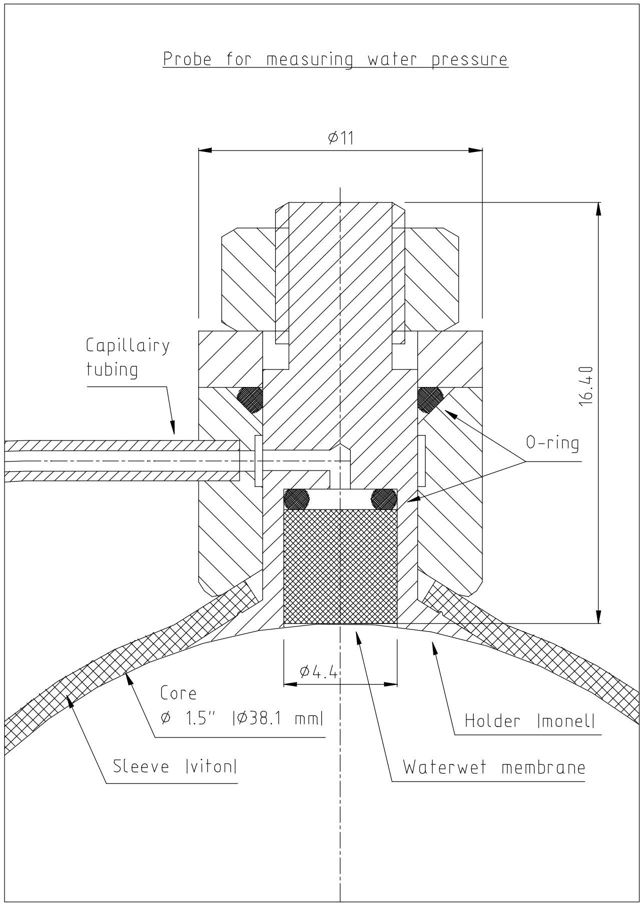


Figure 2: Cross-section of the water probe

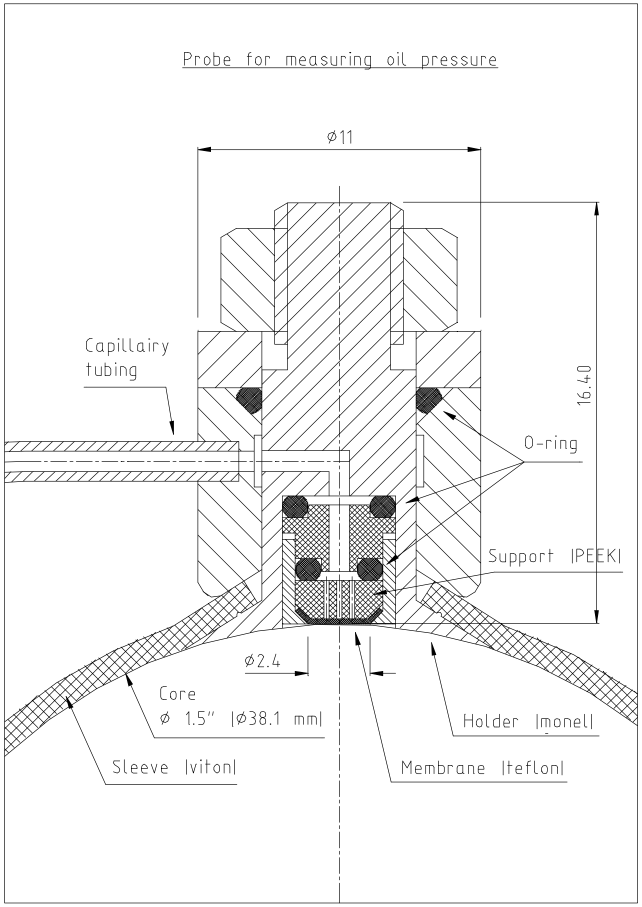
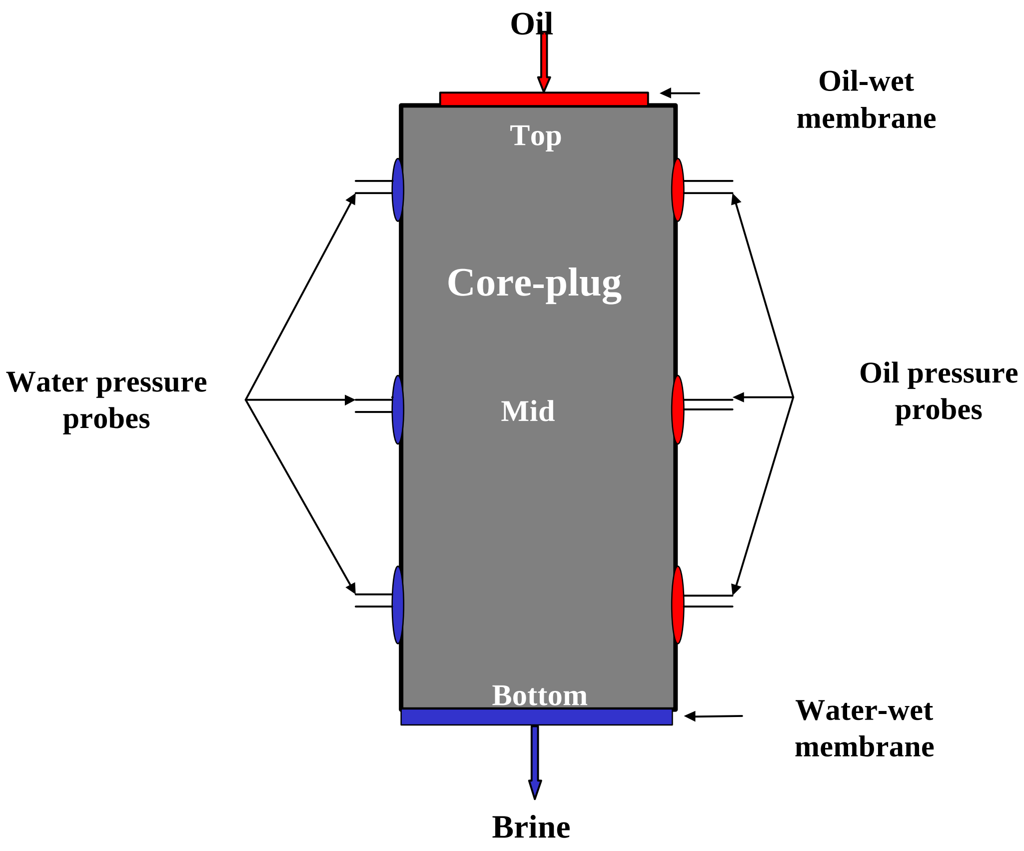


Figure 3: Cross-section of the oil probe.



Schematic drawing of 3 probes capillary pressure set-up

Figure 4: Schematic of the three probe test set-up. In this set-up filters are also mounted at the inflow and outflow ends of the plug.

