Hydrodynamic Performance of Six Lobe Sand Filters

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Abstract

The formation damage to the sandstone bed done due to flow of the produced water during secondary oil recovery is one of the crucial problems that the produced-water industry has been facing for quite some time. The drastic reduction in permeability of these sandstone beds due to the water-shock, is a great concern in petroleum industry. The changes in composition of produced water have made secondary oil recovery difficult. The decreasing permeability of the bed increases the pumping and equipment costs. In formations of weak structural strength regulations limit the allowable pumping pressure and other methods must be applied to restore permeability or new injection wells must be drilled. To a large extent, the migration of clays in the formation cause the decrease in permeability. Hence, the control of clay release is essential to the economic and effective operations in many oil fields.

The main topic of this paper is the effect of electrolytic composition in produced water on the performance of sand-filters. Sand filters are often constructed of sands similar to those found in the underground formations. The purpose of the sand filters is to pretreat the produced water before it is injected into the formation. It is important that the filters themselves not release clay particles into the water. Earlier studies [1-5] revealed that high pH and low salt concentrations of water lead to release of clay from sand-grains of Berea sandstone cores. Also, there might be some clay particles injected into the formation with the produced water. These injected clays get captured by the sandstone bed, causing an increase in the surface area of sandstone particles, both of which significantly reduce the permeability of the bed.

In produced water operations, oil companies need to remove particles from the injection water to avoid formation damage. Consolidated Sand Cartridge filters are an inexpensive means of filtering the particles.

The purpose of this work is to evaluate the hydrodynamic performance of a 6-lobe sand filter and to determine whether the changes in water chemistry cause a change in the filter's permeability. The filter has properties similar to that of sandstone and so we hypothesize that the clay release may be similar to sandstone bed. The Consolidated Sand filter has its outer surface expanded into a six-lobe geometry with a larger surface area for filtration. Hence the filter potentially has higher flow rates at a given pressure drop (compared to a cylindrical filter of equal surface area) and the life of filter increases.

The results of this work show that the filter geometry provides on order of 10% increase of flow rate compared to cylindrical filters of similar surface area. The experiments show that the presence of the glue to bind the sand filter together has a significant effect on zeta potential. The permeability was not affected by changes in

water chemistry (salt concentration or pH), indirectly indicating that there was not a significant migration and recapture of clay particles within the filter.

Introduction

The modeling of the reduction in permeability of the sandstone bed requires the use of volume averaged continuum equations [6]. Darcy's law [7] is the most commonly used equation in filtration industry to quantify resistance to flow of single fluid through a porous media. Darcy's law at the continuum scale is given by

$$\underline{q} = -\frac{k}{\mu}\underline{\nabla \overline{P}} \tag{1}$$

For rectilinear flow through porous medium with uniform porosity and uniform permeability, Darcy's law integrates to its macroscale form

$$Q = \frac{k}{\mu}\frac{A}{L}|\Delta P| \tag{2}$$

For flow of produced water through sandstone media, the phenomena of clay release and capture occurs due to changes in pH and salt concentration. Over the past few decades, a great deal of research has been conducted to develop a generalized model to predict permeability loss observed due to release and capture of clay fines in porous sandstone, with limited success. A model equivalent to Darcy's law is presented here to account for the changing permeability of the bed due to changes in the electrolytic composition of produced water. There are two aspects of the flow of produced water through the porous media. First, it involves multiphase flow and second, it involves mass-transfer between these phases.

Analytical Analysis for Pressure profile and velocity profile

The problem of two phase flow is too complex to be handled without an insight to the flow behavior of a single fluid through the porous media, especially when we are studying the clay release through the consolidated sand cartridge filter, which has its outer surface formed into a six lobe geometry (Figure 1). The flow pattern of a single fluid through the sand filter is determined using a boundary perturbation method. [9, 10]

The continuum mass balance for an incompressible steady state fluid flow through a uniformly porous medium with no chemical reactions and mass transfer, is combined with Darcy's law at continuum scale to obtain the Laplacian of pressure [11]

$$\nabla^2 \overline{P} = 0 \tag{3}$$

For radially inward flow of fluid through the consolidated sand cartridge filter, the Laplacian reduces to

