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Two Phase Streaming Potentials

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ABSTRACT

The streaming potentials generated by the flow of both liquid and gas through either a Pyrex capillary tube or else an unconsolidated Pyrex porous medium were investigated. This mixture of distilled water plus nitrogen gas simulated wet steam but allowed experiments to be run at room temperature.

Single-phase flow of distilled water alone resulted in a constant voltage-to-pressure drop ratio, $E/\Delta p$, of +0.15 v/psi for the capillary tube and -0.52 v/psi for the porous medium. For both single- and two-phase flow through the capillary tube, the upstream potential was always positive relative to the downstream electrode while the opposite was true for the porous medium. The maximum two-phase potentials generated in the porous medium were about four times as great as those generated in the capillary tube for similar gas fractions, Γ.

For the capillary tube experiments the potentials generated when $\Gamma < \approx 0.5$ were equal to or slightly less than those for single-phase flow, while for the porous medium the potentials were always greater than those for single-phase flow. When $\Gamma > \approx 0.5$ for both kinds of flow systems Γ had a profound effect on streaming potential and reached a pronounced maximum when $0.94 < \Gamma < 0.99$. The implications of these streaming potentials for geothermal exploration and delineation of geothermal reservoirs is also discussed in the paper.

INTRODUCTION

The streaming potenial (or electrokinetic potential as it is more commonly known these days) is a voltage difference generated when a fluid flows through an electrically non-conducting conduit such as a tube or a porous medium. It has been recognized and studied in the field of colloid science for almost a century and to a limited extent in petroleum engineering research because of the contribution it is believed to make to the SP log. It is of considerable interest elsewhere in the petroleum industry because of its being the source of ignition for many loading terminal and tanker explosions and fires (Klinkenberg and van der Minne (1958)) Attempts have also been made to use it to monitor the progress of steam and fire fronts in enhanced oil recovery projects (Dorfman et al. (1977) and in the prediction of earthquakes (Corwin and Morrison (1977)). The relationship between self-potenial anomalies and buried geothermal resources have been well documented in a number of papers by Ishido et al. (1983).

Many years ago we studied the streaming potentials generated by the flow of aqueous foams in Pyrex capillary tubes (Raza and Marsden (1967)) and of O/W emulsions in the same kinds of conduits (Dowdle and Marsden (1974)). More recently we have described the streaming potentials produced by the flow of wet steam in Pyrex capillary tubes (Tyran and Marsden (1985) and Marsden and Tyran (1986)). In this latter work we showed that while dry steam produced no measurable potential (as was expected), wet steam generated potentials up to and greater than 100v. These potentials increased with time and probably would have eventually reached greater values if the electrodes had not been intentionally shorted out in order to keep the recorder on scale. They also increased with pressure drop and flow rate but in an unknown and non-linear manner.

While the studies of Tyran and Marsden established that on a laboratory scale wet steam flow generated streaming potentials, the parameters describing the phenomenon were not well defined. It was expected that the volumetric vapor fraction of the steam, Γ, would be important but the difficulties of both maintaining it constant, measuring it accurately and operating at elevated temperatures had already become apparent. Hence, we decided to go to a simulated wet steam which consisted of a reasonably uniform dispersion of nitrogen gas, N_2, in distilled water and with all experiments being done at room temperature. With this arrangement, we were able both to control and to measure Γ to an accuracy of two decimal places. Pressure drop and hence flow rate were both variable and also reasonably well controlled.

In addition, a porous medium consisting of crushed, sieved Pyrex glass contained in a Pyrex tube could be easily substituted in the equipment in place of the capillary tube.

It should be noted that in all of this work we follow the convention that has become established for foam in the petroleum industry of using the volumetric fraction, Γ, and referring to it as steam quality rather than the terminology of using mass fraction of vapor which is widely used in industry.

Experimental

Both the flow conduit and pressure transducer as well as the electrical system were the same as those described earlier by Tyran and Marsden (1985) but the steam generator was replaced by a N_2 tank plus a distilled water reservoir to which N_2 pressure could be applied as a driving force. Also the previous steam flow rate measuring components were replaced with a graduated cylinder for the water followed by a soap-film flowmeter for the gas. A schematic diagram of the equipment is shown in Fig. 1.