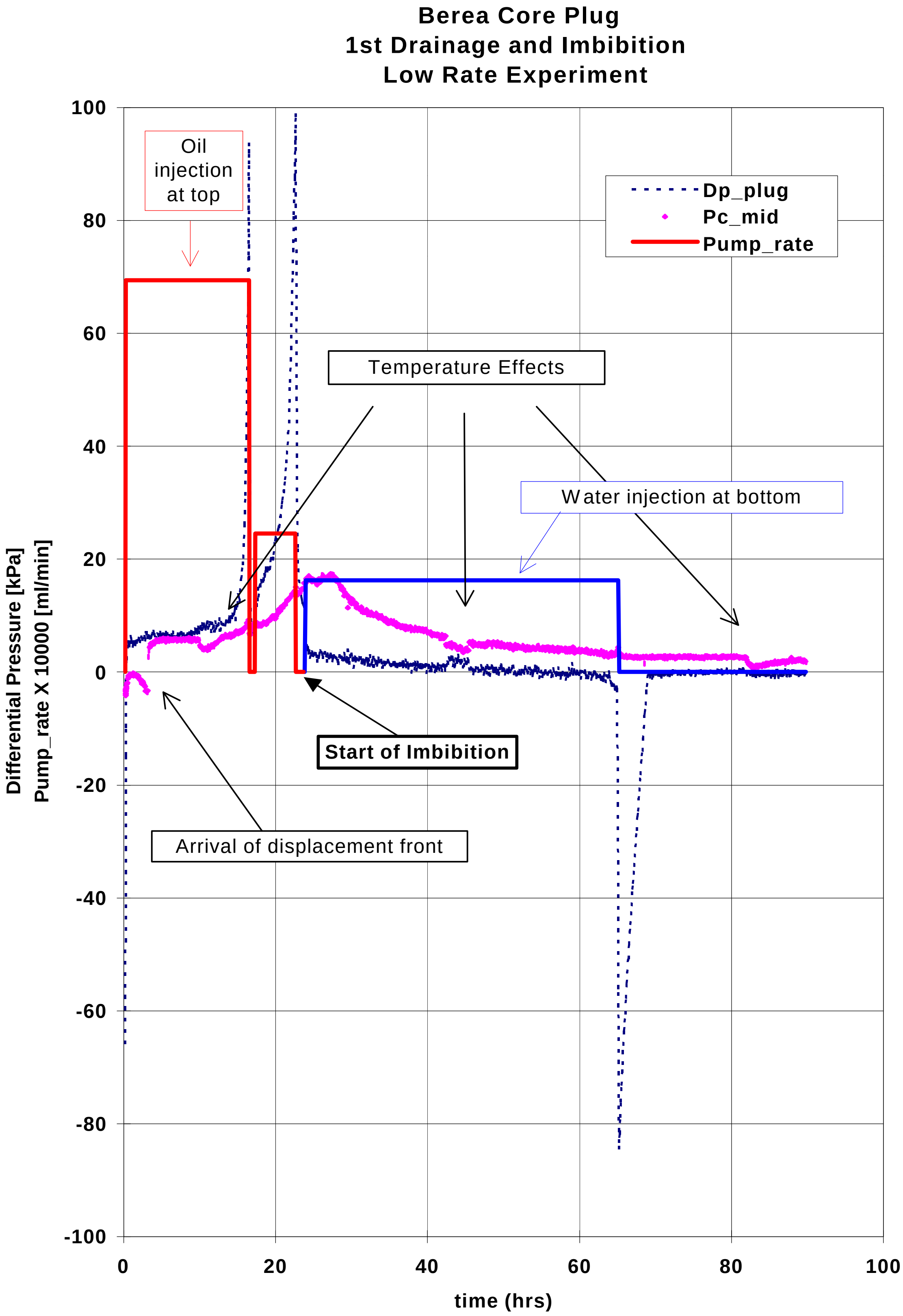


Figure 5: Pressure response during drainage and imbibition of the Berea plug – "Low" displacement velocity experiment.

