

Use of Direct Electrical Current for Increasing The Flow Rate of Reservoir Fluids During Petroleum Recovery

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ABSTRACT

Synthetic cores containing various percentages of different clay minerals were flooded with water which contained different types of salts in varied amounts, and the flow rate was measured during the application of direct electrical current at varying current density. Kerosene also was used as the flowing fluid, and some chemical additives, such as sodium acid pyrophosphate, were tested in conjunction with the application of electrical current.

The experimental results indicated that the increase in the flow rate of liquids was due not only to the electroosmotic effect but also to some changes in the pore structure. These changes in the pore configuration took place during the electrochemical treatment and generally resulted in higher final hydrodynamic permeability. As a result of the physicochemical changes in the clay properties, the tendency of the clay to swell and absorb water was markedly decreased. In these systems, the electrical or electrochemical treatment appeared to be an irreversible process. The extent to which these electrochemical changes were produced depended in general on the amount of current passed, the magnitude of potential gradient imposed, the amount and type of clay minerals present, and the type and concentration of electrolytic solution used.

INTRODUCTION

THE increasing importance of either primary or secondary recovery of oil from tight, clayey formations, and the difficulties encountered in such recovery due to clay swelling, suggested the possibility of utilizing direct electrical current to augment reservoir energy. The effective permeability to oil, especially around the borehole, greatly affects the productivity of an oil zone. A decrease in the relative oil permeability around the well can be caused by infiltration of the mud cake filtrate. This suggested the use of electrochemical

treatment as a method for well stimulation.

THEORETICAL ANALYSIS

The first electrokinetic experiment on record was performed by the Russian physicist Reuss (1807). His apparatus consisted of two pieces of glass tubing which were driven into a block of wet clay and then filled with water. Upon applying an electrical potential across the clay block, the water in the tube connected with the anode assumed a milky appearance due to the electrophoretic migration of colloidal clay particles. At the cathode, the water remained clear but increased in volume, thus exhibiting the phenomenon of electroosmosis.

Wiedemann (1852) produced the first accurate quantitative measurement of liquid conveyed through porous clay diaphragms by means of a current of known strength. He demonstrated that when an electrical field is applied to a liquid in capillaries, the flow is proportional to the electrical current. If, instead, this flow is prevented, the resulting electroosmotic pressure also will be proportional to the current. Wiedemann also found an inverse relation between the electroosmotic flow and the concentration of the electrolyte. At first he was of the opinion that electric endosmosis may be the direct action of mechanical forces produced by the current and acting on the liquid, resulting in the electroosmotic pres-

sure. This concept, however, became untenable when it was later found that the material of the wall and the cross-sectional area of the plug have a definite influence.

Quincke (1859) recognized electroosmosis and streaming potential as inverse phenomena. He explained them on the basis of an electrical double layer at the boundary surface between the liquid and the solid wall. If it is assumed that the positive charge of the double layer is present in the liquid phase and the negatively charged part of the double layer is fixed on the wall surface, then, upon application of an electrical potential, the positively charged mobile part of the double layer will move toward the cathode compartment and, because of viscous drag, draw the liquid with it. Conversely, if a liquid is forced through capillaries, a streaming potential or a streaming current is produced that is proportional to the applied pressure differential (Figure 1).

The migration potential, or the potential of falling particles, was observed by Dorn (1878). He obtained reproducible sedimentation potentials with sand in distilled water, which was placed in a long cylinder with electrodes fixed at the top and bottom.

Helmholtz Equation

Helmholtz (1879) put these laws and theories into a precise mathematical form for electroosmosis in a single capillary tube. In deriving

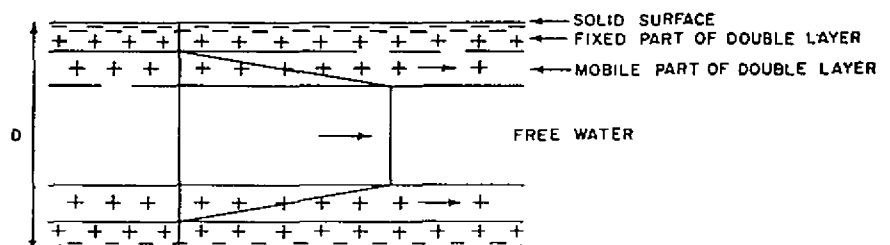


Figure 1.—A schematic diagram illustrating the mechanism of electroosmosis in a capillary tube as a result of the movement of the mobile part of the double layer toward the cathode.

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his equations, he assumed that: (1) the hydrodynamic equations for viscous flow are valid not only for the interior of the liquid but also for the entire region of the double layer; (2) the thickness of the double layer is extremely small as compared with the capillary diameter, but does not vanish; and (3) the external electrical potential gradient is simply superimposed on the potential gradient of the double layer.