Flow Conduits and Fluids

The ends of the capillary tube in the earlier runs or the glass tube containing crushed Pyrex in the later runs were sealed in especially made teflon manifolds, which also had pressure taps, and for the upstream end a N_2 inlet as

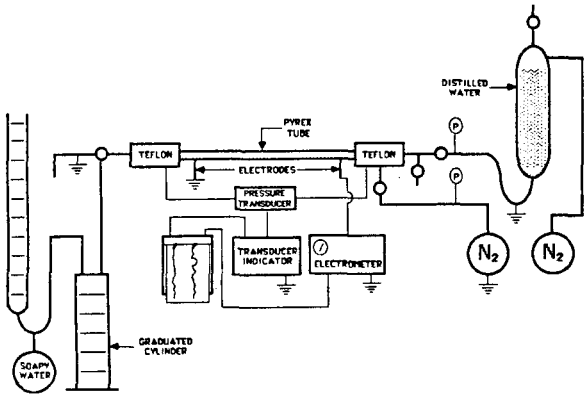

Figure 1: Schematic diagram of the streaming potential apparatus

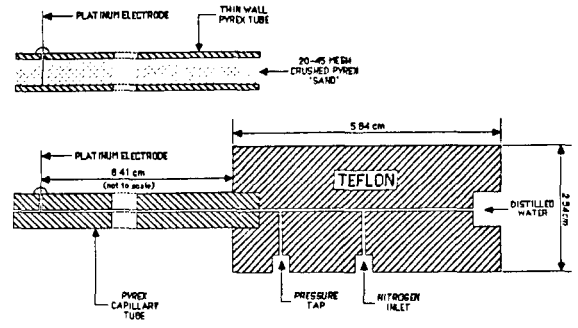

Figure 2: Teflon manifold and Pyrex tubes

well. The OD of both capillary tube and glass tube were almost the same so one manifold was used in both cases. A diagram is shown in Fig. 2. Holes for the Pt electrodes were drilled in both kinds of Pyrex tubing by using a fine diamond tipped jewelers drill. The Pt wires, which had been salvaged from a damaged ring of a duNuoy surface tensiometer, were carefully sealed in place with epoxy resin cement.

The water was distilled and run through the deionizing resins of a Corning Model LD-5A purifier before being stored in a large sealed Pyrex bottle for the short time before use. Its conductivity was measured with a calibrated dip cell and a L & N Model 4866 conductivity bridge.

The capillary tube had a length of 91.3 cm, an OD of 0.803 cm and an ID of 0.775 mm. These dimensions were determined with a meter stick and a micrometer and by weighing a measured column of mercury contained in the tube. The glass tube containing the crushed Pyrex had the same length, an OD of 0.808 cm and an ID of 0.597 cm, both measured with a micrometer. The porous medium was obtained by crushing and sieving another identical, thin-well Pyrex tube to produce a "sand" of 20-45 mesh. In both cases the Pt electrodes were 72.5 cm apart.

Electrical System

The streaming potential was measured with the same Keithley Model 610A high impedence electrometer used earlier by Raza and Marsden (1967) and by Tyran and Marsden (1985). The electrometer output was connected to the second channel of a two-channel Kipp and Zonen Model BD9 chart recorder. Both electrometer and recorder were calibrated with a H-P Model 6215A power supply and a Model 3465A multimeter. The upstream electrode was connected to the electrometer via a Keithley Model 6101A shielded test lead while the downstream electrode was grounded.

Pressure Measuring System

Pressure taps in the two teflon manifolds were 92.5 cm apart and were connected via 1/16 in. OD polyethylene tubing to a Celesco Model KP-15 differential pressure transducer. This was fitted with the 25 psi stainless steel diaphragm and connected to a Celesco Model CD 25A transducer indicator whose output was connected to channel one of the Kipp and Zonen chart recorder. The combination was calibrated with a 30 psi Heise bourdon tube pressure gage.

