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THE STREAMING POTENTIAL GENERATED BY FLOW OF WET STEAM IN CAPILLARY TUBES

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ABSTRACT

For a constant pressure differential, the flow of wet steam generated electric potentials which increased with time and did not reach equilibrium values. These potentials were found to increase to values greater than 100 volts. The reason for this kind of potential build-up behavior was the presence of tiny flowing water slugs which were interspersed with electrically nonconductive steam vapor slugs. The measured electric potential for wet steam increased with pressure differential, but the relationship was not linear. The increase in potential with pressure drop was attributed both to an increase in fluid flow rate and changes in the wet steam quality.

INTRODUCTION

Streaming potential is an electrokinetic potential generated by the flow of a fluid through a conduit such as a tube or porous medium. It results from the physical transfer of ions in the diffuse double layer of the fluid along and out of the conduit. This is counter-balanced by and eventually comes into equilibrium with charge transfer either through the conductive solid material forming the conduit or along its surface or else by ionic conduction in the fluid itself. With especially low electrical conductivity of all three paths, streaming potentials of more than 100 volts are easily generated in the laboratory and more than 10,000 volts in large pumping systems for petroleum products (Klinkenberg and van der Minne 1958). The latter can lead to electrical discharges and sparks which have undoubtedly been the cause of many explosions and fires in oil tankers, terminals and refineries.

The phenomenon of streaming potential was first described and explained almost a century ago by Quincke (1888) and has been studied over the decades by many physical and colloid scientists. An excellent monograph has been published by Klinkenberg and van der Minne (1958) and more recently another on the importance in the petroleum industry by Bustin and Dukek (1983). The streaming potential generated by flowing foam was studied by Raza and Marsden (1967) and an equation derived for describing the potential generated by the flow of such a non-Newtonian fluid. This was later extended to emulsions by Dowdle and Marsden (1974).

The paper is based on the experimental work of C. K. Tyran for his M.S. Degree Research Report submitted in June 1983 to the Petroleum Engineering Department at Stanford University. A portion of it was the basis of a paper presented at the Geothermal Resources Council Meeting in Hawaii in August 1985 and the remainder is presented here.

The SP (self potential) log is widely used in the petroleum industry. It is believed to be derived from the sum of two electrical potentials, the first being a static electrochemical or concentration potential and the second a streaming potential. While the former is more important under most circumstances, the latter can be significant under some.

A number of investigators, including Zohdy et al. (1973), Corwin (1976), Anderson and Johnson (1976) and Banwell (1970), have reported self-potential anomalies which are associated with geothermal activity. It is believed that the streaming potential due to the presence of circulating fluid in a geothermal reservoir contributes to the anomalous electrical potential fields which have been measured at the earth's surface. Whether this is a streaming potential or whether it is due to electrochemical potentials caused by fluid redistributions is not known.

Because we had considerable experience with and still had equipment left for measuring streaming potentials in glass capillary tubes, we felt it was desirable simply to see if these potentials are generated by steam flow, and if so, what were some of the parameters describing the system. The development of the equipment and description of the results are presented here briefly. More detail is given in a M.S. Degree Research Report by one of the authors (C.K.T.) (1983) and results with another worker will be described at a later date (Wheatall and Marsden 1986).

EXPERIMENTAL

Apparatus

The components of the equipment used fell into two general categories, namely, the fluid handling and flow system plus the electrical measurement instrumentation. These will be described in general terms only because exact specifications are unnecessary here and are given elsewhere by Tyran (1983).

A schematic diagram of the equipment is shown in Fig. 1. Steam was generated by heating distilled water in a 2 *l* metallic tank (pressure bomb) wrapped with electrical resistance heating tape and enclosed in thermal insulation. The water was flashed to steam through a needle control valve and then introduced into the pyrex tube. This part of the system also had calibrated, Bourdon pressure gauges (tank and at pyrex tube entrance and exit), thermocouples (at the pyrex tube entrance and exit), and several valves (tank filling, pressure relief, flow control, condensate collector). All lines were also heated electrically and enclosed in sponge-ceramic thermal insulation (Fiberfrax).