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \overline{P}}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 \overline{P}}{\partial \theta^2} = 0 \tag{4}$$

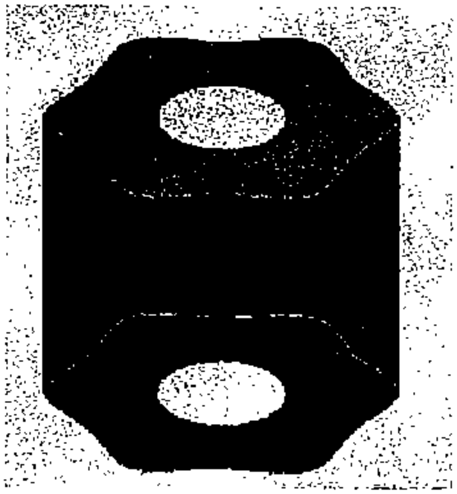

Figure 1. Consolidated Sand Cartridge filter

This partial differential equation is solved with boundary conditions of $\overline{P}_o$ pressure at the outer surface and $\overline{P}_I$ at the inner surface of the filter.

$$\text{At } r = r_I, \qquad \text{we have } \overline{P} = \overline{P}_I \tag{5}$$

$$\text{At } r = ro(1+\overline{\varepsilon}\sin(6\theta)) \qquad \text{we have } \overline{P} = \overline{P}_o \tag{6}$$

Here, the outer surface is modeled as varying sinusoidally with θ. The aim of boundary perturbation method is to find a simpler solution, as radial flow in annulus, whose solution already exists and is the asymptotic representation as $\overline{\varepsilon} \to 0$ of the solution $\overline{P}(r,\theta,\overline{\varepsilon})$. Here, $\overline{\varepsilon}$ represents the extent of distortion of the outer surface from the cylindrical surface. The pressure profile by the boundary perturbation method is determined accurately up to four terms in the series solution.

$$\begin{aligned} P(x,\theta) &= \frac{\ln(x)}{\ln(x_I)} + \overline{\varepsilon}\frac{\sin(6\theta)}{(1-x_I{}^{12})\ln x_I}\left[\frac{x_I{}^{12}}{x^6} - x^6\right] \\ &+ \overline{\varepsilon}^2 \cdot a \cdot \left[1 - \frac{\ln x}{\ln x_I} + \frac{\cos(12\theta)}{(1-x_I{}^{24})}\left(\frac{x_I{}^{24}}{x^{12}} - x^{12}\right)\right] \\ &+ \overline{\varepsilon}^3\left[\frac{d\sin(6\theta)}{(1-x_I{}^{12})}\left(x_I{}^6 - \frac{x_I{}^{12}}{x^6}\right) + \frac{e\sin(18\theta)}{(1-x_I{}^{36})}\left(x^{18} - \frac{x_I{}^{36}}{x^{18}}\right)\right] + \ldots \end{aligned} \tag{7}$$

where

$$a = \frac{1}{\ln x_I}\left[3\left(\frac{1+x_I{}^{12}}{1-x_I{}^{12}}\right) + \frac{1}{4}\right] \tag{8}$$

$$b = \left(\frac{1+x_I{}^{12}}{1-x_I{}^{12}}\right) \tag{9}$$

$$c = \frac{1}{4\ln x_I}\left[\left(\frac{15-21x_I^{12}}{1-x_I^{12}}\right)-\frac{1}{3}\right] \tag{10}$$

$$d = \frac{a}{\ln x_I} - 6ab + 3c \tag{11}$$

$$e = 6ab - c \tag{12}$$

$$x = \frac{r}{r_o} \tag{13}$$

The radial velocity profile is obtained from the Darcy's law, Eq.(1)