If the electrical potential is designated as ϕ when the liquid is at rest, it is assumed to be constant in the interior of the liquid and is equal to ϕ_L . In the region of the double layer, ϕ_L undergoes a rapid change and drops from ϕ_L to ϕ_S (the potential on the surface of the solid), so that $\phi_L = \phi_S$. The imposed external potential along the tube (x -axis) is equal to iRx ; where i is the current density and R is the specific resistance of the liquid. If the total potential due to the addition of the imposed external potential is ψ , then

$$\psi = \phi - i R x \quad (1)$$

If the pressure gradient along the axis of the tube on each volume element is $\partial P/\partial x$ and the force, F , produced by the electric field is balanced by the frictional forces in the liquid, the hydrodynamic equations are represented by

$$F \frac{\partial P}{\partial x} = -\eta \left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (2)$$

where u is the volumetric velocity, η is the liquid viscosity coefficient, and $\partial u/\partial x = 0$.

$$F \frac{\partial P}{\partial x} = -\eta \nabla^2 u \quad (3)$$

where ∇^2 is Laplace's operator and

$$\text{is equal to } \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right).$$

But $F = \delta iR$ where δ is the volume charge density. Also, from

$$\text{Poisson's equation: } \nabla^2 \psi = -\frac{\delta}{D}$$

$$\text{and, from equation (1): } \nabla^2 \psi = \frac{4\pi\delta}{D}$$

$$\nabla^2 \phi = -\frac{4\pi\delta}{D}$$

By substitution for δ in $F = \delta iR$, therefore

$$F = -\frac{iDR}{4\pi} \nabla^2 \phi \quad (4)$$

where D is the dielectric constant (originally omitted by Helmholtz or probably assumed as unity).

By substitution for F in equation (3) one obtains:

$$\frac{\partial P}{\partial x} + \frac{iDR}{4\pi} \nabla^2 \phi = \eta \nabla^2 u \quad (5)$$

Inasmuch as, for pure electroosmotic effect, the pressure gradient along the tube equals zero,

$$\frac{iDR}{4\pi} \nabla^2 \phi = \eta \nabla^2 u \quad (6)$$

where u hereafter indicates electroosmotic velocity only.

By expressing ∇^2 in cylindrical coordinates (x, r, θ), and inasmuch as ϕ and u are independent of x and θ ,

$$\frac{iDR}{4\pi\eta} \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) \right) = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) \quad (7)$$

Upon integration, assuming no slippage ($u_0 = 0$), and because, at the wall ϕ_L decreases to ϕ_S ,

$$u = \frac{iDR}{4\pi\eta} (\phi_L - \phi_S) \quad (8)$$

$$= \frac{ED}{4\pi\eta L} (\phi_L - \phi_S)$$

where E is the electrical potential and is equal to iRL .

Helmholtz-Smoluchowski Equation

Smoluchowski (1903, p. 182) corrected Helmholtz's equation for the capillary tube and generalized it for a receptacle of random shape.

For a capillary tube with length L and cross-sectional area A , the electroosmotic flow rate is given by:

$$V = \frac{A \zeta DE}{4\pi\eta L} \quad (9)$$

where ζ is the electrokinetic or zeta-potential and is equal to $(\phi_L - \phi_S)$.

By the application of Ohm's law, A is eliminated. Inasmuch as for a capillary tube with unit length

$$A \cdot E = 1/\lambda,$$

$$V = \frac{D \zeta i}{4\pi \eta \lambda} \quad (10)$$

where λ is the specific conductivity of the liquid. This is valid only for the case without surface conductance. As a consequence of the accumulation of ions in the double layer, however, a greater conductance exists along the surface of the capillary. The influence of this surface conductance, as compared with the specific conductivity of the fluid, increases in dilute solutions, and the proportionality between i and λ is lost.

If surface conductance is present.

$$AE \lambda + SE \lambda_s = i$$

where S is the circumference of the capillary and λ_s is the specific surface conductance; then

$$V = \frac{D \zeta i}{4\pi\eta \left(\lambda + \frac{S \lambda_s}{A} \right)}$$

$$= \frac{D \zeta i}{4\pi\eta \left(\lambda + \frac{2 \lambda_s}{r} \right)} \quad (11)$$

Smoluchowski (*in* Kruyt, p. 202) also established the validity of the electroosmotic flow rate equation for a porous plug by assuming that the diameter of the pore is much larger than the thickness of the double layer. The flow of electricity and of the liquid at the boundary are assumed to be parallel to the wall. The liquid is incompressible and the electric field also acts as an incompressible liquid. He finally supposed that the electroosmotic equation holds not only at the boundary layer, but also throughout the whole liquid phase.