A pyrex tube 48.0 cm long and 0.0775 cm inside diameter was used. The latter was determined by weighing

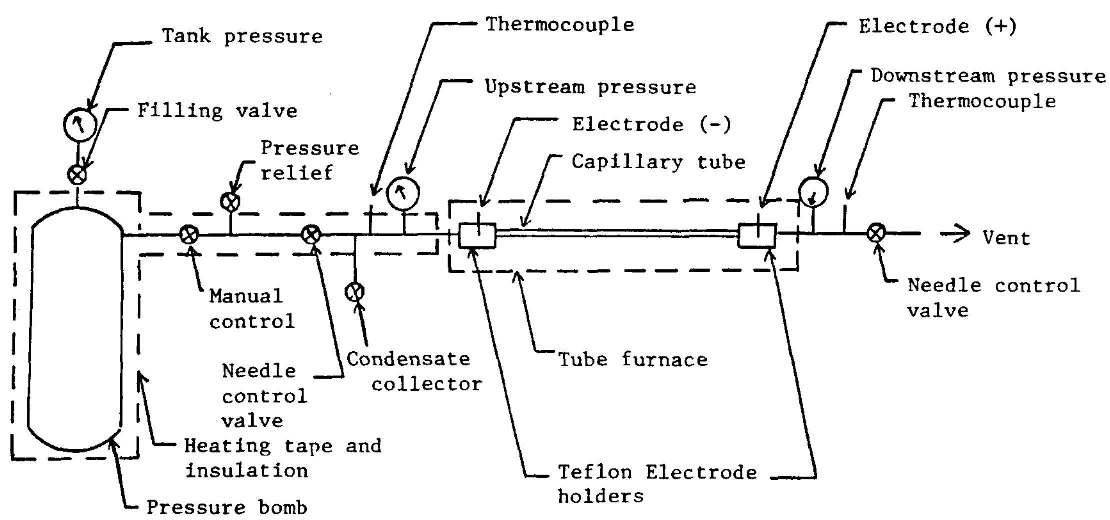

Fig. 1 - Schematic diagram of the streaming potential apparatus

it empty and then filled with H_g. This was enclosed at both ends in especially made teflon holders which also contained Pt-Ir wire electrodes. At the tube exit, pressure and temperature were again measured just upstream of another needle control valve. This part of the system was contained in a horizontal tube furnace.

The streaming potential was measured with the Keithley Model 610A Electrometer used previously by Raza and Marsden (1967). The output of this was also put into a voltage divider and a section of this was connected to a recording potentiometer. A 0.43 F capacitor was connected across the voltage divider to improve stability of the voltage tracing. It was determined that the tube furnace provided electrical shielding for the pyrex tube and its teflon holders, and a braided metallic shield was used for the usually positive (downstream) electrical lead. All measuring components were properly grounded, which is very important in this kind of work to avoid drift, and were carefully calibrated before the work and later rechecked.

Procedure

The cleaning procedure for the pyrex tube was similar to that used by Raza and Marsden (1967), i.e. nitric acid, distilled water and heating to about 150°C, and for the electrodes nitric acid and distilled water.

After measuring the electrical conductivity of the water used to fill the tank, the latter, the flow system and the tube were all heated until the bomb pressure was 30-35 psig (207-241 kPa). Before flow started the static electrical potential across the tube was checked. The tube furnace was shut off to eliminate the slight effect it had on potential measurements and then the control valves opened to start steam flow. After a period of adjustments to get flow stabilization, measurements were started. Condensate was removed intermittantly while attaining stabilization and frequently thereafter. Pressure drops and potentials generated were measured along with visual observations of water slugs and their effects on the potentials.

RESULTS AND DISCUSSION

To check the performance of the system, a temporary modification was made to allow nitrogen pressure to force distilled water to flow through it at room temperature. Using several samples of distilled water with slightly different resistivities in different runs, the ratio of measured streaming potential, ΔE, to pressure drop, ΔP, was constant, as it should have been. A graph of ΔE vs ΔP (Fig. 2) gave straight lines that extrapolated to a slightly positive ΔE value of about 0.5 volt, which was probably due to the not uncommon polarization effect reported by Korpi (1960). The calculated zeta potential values of 0.048 to 0.054 volts certainly agreed well with those in the literature of 0.046 to 0.054 volts for the glass-water interface (Glasstone 1946).

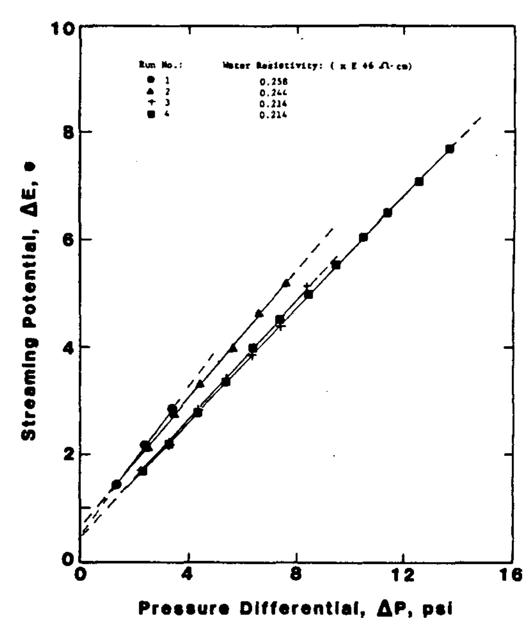

Fig. 2 - Streaming potential, ΔE, vs pressure differential, ΔP, for several samples of distilled water at 68°F.