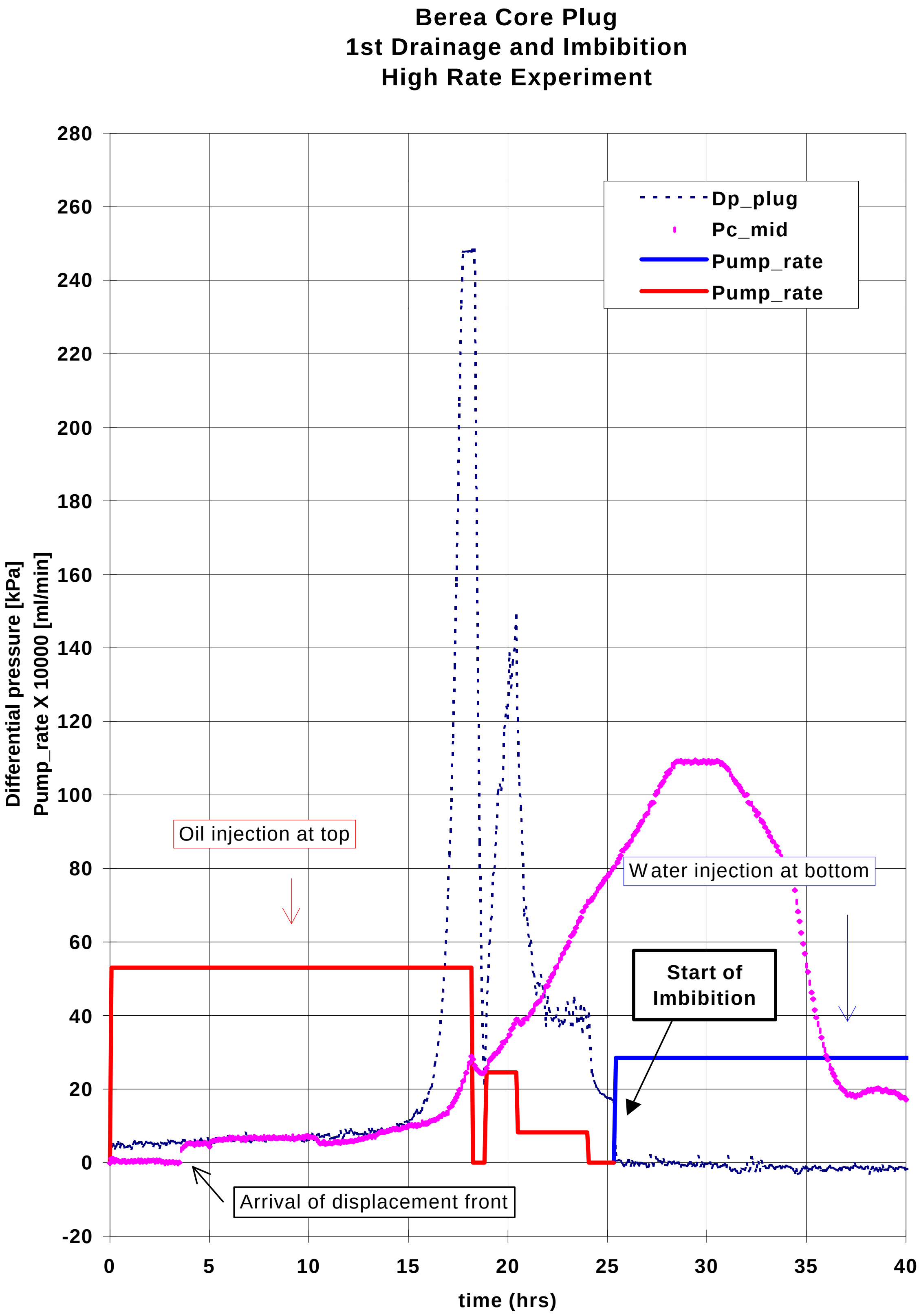


Figure 6: Pressure response during drainage and imbibition of the Berea plug – “High” displacement velocity experiment.