The total electrical current, i , is given by

$$i = \int E \lambda d\omega$$

and the total amount of liquid passing per unit time is

$$V = \int u d\omega$$

where $d\omega$ is an infinitesimal part of an arbitrary cross-sectional area; therefore,

$$V = \int \frac{D\xi E}{4\pi\eta} d\omega = \frac{E\xi}{4\pi\eta} \int E d\omega \quad (12)$$

$$= A \frac{D\xi}{4\pi\eta} \cdot \frac{i}{\lambda}$$

Overbeek and Wijga (1946) showed that the generalization of the electroosmotic equation for a porous plug as made by Smoluchowski, does not hold where the plug has considerable surface conductance. They concluded that it is impossible to use a correction factor for it, as in the case of a single capillary tube.

Neal and Peters (1946) indicated the possibility of correcting for the surface conductance by using the following equation:

$$V = \frac{D\xi i}{4\eta\pi\lambda'} \quad (13)$$

where λ' is the specific conductivity for the electrolyte while it is contained in the porous plug, and thus includes the bulk conductivity, λ , and the surface conductivity, λ_s . The corrected specific conductivity may be determined experimentally from the measured resistance, R , across the plug, and its cell constant, C , or

$\lambda' = C/R$; and therefore

$$V = \frac{D\xi E}{4\lambda\eta C} \quad (14)$$

According to Manegold and Solf (1931):

$$C = \frac{L}{A(1-f)\sigma}$$

where $(1-f)$ is the volume fraction available for ionic migration, σ is an experimentally evaluated orientation factor, and A and L are the cross-sectional area and the length of the plug, respectively; therefore

$$V = \frac{AD\xi(1-f)\sigma}{4\pi\eta} \cdot \frac{E}{L} \quad (15)$$

A more convenient form of the equation will result by using the formation factor, F , which is the ratio of the conductivity of the electrolytic solution to the conductivity of the porous plug saturated with the electrolytic solution, or,

$$F = \frac{AC}{L} = \frac{1}{(1-f)\sigma}, \text{ and therefore}$$

$$V = \frac{AD\xi E}{4\pi\eta FL} \quad (16)$$

For practical purposes in engineering calculations of the electroosmotic drainage of soil, Casagrande (1947) assumed that the electroosmotic coefficient would stay fairly constant for a given soil. It was termed the electroosmotic permeability coefficient k , and is given in cm/sec per v/cm.

$$V = \frac{AD\xi}{4\pi\eta F} \cdot \frac{E}{L} = A k_e \cdot \frac{E}{L} \quad (17)$$

Casagrande (1949) has carried out laboratory investigations on the electroosmotic transport of liquid for a variety of materials, using different types of electrodes and flooding arrangements. He concluded that, from the practical point of view, k_e could be considered constant, and is equal to 5×10^{-5} cm/sec per v/cm for all soil samples. Although this assumption has no basis, it is invariably used in the literature of soil mechanics and civil engineering. Casagrande, however, has reported discrepancies in cases where the soil contained appreciable amounts of colloidal matter. His studies indicated the formation of tiny fissures in the clay mass which facilitate the flow of water as a result of applying the electrical potential gradient across the clay sample. He noted also that the formation of these fissures is greatly promoted by a higher potential gradient.

APPARATUS AND EXPERIMENTAL PROCEDURES

A schematic diagram and a photograph showing the electroosmotic cell, with the connections used by the writers, are presented in Figures 2 and 3, respectively. Two steel cylinders, with capacities of 30 and 15 litres, were used as reservoirs for the electrolytic solution and kerosene, respectively. The liquid was displaced by air (at approximately 100 psi), connected through a pressure regulator to the top of the cylinders. The dis-

placed liquid was then passed through a fine porous alundum disc (Braun, No. 282-76), and was transmitted to the inlet of the core. A pressure gauge (with range of 0-60 psi) was connected to the flow line after the micro-filter in order to record the pressure at the core inlet.

The direct current was supplied by a regulated electronic power supply (tension capacity 0-500 volts at 0-300 milliamperes) and was transmitted to the core through platinum electrodes placed in separate electrode chambers. These chambers consisted of 2-inch Lucite cylinders having permanently sealed Lucite bottoms and removable Lucite lids. They were machined and permanently sealed to the current transport tube by means of Lucite glue. This glue was prepared by dissolving Lucite scraps in dichloromethylene. A continuous washing system was used to wash out the acidic solution formed in the anode compartment and the basic solution formed at the cathode compartment, thus keeping the solutions in both compartments neutral. The concentration of the washing solution was roughly equal to that of the flowing fluid. The current was transferred to the core through high-pressure agar-plugs acting as salt bridges between the current electrode compartments and the main body of the core. The agar-plugs were made by plugging an alundum disc (Braun, 282-76) with agar. The agar solution was prepared by dissolving agar powder in sodium chloride solution and then heating in a water bath. The small pores of the alundum disc were first filled by filtering the dilute agar solution through the disc with the help of a vacuum pump. Then, a generous amount of agar was left to coagulate on each side of the disc by cooling and water evaporation. The potential drop was measured by means of a vacuum tube volt-