$$\underline{q} = -\frac{k}{\mu}\frac{\partial P}{\partial r} \tag{14}$$

Hence,

$$\begin{aligned}\underline{q} = -\frac{k}{\mu}\frac{(\overline{P}_I-\overline{P}_o)}{r_o}&\left[\frac{1}{x\ln x_I}-\frac{6\bar{\varepsilon}\sin(6\theta)}{(1-x_I^{12})\ln x_I}\left(\frac{x_I^{12}}{x^7}+x^5\right)\right.\\ &-\bar{\varepsilon}^2 a\left\{\frac{1}{x\ln x_I}+\frac{12\cos(12\theta)}{(1-x_I^{24})}\left(\frac{x_I^{24}}{x^{13}}+x^{11}\right)\right\}\\ &\left.+\bar{\varepsilon}^3\left\{\frac{6d\sin(6\theta)}{(1-x_I^{12})}\left(x^5+\frac{x_I^{12}}{x^7}\right)+\frac{18e\sin(18\theta)}{(1-x_I^{36})}\left(x^{17}+\frac{x_I^{36}}{x^{19}}\right)\right\}\right]\end{aligned} \tag{15}$$

The analysis shows 9.9% increase in flow rate with Consolidated sand cartridge filter with six lobe geometry compared to the flow rate through a simple cylindrical geometry with similar dimensions and similar pressure drop.

Zeta Potential and the Double Layer theory

The release and capture of clay particles are governed by the forces arising from the interaction between the sand surface and the clay particles. There are four prominent forces [12] which affect the release and capture phenomena.

1) The London-Vander Waals force
2) The electrical double layer force
3) The Born repulsion force
4) The hydrodynamic force

The hydrodynamic forces have generally been found insignificant. The London-Vander Waals forces and the Born repulsion forces are found to be independent of ionic strength of the water. The double layer forces however, are strongly affected by the ionic strength of the water. So, the reduction in permeability due to change in ionic strength of the water is best explained using the double layer theory.

The clay particles usually have a net negative charge in dry conditions, neutralized by surrounding cations on the surface. When the clay is dispersed in brine, an electrical double layer is formed in the fluid. It is essentially a distribution of electrical charges different from that in the bulk of brine. The inner immobile layer is a one hydrated-ion thick layer of physically adsorbed positively charged ions (for example Na^+, K^+, Ca^+ etc). This inner layer called the Stern layer has fixed charges at the boundary. The outer layer called the Diffuse layer represents charges under influence of the fluid motion. The zeta potential [12, 13] qualitatively is the surface potential at the slip plane between the stern and diffuse layers and the bulk fluid. With all the forces contributing to clay-sand capture or release, the net interaction energy is the sum of the attractive Vander Waals and double layer potentials.

When the salt concentration of the water is high, then the diffuse layer is compressed. The thickness of the diffuse layer is inversely proportional to the ionic strength of the solution. This is due to the fact that there will be greater number of ions in the bulk to attract away the negative charges present in the diffuse layer. Because of the compressed diffuse layer, the distance of separation between the clay and the sand particle decreases. The attractive Vander Waals forces dominate over the repulsive double layer forces. So, the clay particle remains attached to the sand. Conversely, when the salt concentration is low, then the diffuse layer is thick and the repulsive double layer forces dominate over attractive Vander Waals forces. Here, the clay particles may detach from the sand and migrate through the bed. Eventually these clay particles get caught in the pore throats in the bed and the permeability of the bed decreases.

The effect of pH can be explained on similar lines. When the pH of the bulk fluid is low, the H^+ ions in the bulk replace the cations from the surface of the particles. Thus, the concentration of the cations in the bulk increases, resulting in lower repulsive forces and hence, the clay particles do not release. Conversely, higher pH will result in clay release and hence, the permeability of the bed will decrease.

The combination of high pH and low salt concentration has proved highly detrimental to the sandstone formations. Various studies are conducted to reduce these effects. Salt levels are also expected to adversely affect the performance of the sand filters. It is not known for sure if the filter too will get damaged due to low salt concentration and high pH.

Zeta potential measurements made using an Anton Paar Electro-Kinetic Analyzer are used to study the behavior of the filter with change in pH. The cylindrical cell in the EKA is filled with the sand sample soaked previously in the electrolyte solution (distilled water in this case) for a period of 24 hours. The EKA cylindrical cell uses silver electrodes coated with AgCl, between which the sand sample is placed. The sand sample is incompressible, so the zeta potential is calculated using the Fairbrother and Mastin equation [13].

$$\xi = \frac{U_p * \eta * \nu}{\Delta P * \in * \in_o} \tag{16}$$

One liter of electrolyte solution is pumped through the sample with recycle. The streaming potential U_p resulting from the motion of ions, is measured by the electrodes.