Dry Steam

The first series of experiments after the blank runs with water was on dry (superheated) steam. The tube furnace was heated to well above 100°C and with downstream pressure maintained at atmospheric, the upstream temperature varied from 129°C for a ΔP of 15 psi (103 kPa) down to 116°C for a ΔP of 4 psi (28 kPa). Condensate was carefully and completely bled off before it reached the capillary tube and no condensed water came out of the fluid exit. The dry steam came out with a whistling sound rather than the soft gurgling sound observed later on for the wet steam.

No electrical potential due to the flow of dry steam through the capillary tube was observed. A small constant potential of 0.2 volts independent of temperature and ΔP was observed, but this was only the electrode polarization mentioned earlier. It also existed here at these temperatures when steam was not flowing.

It is evident that there is no transport of ions or other charged particles here leading to generation of a streaming potential. If there is adsorption of water vapor, which is likely to at least a modest extent, then this is an essentially immobile water layer under these experimental conditions.

In a separate experiment, dry nitrogen was flowed through the system and no streaming potential was also observed. Thus steam behaved like an inert gas here.

Wet Steam

To get wet steam flowing in the system, the tube furnace was heated to nearly 100°C and the steam source operated at conditions of temperature and pressure which would produce high quality steam. (Please note that the term quality here refers to the mass ratio of vapor to total fluid and not the volume ratio as is used for foam (Raza and Marsden, 1967)). Pressure drops along the capillary ranged from 5 to 25 psi (34 to 172 kPa), upstream temperatures from 119°C to 134°C and downstream temperatures slightly under 100°C. Even with these relatively large pressure and temperature drops along the capillary tube, stable flow of the wet steam was possible. Large slugs of water, which led to erratic electrical behavior, were avoided by draining the condensate trap frequently but small slugs, which had little effect on the potential readings, were impossible to eliminate entirely.

In contrast to dry steam, easily measurable streaming potentials were found for wet steam. These potentials, however, did not reach equilibrium values but instead increased with time. It was observed that in many cases the potentials were still increasing when they reached 100 volts, the maximum that could be measured with this electrometer and voltage divider combination. These large electrical potentials could be attributed to the very high electrical resistances that existed between the electrodes and decreased the flow of the reverse or conduction current. Not only was the resistivity of the condensed steam high but that of the vapor itself even higher.

In order to compare the potential data recorded for different pressure drops, a procedure was adopted which dissipated the charge accumulated at the electrodes by shorting them momentarily, and thus allowing the observed potential to return to essentially zero. This was done at an arbitrary but consistent time period of 50 s before being short-circuited again. During this time period, the potential built-up as is shown in Figs. 3 & 4 for a number of consecutive periods at the same temperature and pressure, before the latter was changed for another series of measurements.

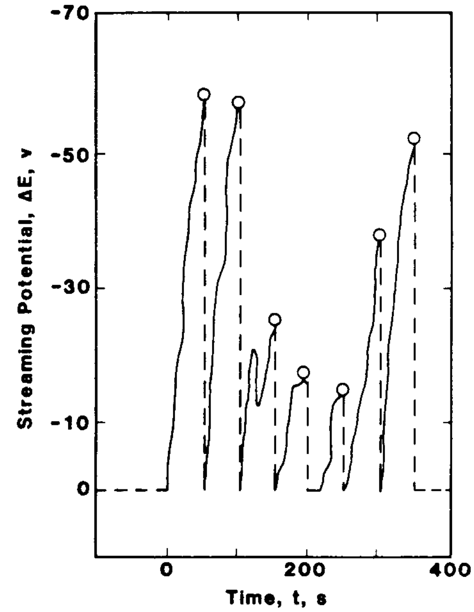

Fig. 3 - Streaming potential, ΔE, vs time, t, for a pressure differential of 10 psi. Upstream temperature 124°C and downstream temperature 97°C.