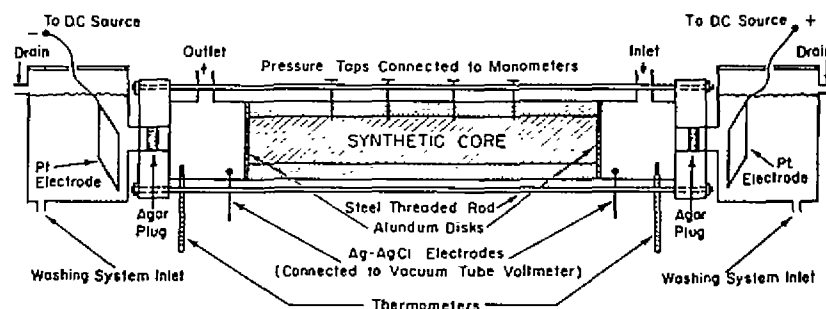


Figure 2.—A schematic diagram showing the improved electroosmotic cell, with connections.

meter through special measuring Ag-AgCl electrodes, placed at the surface of the core. This precaution was taken in order to prevent electrolytic reactions and gas evolution. The void space between the agar-plug and the core surface was

designed to allow the current flow lines to fall uniformly on the core surface. Neoprene rubber "O" rings were used to join the various parts of the electroosmotic cell and insure perfect contact. The electrode chambers, the agar-plug and

the mounted core were tightly connected to each other by means of three or four threaded steel rods. The four pressure taps (Figure 3) were connected to mercury manometers for measuring the pressure gradient along the core. This was done in order to correct for the end effect and to test the influence of electroosmosis on pore pressure. The temperature measurements (not considered in the beginning of this experiment) were made by means of two thermometers mounted at the inlet and outlet of the core.

Synthetic Core Preparation

Various percentages of different types of clay were thoroughly admixed with 200-mesh-size silica or CaCO₃ powder. The mixture was packed in a 1-inch-internal-diameter polyethylene sleeve having a one-inch aluminum disc (Braun, No. 282-75) and a rubber stopper at each end (Figure 4). The packed mixture column (or "sausage") was next placed in a 1 3/4-inch copper container. This copper container was made from 30-gauge copper sheets in order to be flexible enough to transmit pressure. The inside of the copper container and the two rubber stoppers were greased so that they could be removed easily after the resin mould was set around the sand pack. The packed mixture column was centralized in the copper container by means of screws attached to the rubber stoppers at the top and bottom of the core. Epoxy resin was prepared from 100 parts of Hysol-base 2020, plus 5 parts of the fast Hysol-hardener C-2, plus 5 parts of