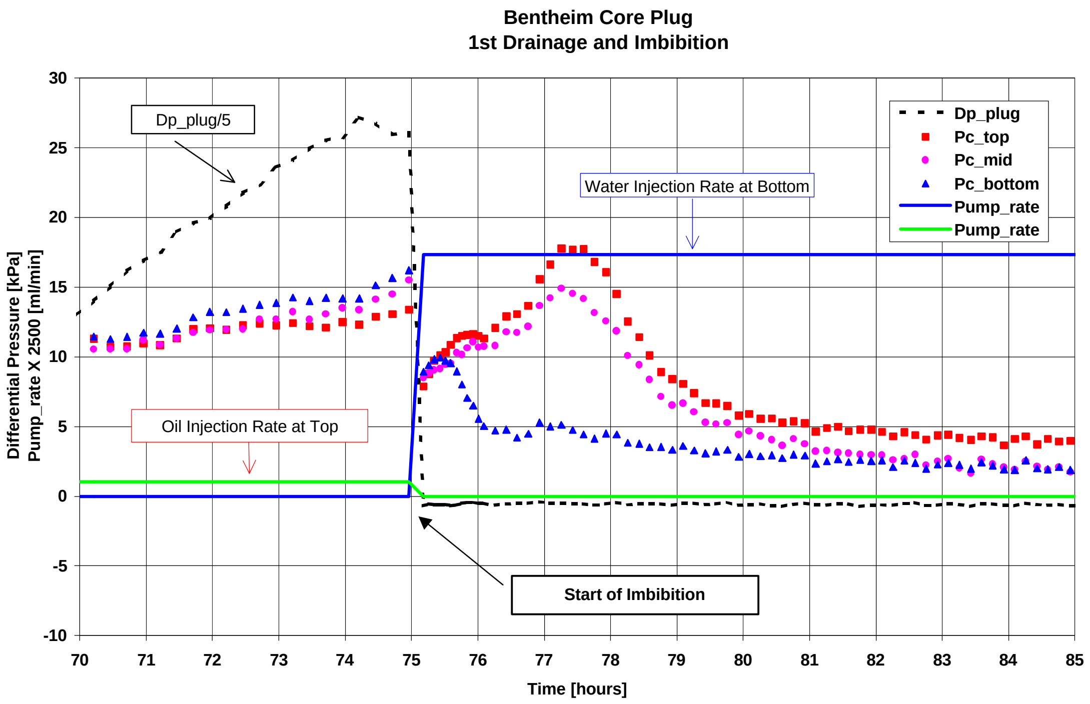
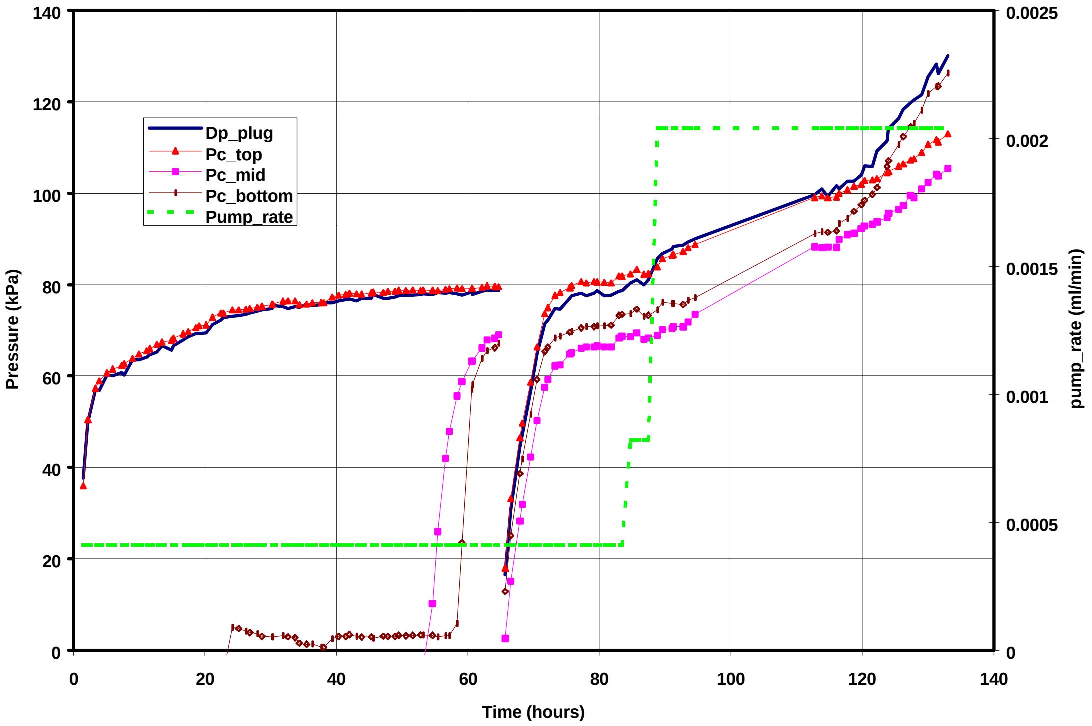


Figure 7: Three probe displacement experiment in a Bentheim core plug



.Figure 8: Three probe displacement experiment in a Carbonate core plug.