The pressure gradient is thus used to generate an electric current over stationary particles. The zeta potential is calculated from the slope of streaming potential versus the pressure drop curve. The curve of the streaming potential and the pressure drop has to be linear for the reading to be acceptable. This criterion was met while taking all the measurements with EKA. The zeta potential measurements were made for both loose unglued sand and the crushed glued sand used for making the consolidated sand cartridge filter.

If the difference in the zeta potential of the clay and sand is very large then the formation damage is less, while small difference in zeta potential of the sand and clay indicates significant formation damage. Earlier work [8] has demonstrated that the value of zeta potential of the clay remains negative, even though that value may change to a small extent with the change in pH and salt concentration. Therefore, negative values of the zeta potential of the sand would result in small difference in the zeta potentials and hence, significant clay release and capture, while higher values of zeta potential of the sand would result in large difference in the zeta potentials and hence, less formation damage.

As the zeta potential of the clay is known in literature [8] and its range lies somewhere between –20 to –40 mV depending on pH and salt concentration, only the zeta potential of the sand is reported in the paper. Runs 1 through 6 are done with loose unglued sand sample and distilled water as the electrolyte. The zeta potential is consistently decreasing with increase in pH and hence, the chances of clay release are greater. This behavior is similar to that of Berea sandstone, where the formation damage takes place at high pH and low salt concentration. While the runs 7 through 10 done with crushed glued sand of similar size and distilled water, distinctly shows insignificant changes in zeta potential with increase in pH. Comparing the curves shows that the glue dramatically alters the zeta potential and it is expected that the consolidated sand cartridge filter will not be as susceptible to permeability loss as is the conventional unglued sand filter.

Permeability Experiments

The permeability experiments were carried out to determine whether the filter's permeability decreases as does the Berea sandstone cores under similar pH and salt concentration conditions. The Consolidated Sand Cartridge filter was held firmly in a casing and water of different pH and salt concentration was pumped through the filter. The pressure drop across the filter was continuously monitored using pressure-transducer and while the flow rate was kept constant at 1 gpm. A computer was used for logging the pressure-drop readings.

The length of time for which the fluid flows through the filter gives the measure of number of pore volumes of water passed. To compare with the Berea sand core results, the reduction in permeability is expected in less than 50 pore volumes [reference beth's dissertation or paper]. The volume of a typical filter is 40.197 in^3 (6.5872×10^{-4} m^3) and its porosity is around 0.27-0.36. For a porosity of 0.36, the porous volume of the filter is 14.471 in^3 (2.3713×10^{-4} m^3). Thus, every gallon of fluid through the filter corresponds to 15.9 pore volumes.