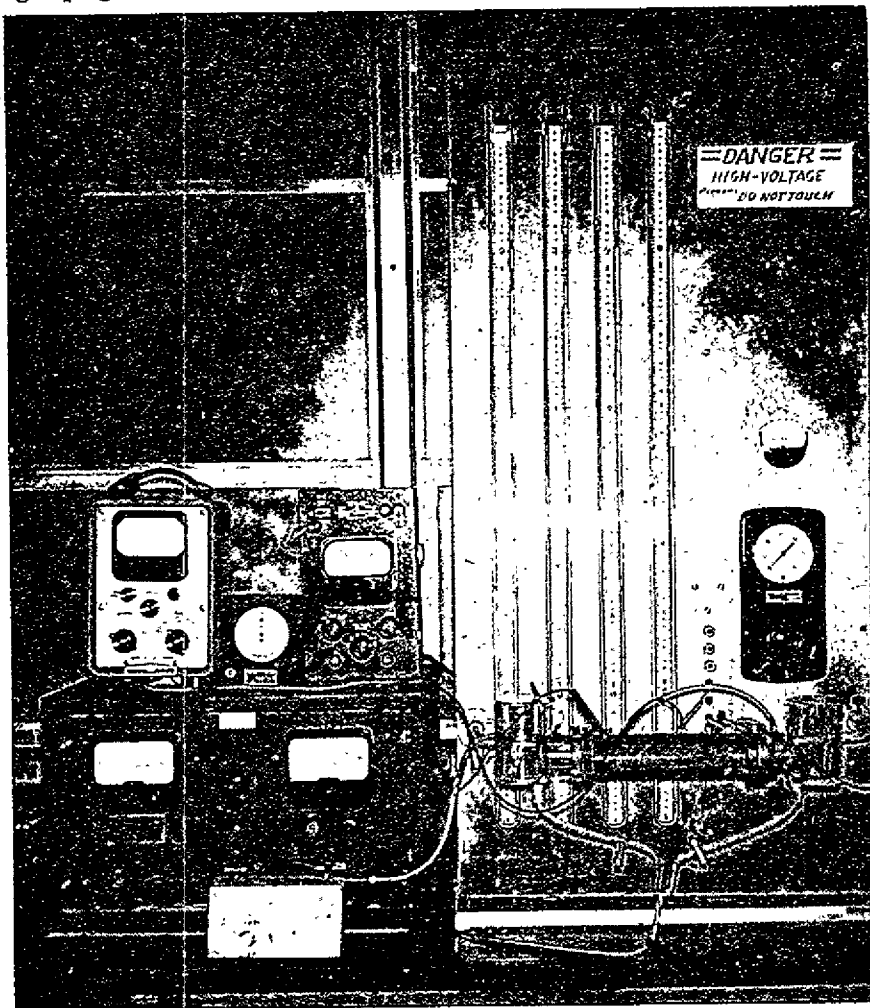


Figure 3.—A photograph of the improved apparatus showing the electronic power supply, the vacuum tube voltmeter and the assembled electroosmotic cell, with connections.

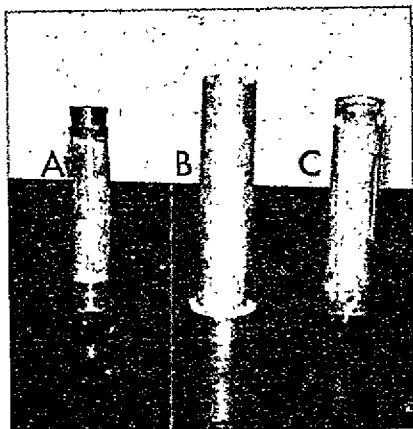


Figure 4.—A photograph of a synthetic core during various steps of preparation: (a) Polyethylene sleeve packed with silica-clay mixture. (b) Copper container. (c) Mounted synthetic core with completed threaded holes.

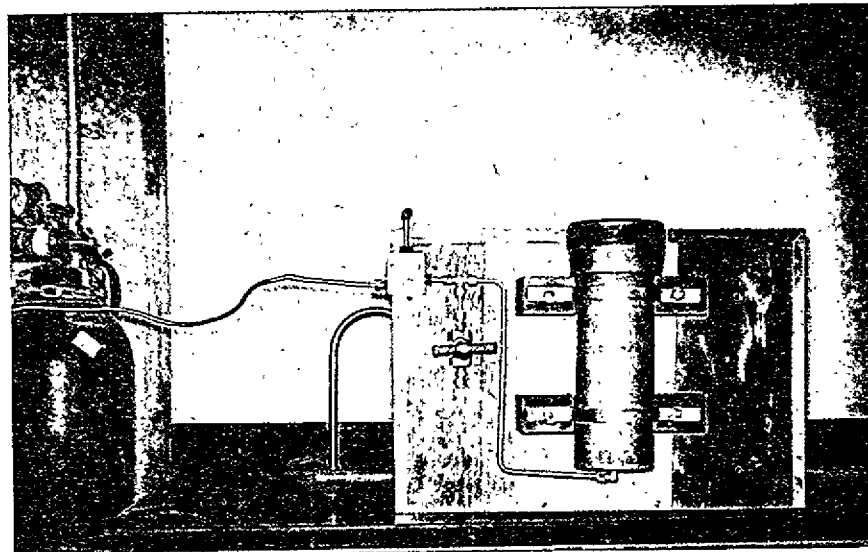


Figure 5.—A photograph of the pressure bomb, with connections.

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the slow Hysol-hardener B. The epoxy resin was then poured into the annular space of the copper container around the polyethylene sausage. The copper container was next placed in a pressure bomb (Figure 5), and the resin was allowed to set overnight under a pressure ranging from 750 to 1,250 psi, according to compaction requirements. The core was transferred to a vacuum oven in order to heat-cure the resin. This required about two hours and a temperature

of 140-160°F. The copper container was then peeled off and the rubber stoppers at each end were removed. After cleaning the mounted core, the required holes were drilled and threaded (Figure 4). The air permeability and porosity were obtained before the core was flooded with the specific electrolyte solution.

Flooding Test Procedure

The required electrolyte solution for flooding was prepared from dis-

tilled water and the specified amount of salt. Fifty to one hundred parts per million of formaldehyde was added to the solution in order to prevent or decrease bacterial growth.