Flow Rate System

The N_2-water mixture exiting from the outlet manifold went via surgical tubing through a two-holed neoprene stopper into a 50 cc graduated cylinder. The N_2 coming out of the latter went to a 100 cc burette serving as a soap film flowmeter. The former, of course, measured the aqueous flow rate and the latter the total flow rate (water plus gas) so the ratio gave the complement of the gas volumetric fraction, Γ.

Cleansing of the System

The upstream end of the flow system up to the inlet manifold consisted of a 1-l.#316 stainless steel water reservoir and associated tubing which was cleansed by filing successively with 70 wt. % HNO_3, 37 wt. % HCl, acetone and soapy water, with distilled water flushes in between. The exterior surfaces of the glass components and the electrodes were also carefully rinsed with acetone, soapy water and distilled water and then carefully dried.

Making the Runs

Water deliberately left in the system at the end of the previous runs was flushed out and the reservoir refilled with newly distilled water whose resistivity and temperature was measured at first and again at the end of the run. With the flow conduit empty of liquids, the electrodes were shorted briefly and both chart zeros adjusted here and also when flow ceased during and at the end of the runs. After emptying the graduated cylinder and wetting the burette walls with soapy water, the flow was ready to begin.

After water flow was started, N_2 was admitted to produce a steady two-phase flow. A fine dispersion of bubbles in water rather than slug flow was determined visually. While the electrical potential and pressure drop were being recorded automatically, both liquid and total fluid rates were being measured by noting volumes and using stop watches. Only when all four quantities remained reasonably constant and when the pens returned to zero after flow stopped, were the results accepted as being valid.

RESULTS AND DISCUSSION

While the experiments of importance involved the flow of N_2 plus distilled water in either the capillary tube or else the porous medium, it was also essential to carry out preliminary experiments with water alone both to check the performances of the equipment and to see if the results are in agreement with what was expected. In all cases no attempt was made to control temperature and so the measurements were made at "room temperature" and downstream

pressure was atmospheric. Nominal variations of both were expected to have no significant effect on the results obtained.

Capillary Tube, Single Phase Flow

As was expected, a linear relationship between pressure drop, Δp, and flow rate, q, was found for a dozen or so measurements. All flow rates were calculated to fall well within the viscous flow regime. In all cases the upstream electrode was found to be positive with respect to the downstream one. A graph of pressure drop, Δp, vs streaming potential, E, is shown in Fig. 3 and while there is a linear relationship, it does not go through the origin as would be predicted by the Helmholtz-Smoluchowski Equation. Most other studies similar to this one have verified the linearity and have shown similar finite intercepts for liquids having little or no electrolyte dissolved in them. This is believed by Overbeek and others to be due to the contribution made by the surface conductivity of the glass when the liquid conductivity is extremely low as it is here. Everything considered, the results were believed to be acceptable and warranted our going on to the two-phase flow measurements.

Capillary Tube, Two-Phase Flow

By careful adjustment of the N_2 regulator, stable flow of both fluids was achievable over most of the Γ range. A two-phase, Reynolds number calculation using an apparent viscosity showed that all flow should have been well within the laminar regime. Again the upstream electrode was positive.

While the pressure remained steady over the course of a run, the fluctuations in the streaming potential increased as Γ did. It was observed that these fluctuations were associated with slugs of bubbles going through the tube and that this led to a momentary increase to a higher potential. This was probably due to increased electrical resistivity of the system as a result of the non-conducting gas bubbles and therefore a momentary decrease in the conduction current. The maximum electrical potential usually had about the same value and we designate it as as E_{max} while E is simply the time averaged potential. The difference between the two values of potential was generally less than 10% and graphs of both vs Γ were very similar in their various features. Throughout this report we shall simply deal with E.

A graph of E vs Γ is presented as Fig. 4. The octagon symbols used for the data points represent the calculated uncertainty in the points based on an error analysis. Although most points were taken at 10 psi, pressures ranged from 6 to 10 psi. The four data points for $0 < \Gamma \leq 0.05$ had the greatest scatter because they are for almost single-phase flow and here the flow is a strong function of pressure. For higher values of Γ up to about 0.4 the streaming potential is essentially constant. Here the N_2 flow rate was more easily controlled because there was more of it than at the lower values of Γ.