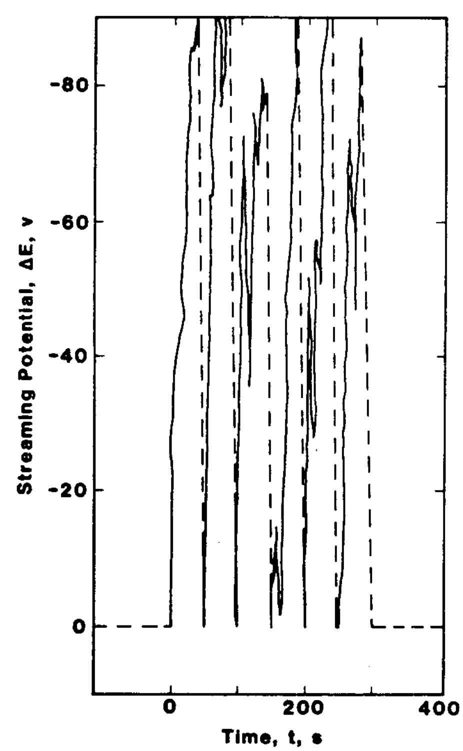

Fig. 4 - Streaming potential, ΔE, vs time, t, for a pressure differential of 20 psi. Upstream temperature 129°C and downstream temperature 96°C.

The chart readings of Streaming Potential vs Time for ΔP's of 10 psi (69 kPa) and less were fairly stable, but those for higher ΔP's were somewhat erratic. The latter often went off scale (90 volts for the recorder and 100 volts for the electrometer). While the trends of an increase ΔE with time were evident, the reproducibility from one 50 s interval to the next was poor, probably because of instabilities and variations in the two-phase flow in the capillary tube.

Data similar to that in Figs. 3 and 4 were collected for ΔP values starting at 5 psi (35 kPa), increasing in intervals of 5 psi (35 kPa) to 25 psi (173 kPa) and then decreasing stepwise again. The maximum ΔE's were then read from the chart for each of the 50 s periods and these averaged. These average ΔE values were then plotted vs ΔP in Fig. 5 with the points connected by curved lines with arrowheads merely to show the sequence.

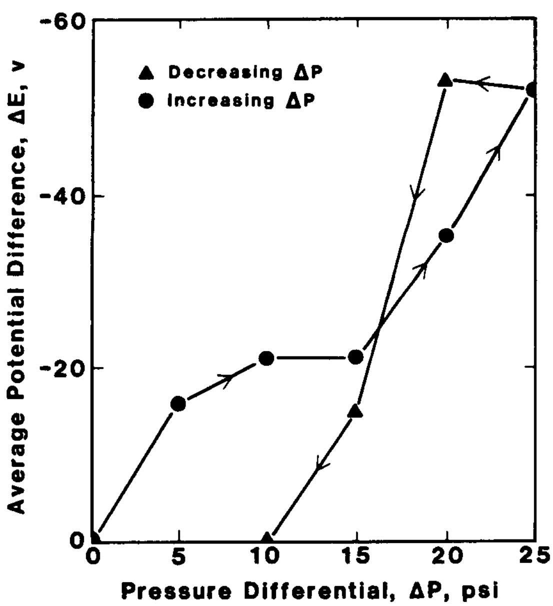

Fig. 5 - Average potential difference, ΔE vs pressure differential, ΔP, for wet steam.

It is certainly evident that the magnitude of the electrical potentials generated increased with pressure drop in a non-linear manner and then decreased again with hysteresis. We cannot say if this increase in charge transport was due to a greater fluid flow rate or to a change in steam quality or possibly both, but it is certainly evident. This question has been addressed in a subsequent study to be reported elsewhere (Wheatall and Marsden, 1986).

Application to Natural Geothermal Systems

We have shown here that streaming potentials can be generated in the laboratory by the flow of wet steam but not dry steam in a clean, single-channel conduit made of a good dielectric (pyrex glass). The phenomenon has been demonstrated but no attempt made to scale the results for application to any situation in nature. Although higher ΔP's and flow rates have been used than exist in nature and higher ΔE's observed, proper modelling and scaling may show that this is acceptable.

In the equipment used here, the electrical resistance for the conduction current is much lower than is likely in a subsurface formation. Alternate electrical paths containing immobile water such as those existing in porous media, as well as the possible presence of electrolytes in this water and conductive minerals such as clays in the pores all contribute to conductivity. Additional laboratory experiments simulating some of these conditions have been done and will be reported elsewhere (Wheatall and Marsden 1986).

CONCLUSIONS

The following conclusions apply to wet steam flowing through a pyrex capillary tube at somewhat elevated temperatures and pressures:

1. The flow of wet steam under a constant pressure differential generated a streaming potential which increased with time but did not reach equilibrium values. This potential was found to increase to values of at least 100 volts, the upper limit of measurement in our equipment. This behavior was probably due to the presence of small flowing water slugs interspersed and alternating with non-conductive steam slugs.
2. The measured electrical potential for wet steam increased with pressure differential but not linearly. This was probably due to an increase in fluid flow rate as well as changes in steam quality.

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