EXPERIMENTAL RESULTS

The results obtained by the writers are presented in Table I and are plotted in Figures 6-12. The major variables involved were (1) electrical potential gradient, (2)

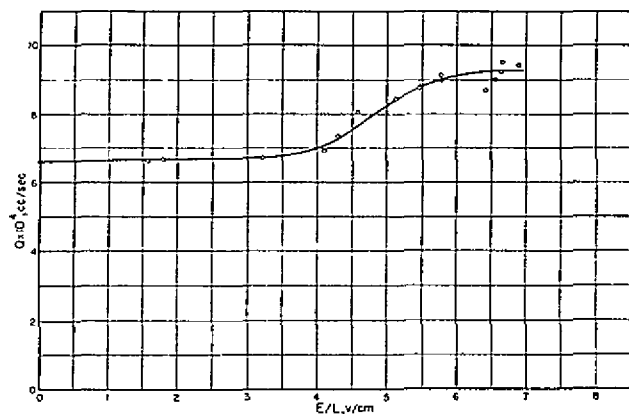


Figure 6.—Electrical potential gradient versus total flow rate. (Syn. core no. 1: 99% silica flour + 1% Wyo-gel; flowing 0.1% wt. NaCl soln.)

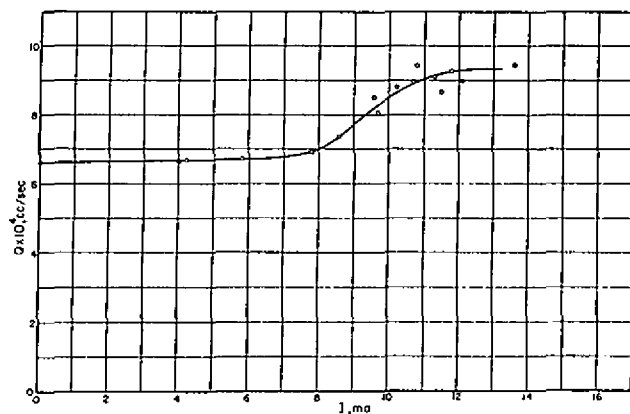


Figure 7.—Electrical current versus total flow rate. (Syn. core no. 1: 99% silica flour + 1% Wyo-gel; flowing 0.1% wt. NaCl soln.)

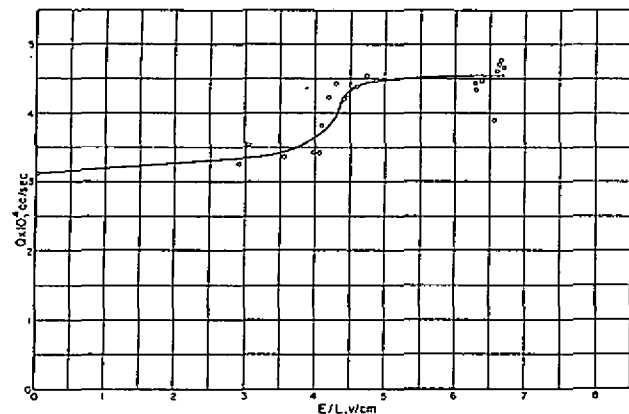


Figure 8.—Electrical potential gradient versus total flow rate. (Syn. core no. 2: 95% silica flour + 5% Wyo-gel; flowing 0.1% wt. NaCl soln.)

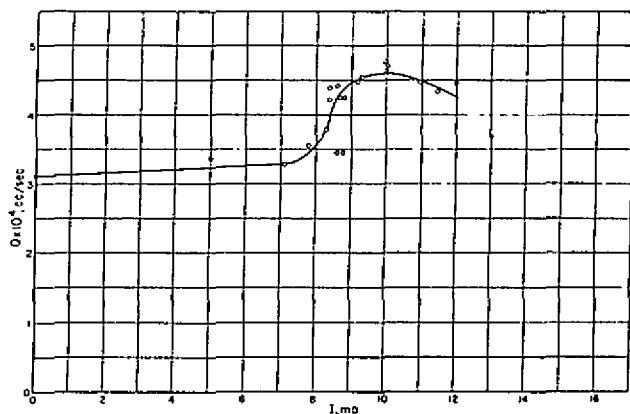


Figure 9.—Electrical current versus total flow rate. (Syn. core no. 2: 95% silica flour + 5% Wyo-gel; flowing 0.1% wt. NaCl soln.)

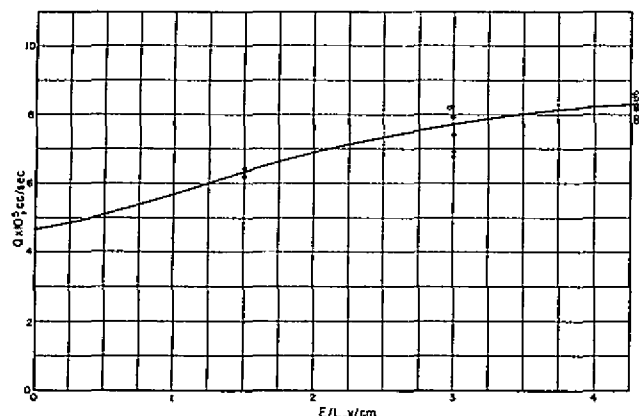


Figure 10.—Electrical potential gradient versus total flow rate. (Syn. core no. 3: 90% silica flour + 10% Wyo-gel; flowing 0.1% wt. NaCl soln.)