The first two-phase effects were noticed at $\Gamma \approx 0.5$, where the E rose slightly and then declined linearly (slope ≈-1) until $\Gamma \approx 0.75$. This may have been due to a decrease in flow rate at essentially constant pressure because of gradually increasing effective viscosity of the two-phase mixture. No data could be obtained for $0.79 <= \Gamma \leq 94$ because the flow was very unstable in this region.

The flow restabilized at $\Gamma \approx 0.94$ and E increased rapidly to a peak at $\Gamma \approx 0.98$. Here there is still enough water flowing to produce the convection current but the increasing concentration of N_2 increased electrical resistivity

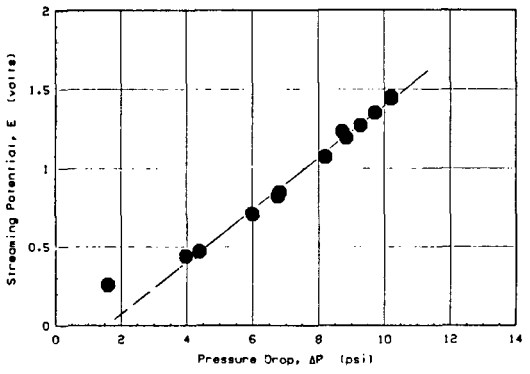

Figure 3: Streaming potential vs pressure drop

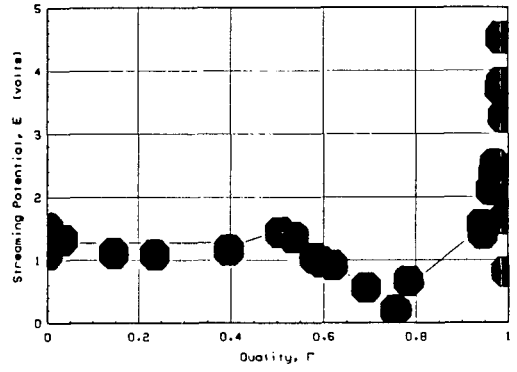

Figure 4: Streaming potential vs quality

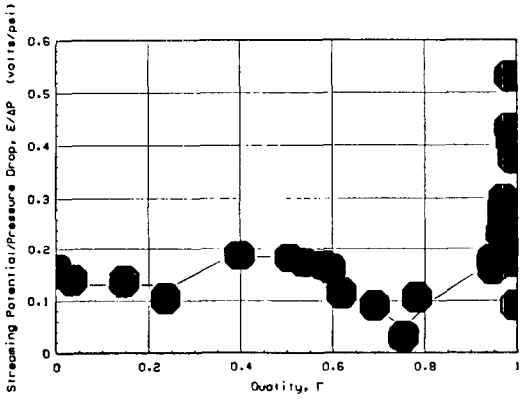

Figure 5: Streaming potential/pressure drop vs quality

and hence decreased the conduction current. Beyond this maximum, E decreased rapidly to almost zero at $\Gamma = 1.00$; this was probably due to a thin film of water left on the tube and being dragged along by the N_2 flow.

While the streaming potential is sensitive to changes in pressure for single-phase and low Γ two-phase flow, it is generally more sensitive to changes in Γ than in pressure for most two-phase flow. This is shown in Fig. 5 which is a plot of E/Δp vs Γ. The features of this plot are somewhat similar to those of the previous one and hence further discussion is not needed at this point.

Porous Medium, Single Phase Flow

Calculations showed that under all of the flow conditions for the ten measurements made with only water flowing, we were still in the viscous flow regime. Once the valve adjustments were made, both the potential and the pressure drop pens on the recorder remained both steady and constant. However, here it was found that the downstream electrode was always positive relative to the upstream one which was just the opposite of what we had found for the capillary tube runs. This is what we would expect for cations being transported downstream by the flowing liquid.

A graph of Δp vs flow rate (not shown) gave the expected straight line with a not unexpected intercept of about 1.0v. Because the flow resistance of the porous medium was significantly greater than that for the capillary tube, we could not use the same Δp's and flow rates for both flow conduits without changing some other parameter such as the cross-sectional area or length. Because it was experimentally simpler, we decided to keep the pressure drops similar. Therefore, the flow rates for this set of runs was about 20% of the capillary tube runs for similar pressure drops.