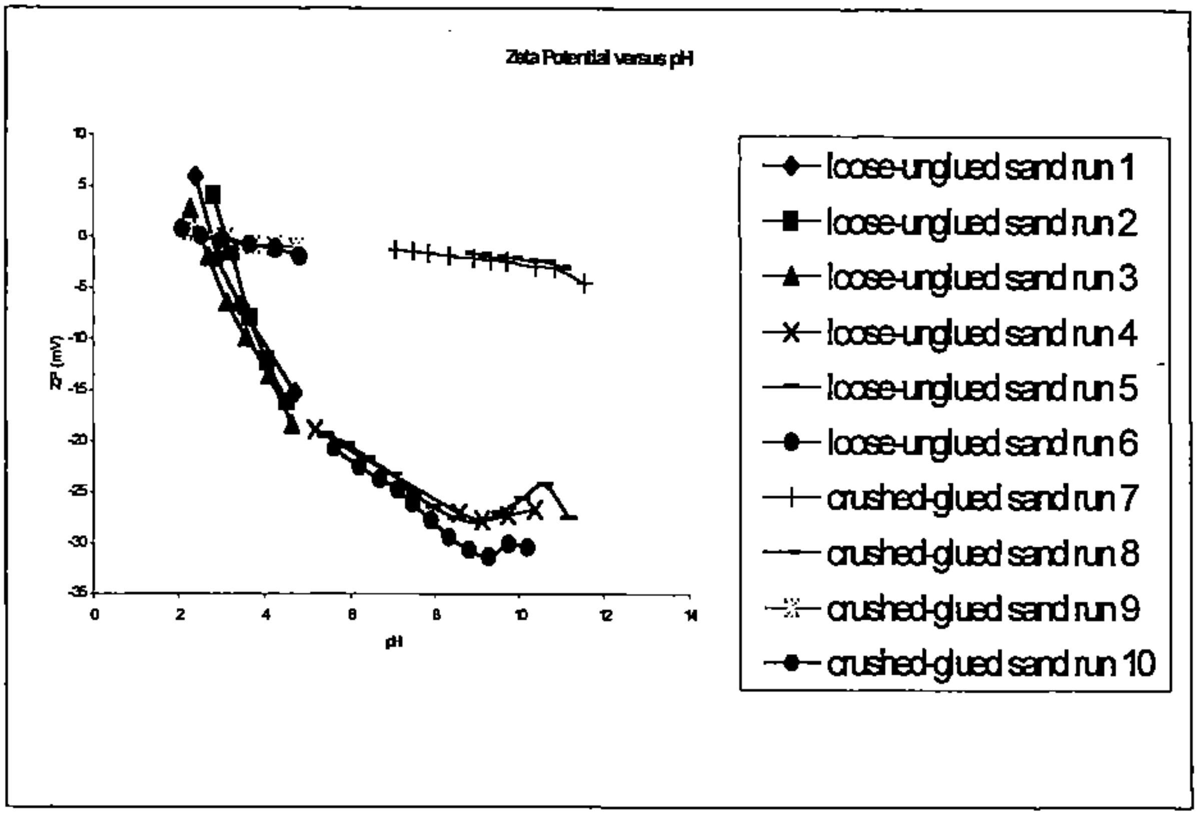

Figure 2. Zeta Potential verses pH for crushed glued sand and loose unglued sand

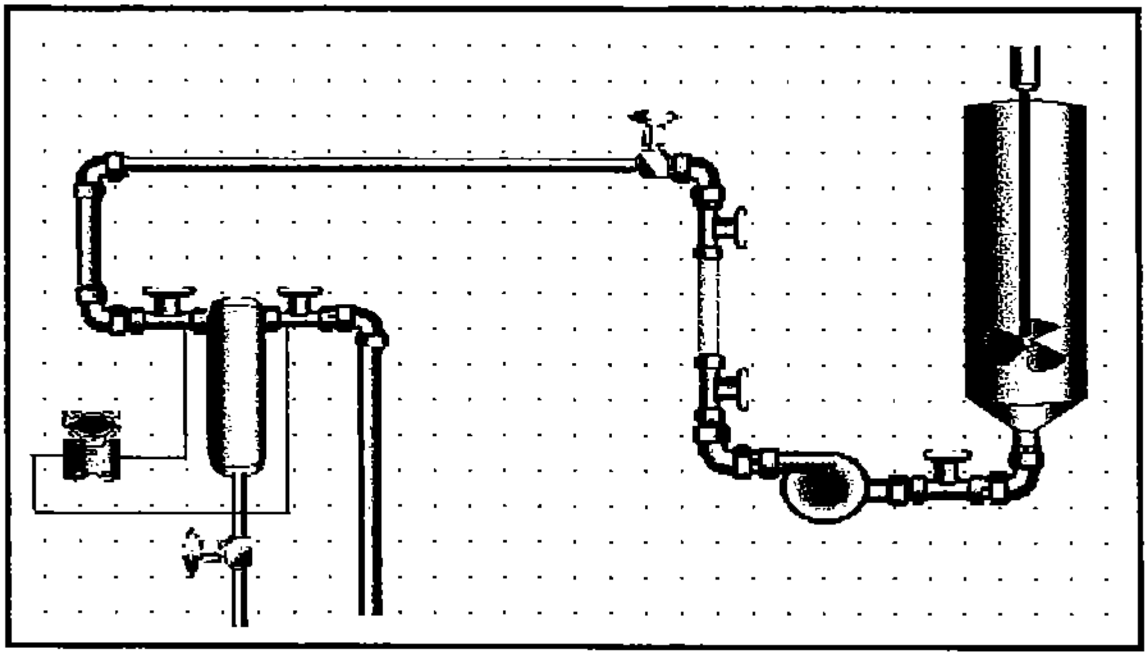

Figure 3. Core flood Experiment Apparatus

Several runs were carried out to study the behavior of salt-concentration and pH on the filter. Figure 4 shows results from only some of the representative runs. Fluid of a particular electrolytic composition was allowed to flow through the filter for more than an hour to bring the system to equilibrium. Then, the electrolytic composition of the fluid was given a step change and it was allowed to flow for more than an hour, which is sufficient enough to bring changes in the permeability if any.

Earlier studies of core flood experiments done with Berea sandstone revealed that the pressure-drop increased for fluids with high pH and low salt-concentration. However, the experiments with Consolidated Sand Cartridge filter show that it does not follow the same behavior as the Berea sandstone. The plot of pressure-drop versus time for the Consolidated Sand Cartridge filter indicates that there is not much change in pressure-drop with the number of pore volumes of fluid flowing through the filter, even when step changes were made in the electrolytic concentration of the fluid. The permeability of the filter does not decrease with time and formation damage does not occur. This is in full agreement with the zeta potential measurements, which predicted that there would be no clay release or capture in these filters. Again, the role of glue in prevention of clay release and capture becomes apparent. The glue binds the clay particles firmly to the sand and does not allow clay to detach from the sand, even under the effect of pH and salt concentration.