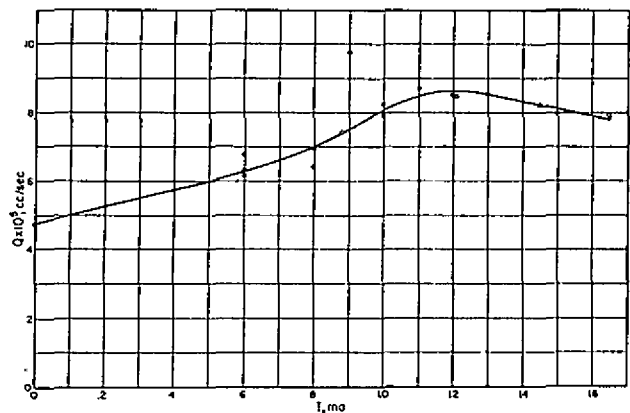


Figure 11.—Electrical current versus total flow rate. (Syn. core no. 3: 90% silica flour + 10% Wyo-gel; flowing 0.1% wt. NaCl soln.)

TABLE I.
EFFECT OF CLAY CONTENT ON THE TOTAL FLOW RATE
(flowing 0.1% wt. NaCl soln. at $\Delta P = 5$ psi, cores compacted under
1,250 psia)

A. *Synthetic Core 1: (1% Wyo-gel + 99% silica flour 200 mesh)*
L = 15.5 cm, A = 5.05 cm², $\phi = 33.6\%$, $K_a = 17.9$ md, $K_w = 5.98$ md

Flow Rate, $Q \times 10^4$, cc/sec	Potential Gradient, v/cm	Electrical Current, ma	Normalized Flow Rate, Q/Q_1	Per cent Increase, $100(Q-Q_1)/Q_1$
6.64	0.00	0.0	1.000	0.0
6.68	1.61	4.0	1.006	0.6
6.69	1.80	4.2	1.010	1.0
6.75	3.23	5.8	1.018	1.8
6.92	4.13	7.8	1.042	4.2
7.40	4.32	8.6	1.115	11.5
8.08	4.66	9.7	1.216	21.6
8.42	5.16	9.6	1.270	27.0
8.79	5.47	10.2	1.323	32.3
8.98	5.80	10.7	1.349	34.9
9.13	5.80	11.3	1.375	37.5
9.47	6.71	13.6	1.425	42.5
8.70	6.40	11.5	1.310	31.0
8.99	6.64	12.1	1.350	35.0
9.28	6.71	11.8	1.400	40.0
9.46	6.91	10.8	1.424	42.4

B. *Synthetic Core 2: (5% Wyo-gel + 95% silica flour 200 mesh)*
L = 15.8 cm, A = 5.07 cm², $\phi = 34\%$, $K_a = 16.6$ md, $K_w = 2.53$ md

3.13	0.00	0.0	1.00	0
3.38	3.55	5.0	1.08	8
3.55	3.03	7.8	1.13	13
3.27	2.91	7.1	1.05	5
3.45	4.03	8.6	1.10	10
3.79	4.11	8.3	1.24	24
4.23	4.18	8.4	1.35	35
4.26	4.44	8.8	1.36	36
4.41	4.62	8.6	1.41	41
4.48	4.30	8.4	1.43	43
4.56	4.74	9.3	1.46	46
4.48	4.81	9.2	1.43	43
4.45	6.33	12.0	1.42	42
3.69	6.58	13.0	1.19	19
4.35	6.33	11.5	1.39	39
4.48	6.39	11.0	1.43	43
4.64	6.58	10.0	1.48	48
4.67	6.71	10.0	1.49	49
4.76	6.65	10.0	1.52	52
4.72	6.65	10.0	1.51	51

C. *Synthetic Core 3: (10% Wyo-gel + 90% silica flour 200 mesh)*
L = 16.2 cm, A = 4.02 cm², $\phi = 33.2\%$, $K_a = 16.8$ md, $K_w = 1$ md

0.47	0.0	0.0	1.00	—
0.98	1.5	0.9	2.05	105
0.62	1.5	0.6	1.29	29
0.64	1.5	0.6	1.34	34
0.63	1.5	0.6	1.32	32
0.82	3.0	1.0	1.72	72
0.80	3.0	1.0	1.66	66
0.74	3.0	0.9	1.56	56
0.70	3.0	0.8	1.45	45
0.68	3.0	0.6	1.43	43
0.82	4.5	1.1	1.72	72
0.85	4.5	1.2	1.79	79
0.87	4.5	1.1	1.82	82
0.79	4.5	1.5	1.65	65
0.80	4.5	1.5	1.67	67
0.85	4.5	1.3	1.79	79
0.82	4.5	1.5	1.72	72
0.85	4.5	1.2	1.78	78

electrical current, (3) electrolytic concentration, (4) applied pressure differential, and (5) total flow rate. During experimentation, some of these variables were held constant, while others were varied and the effect of their variation on the flow rate was recorded.