A graph of E vs Δp is shown in Fig. 6. Again we have a linear relationship but of negative slope and having a slightly positive E value of $\approx$ 0.5v at Δp=0. In comparing the slope of this to that of Fig. 3, we see that the streaming potential generated by the porous medium is about four times as great as that generated by the capillary tube. This may have been due to the surface area of the former being almost 100 times that of the latter.

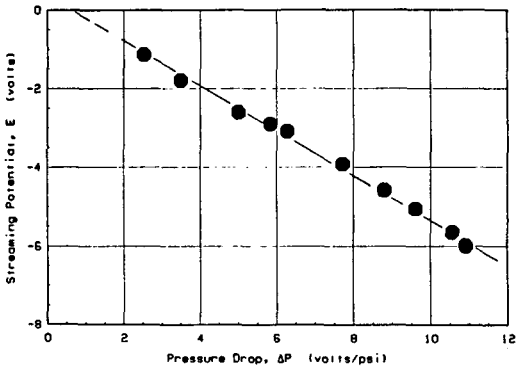

Figure 6: Streaming potential vs pressure drop

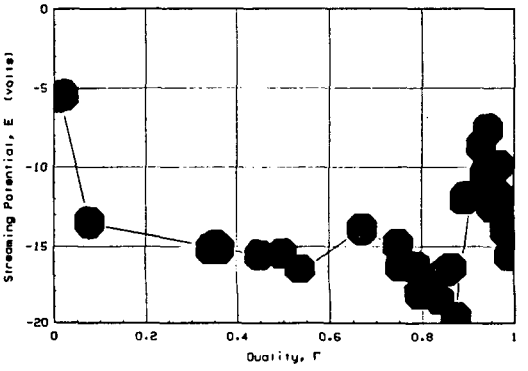

Figure 7: Streaming potential vs quality

Porous Medium, Two-Phase Flow

Two phase flow in the porous medium appeared to be quite homogeneous and without any gravity override. The upstream electrode was again negative and although the streaming potential did fluctuate somewhat, the spikes were toward lower potentials on the strip chart. This means that the spikes were toward the maximum, i.e. less negative, potentials as was qualitatively the same for the two-phase capillary flow.

In the graph of E vs Γ (Fig. 7) the size of the octagons again represents the maximum calculated uncertainty for each data point. It was almost impossible to obtain any data in the range of essentially $0<\Gamma<0.35$ because of the difficulties with controlling small N_2 flows, but the one point obtained indicates that E falls off quickly, i.e. becomes more negative, as gas enters the system. This differs considerably from the two-phase capillary tube case (Fig. 4) where E was almost constant for $\Gamma<=0.5$.

The right-hand half of Fig. 7, however, bears a remarkable resemblance to Fig. 4 (after a proper adjustment for the difference in sign) with a slight decrease in E for $\Gamma \approx 0.55$ to ≈ 0.65 followed by an increase (slope again $\approx$-1) ending at $\Gamma \approx 0.85$. Next there is a sudden decrease in Γ to about $\Gamma \approx 0.95$ and finally an increase in E as Γ goes to unity.

An important point to consider in analyzing this data is the probable relationship that exists between the measured Γ value and the actual gas saturation that exists within the capillary tube or porous medium. (In petroleum engineering terms the former would be fractional flow of gas and the latter would be the resident gas saturation.) We have defined Γ as being the flowing gas volume fraction and for the capillary tube, it would be essentially the same as the resident gas saturation with possibly a small and negligible correction for an immobile water film on the glass. It is well-known that (in the absence of foam) gas and liquid generally flow at different volumetric rates in porous media and at rates which differ from their resident saturations in the porous medium. Even when gas is still being injected and water is not, there is still a finite water saturation which in the case of an unconsolidated porous medium like ours might occupy about 5% of the pore space. This water is essentially immobile and is held at the grain contacts as pendular rings. This residual water plus the water films remaining on the pyrex grains serves as an electrically conducting film for the conduction current which counter-balances the convection current generating the streaming potential. It is remarkable that even after no more water is being injected and none being produced, there is still a relatively high streaming potential being generated. We did not run the porous medium experiments to the point where all of this residual water was vaporized by the flowing N_2 but this should be tried in the future.