The reduction in permeability is considered to be a direct implication of clay release and capture phenomena taking place, even though clay swelling and other phenomena also could result in permeability reduction. That the permeability of the bed remains unchanged suggests that none of these phenomena occur. A sample of fluid flowing out from the filter, was analyzed to detect presence of clay. The particle counter BR-8 did not detect presence of any extra amount of particles other than what was originally present in the fluid flowing into the filter.

Conclusions

The work has demonstrated the advantages of the consolidated sand cartridge filter over conventional sand filters. The flow characteristics through consolidated sand filter has been studied. Higher flow rate is achieved with the six-lobe geometry of the filter, as compared to the conventional cylindrical sand filter with the same pressure drop. The zeta potential studies revealed that while the sand from which the consolidated sand cartridge filter is made, is similar to Berea sandstone and can get damaged under high pH and low concentration, the actual consolidated sand cartridge filter should remain more or less stable even under high pH and low salt concentration. The zeta potential predictions conform to the results from core flood experiments. The glue which binds the loose sand to form the filter, alters the surface properties of the filter as a whole and minimizes formation damage.

Future work

The model proposed for two phase flow through the porous media, has to be tested. Experimental data should be fitted with the model using efficient techniques like Genetic algorithm to determine the three model parameters. So far, the core flood experiments have been carried out only with brines to study the clay release and capture phenomena. Proper experimental technique should be developed to study the clay release and capture in two phase fluid flows.