The effect of electrochemical treatment on the pore configuration and the change in the core structure was indicated by a higher final hydrodynamic or Darcy's permeability, and, in some cases, by an hysteresis effect. In order to indicate clearly the variation of the hydrodynamic permeability, K_w , during the electrical or electrochemical treatment, the application of electrical current was carried out in an interruptive manner and the hydrodynamic flow rate was separately measured after each voltage setting.

The results presented in the table are shown in the form of flow rate (Q , cc/sec), normalized flow rate (Q/Q_1) and per cent increase in the flow rate $100(Q-Q_1)/Q_1$, as related to the applied electrical potential gradient (E/L , v/cm) and the electrical current (I , ma). Some of the data are also plotted in graphs (Figures 6-12) relating either the flow rate to the electrical potential gradient and current, or the normalized flow rate to the electrical potential gradient and current. This was done in order to indicate clearly the trend of the increase in the flow rate as a result of increasing the electrical potential gradient. The advantage of using normalized flow rate versus potential gradient for correlation purposes was the elimination of discrepancies caused by differences in lengths, areas or initial hydrodynamic permeabilities. The reason for plotting either Q or Q/Q_1 versus the electrical current was the fact that the core resistance varied with time.

The effect of changing the clay content of the core on the electroosmotic flow rate is shown in Table I. The electrolytic concentration, the pressure used in core compaction, and the pressure difference used during the flooding test were all identical for cores numbered 1, 2 and 3. The results shown in Table I are also plotted in Figures 6 to 12. From Table I and Figure 12, it is noted that the electroosmotic flow rate increases when the amount of clay present in the core is increased in the range investi-

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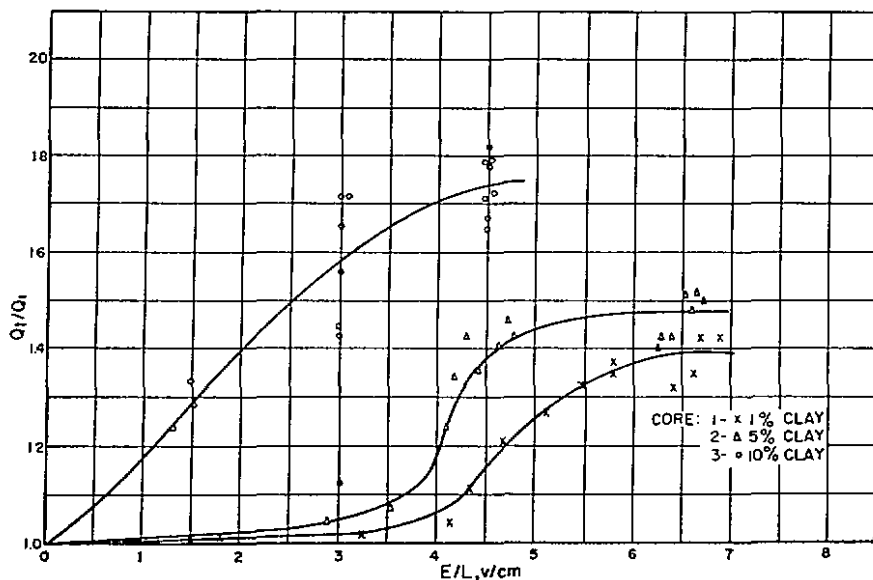


Figure 12.—Effect of the amount of clay present on the normalized flow rate, Q_1/Q_0 . (Cores no. 1, 2, and 3).

gated. The comparison of cores numbered 1, 2 and 3 is based on a reasonable similarity between the three cores, as evidenced from the values of their porosities and air permeabilities and from the identical experimental procedures used for their flooding.

CONCLUSIONS

On the basis of theoretical analysis of the electrokinetic phenomena, experimental investigation and prior application of direct electrical current in related engineering fields, the possibility of utilizing direct electrical current in oil production became apparent. Some of these applications are summarized as follows: (1) the flow rate of oil and water may be increased by the application of current during primary or secondary oil production; (2) chemical additives may be used in conjunction with electrical treatment to augment the flow rate of oil and water; (3) electrochemical treatment may be used for well stimulation; and (4) electroosmosis may be used as a selective ion-drive process.

No definite conclusion regarding the economic feasibility of these processes for field application can be drawn at this stage. Depending on the different variables involved, the utilization of electrical current may be considered economical in one case but not in another.

The present study of the application of electrokinetic phenomena in oil production is not complete, and many other problems remain to be explored. Several other papers on the subject will be published by the writers in the near future.

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