The question remains as to why the polarity of the streaming potentials generated in the capillary tube was the opposite of that generated in the porous medium. Each had the same Pt electrodes in the same teflon holder and both were constructed of Pyrex glass. Although different types of Pyrex are available, their chemical compositions are nearly the same and so an error in selecting the materials for the two kinds of flow conduits is unlikely the source of the polarity differences. We understood that precision bore capillary tubing of the sort used here is annealed in manufacture while the crushed Pyrex for the porous medium may well have strains in it and certainly had a cleaved

rather than annealed surface, but again this would be expected to be insufficient.

Glass surfaces in contact with water lose cations to the diffuse layer near the solid surface, which then assumes a negative charge. When the water is forced to flow parallel to the surface, the cations are removed downstream and the static glass surface upstream then has a negative charge. Hence, we would expect the upstream electrode to be negative relative to the downstream, which is what we have found for the experimental results with the porous medium. Why the capillary tube results were different, we don't know for sure but it may have been due to adsorption of detergent or other ions used in the preliminary cleaning operation. More work is obviously needed to clarify this important matter.

The potential applications of these results are widespread as is the additional work needed. If there is indeed a difference in polarity for the two kinds of flow conduits, we may have a means of distinguishing between fracture and matrix flow in subsurface formations. The relationships between streaming potential and gas or vapor content of the flowing fluid mixture may give us information on the relative amounts of each fluid in the subsurface formations. Finally, as Ishido et al. (1987) have just reported at this Geothermal Workshop, the change of measured potentials during geothermal fluid production will add considerably to our knowledge of geothermal reservoir engineering.

Acknowledgements

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CONCLUSIONS

The following conclusions are based up on the results of experiments involving the flow of both distilled water and nitrogen gas through either a Pyrex capillary tube or a Pyrex unconsolidated porous medium. We believe, however, that they may be applied to other physical systems, in particular, to the rock-water system thought to be the main contributor to the self-potential anomalies measured near geothermal resources.

1. The flow of either distilled water alone or else distilled water and nitrogen mixtures through a Pyrex capillary caused the upstream electrode to be positive with respect to the downstream electrode. When these same fluids flowed through an unconsolidated, crushed-Pyrex porous medium, the upstream electrode was negative with respect to the downstream one. The reason for these differences is not clear.
2. For the two-phase flow of water plus N_2 through the capillary tube, the measured streaming potential, E, did not change with the flowing volume fraction of gas, Γ, until the latter reached about 0.5. In this range of compositions, E was principally dependent on pressure drop, Δp. Here the gas flow did not materially disturb the ionic distribution in the double layer and also did not significantly affect the total fluid resistivity unless there were counterbalancing effects.
3. For $\Gamma > 0.5$ there was first a slight increase of E with Γ, then a consistent decrease to a minimum at about $\Gamma \approx 0.75$, next a pronounced maximum at about $0.95 < \Gamma < 0.99$ and finally a decrease to zero at $\Gamma = 1.00$, i.e. with only gas flowing. The pronounced second maximum was probably due to the large concentration of non-conducting N_2 bubbles, which decreased the conduction current significantly while not affecting the convection current materially. The reasons for the slight increase in E with Γ followed by the decrease before the second maximum are not now known.
4. For two-phase flow through the porous medium, the E was also found to be Γ dependent, and in a very pronounced way the relationship between the two variables was similar to that for the capillary tube. Because E was of the opposite sign as for the results with the tube, the two curves were something like mirror image with the rotation being about the horizontal axis. The strong maximum in E at very high values of Γ was again quite apparent and it was probably due to the same reasons here.
5. There were two significant differences in the results for the porous medium and the capillary tube. The values of E for the former were about four times those for the latter for comparable values of Δp. This may have been related to the surface area of the porous medium being an estimated 100 times that of the capillary tube. Also E did not return to zero when the flowing Γ reached 1.00 which may have been related to the finite value of the irreducible water saturation, S_{wi}. While the flowing and resident values of Γ were the same for the capillary tube, they were not always the same for the porous medium.

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