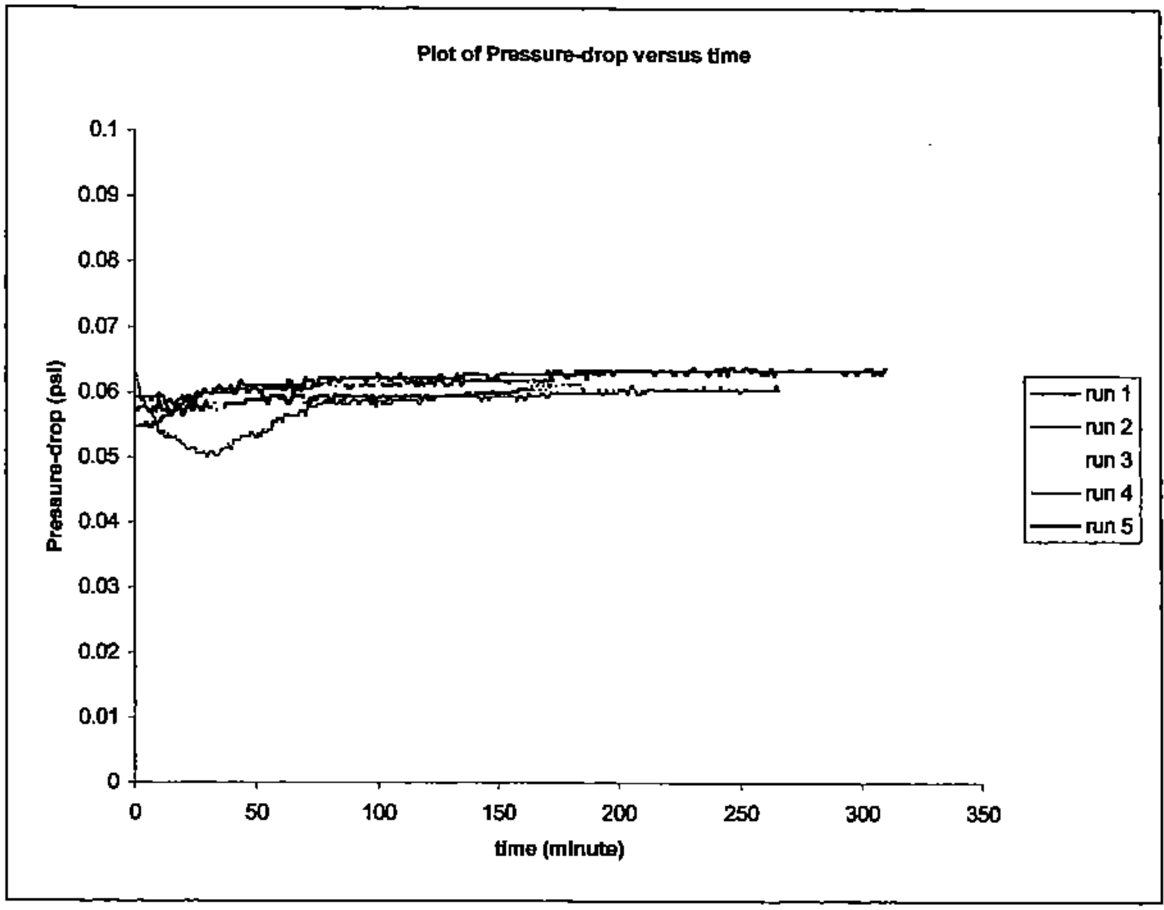

Figure 4. Results from Core flood Experiment, plot of pressure-drop versus time

Run 1 – Distilled water for 3 hr 6 min

Run 2 – Distilled water for 1 hr 26 min, then 3 pH HCl solution for 1 hr 28 min

Run 3 – Distilled water for 1 hr 44 min, then 11 pH NaOH solution for 1 hr 26 min

Run 4 – Distilled water for 2 hr 11 min, then 0.1 M NaCl for 2 hr 15 min

Run 5 – Distilled water for 2 hr 26 min, then 0.01 M NaCl for 2 hr 24 min

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Notation

a,b,c,d,e	constants given by Equations (8)-(12)	
$\underline{q}$	local bed averaged fluid velocity	m/s
k	permeability	m^2
$\overline{P}$	pressure	N/m^2
μ	viscosity	kg/ms
r	radial coordinate	m
r_I	radial length of the inner surface of the filter	m
r_o	average radial length of the outer surface of the filter	m
θ	angular coordinate	-
Q	volumetric flow rate	m^3
$\overline{\varepsilon}$	dimensionless length, perturbation parameter	-
P	dimensionless pressure	-
x	dimensionless radial coordinate	-
v	velocity	m/s
ρ	density	kg/m^3
ξ	zeta potential	
Up	streaming potential	
η	dynamic viscosity of the solution	
ν	specific electrical conductivity	
$\in_o$	permittivity of free space	
$\in$	permittivity of test solution	
L	Length of the filter	m
A	flow area	

Subscript

x	direction
I	inner surface of the filter
O	outer surface of the filter

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