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Effect of microbial growth on pore entrance size distribution in sandstone cores

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SUMMARY

The in situ growth of microorganisms in Berea sandstone cores preferentially plugged the larger pore entrances. The largest pore entrance sizes after microbial plugging ranged from 20 to 38 μm, compared with 59 to 69 μm before plugging. The pore entrance size distribution of plugged cores was shifted to smaller sizes. A mathematical model based on Poiseuille's equation was found to adequately predict permeability reductions (greater than 90%) caused by microbial growth in the large pore entries.

INTRODUCTION

Porous geological materials are composed of a network of interconnected pores with a wide pore size distribution. The method used for measurement of this distribution of pore sizes more closely measures the pore entry size distribution. The variation in the pore entrance size within porous media has a significant effect on the success of a waterflood or enhanced oil recovery (EOR) process. With a large variation in pore entrance size, variation of the permeability of the reservoir [2,3,7,17] exists, and thus most of the injected fluid will flow through the larger pores, leaving valuable hydrocarbons behind in the smaller pores. Selective plugging has been proposed to reduce the variation in permeability and thus force water injected to displace the oil to enter the smaller pores and displace the trapped oil.

Many methods of selective plugging have been proposed, including the use of colloidal clays, gels, organic resins, waxes, inert solids and cements [1,2,6,9,11,19]. Size selection, penetration depth, and stability of the plugs are problems that have

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Nomenclature: Q, volumetric flow rate (L_3/t); C, orifice constant (dimensionless); A, cross-sectional area (L_2); g, gravity (L/t^2); h, pieziometric head (L); λ_s, transmittivity (L^2); R_e, Reynolds number (dimensionless); a, constant (dimensionless); ρ, density (M/L_3); μ, viscosity (M/Lt); d, diameter (L); L, length (L); ΔP, pressure change (M/L_2).

prevented the wide scale use of these agents. Crawford [4,5] reported that microorganisms can be used to selectively plug a reservoir to correct stratification problems.

Jenneman et al. [14,15] and Jang et al. [12,13] have shown that microorganisms and nutrients required for their growth can be transported through sandstone cores. The in situ growth of microorganisms in sandstone results in significant reductions in permeability because the organisms selectively grow in the more permeable regions [14,15]. This work was designed to show that the microorganisms preferentially grow in the larger pores and plug the larger pore entrances, resulting in large permeability reductions in the cores and improved oil recovery.

THEORY

The larger pores in a porous geologic medium conduct most of the flow through the system, since the larger pores offer the least resistance to fluid flow through the rock. Consequently, most nutrients injected into a reservoir will enter and flow through the larger pores, rather than the smaller pores. Microorganisms that reside within the larger pores thus have access to the largest quantity of nutrients, which results in preferential growth of the microorganisms in the larger pores.

With this information, a simplified mathematical model was derived to explain flow through porous media. This model considers the porous medium (i.e., sandstone) as a collection of sieves, and each sieve is considered to be a bundle of orifices.

From basic fluid mechanics [21] for an incompressible flow of a uniformly dense fluid through a single orifice, the flow rate, q, depends on the difference in the pieziometric head:

$$q = CA\,(2g\,(h_1 - h_2))^{1/2} \tag{1}$$

If Eqn. 1 is valid when more than one orifice is present, then for a bundle of orifices, the total flow can be expressed as:

$$Q_T = (2g\,(h_I - h_0))^{1/2} \sum_{i=1}^{n} C_i A_i \tag{2}$$

If the porous medium is considered to be a collection of sieves as shown in Fig. 1, then Eqn. 2 can be written for each sieve as follows:

$$\begin{aligned} Q_T &= (2g\,(h_I - h_1))^{1/2} \left(\sum_{i=1}^{n} C_i A_i \right)_{S=1} \\ Q_T &= (2g\,(h_i - h_2))^{1/2} \left(\sum_{i=1}^{n} C_i A_i \right)_{S=2} \\ Q_T &= (2g\,(h_{L-1} - h_L))^{1/2} \left(\sum_{i=1}^{n} C_i A_i \right)_{S=L} \end{aligned} \tag{3}$$

The above equations can be solved for the potential across the orifice plate, or sieve, as follows:

$$\begin{aligned} (h_I - h_1) &= \frac{\left[Q_T / \left(\sum_{i=1}^{n} C_i A_i \right)_{S=1} \right]^2}{2g} \\ (h_1 - h_2) &= \frac{\left[Q_T / \left(\sum_{i=1}^{n} C_i A_i \right)_{S=2} \right]^2}{2g} \\ (h_{L-1} - h_L) &= \frac{\left[Q_T / \left(\sum_{i=1}^{n} C_i A_i \right)_{S=L} \right]^2}{2g} \end{aligned} \tag{4}$$

The total flow rate for the entire collection of sieves is found by adding the above equations and solving for the total flow rate, Q_T:

$$Q_T = (2g\,(h_I - h_L))^{1/2} \left[\sum_{S=1}^{L} 1 / \left(\sum_{i=1}^{nS} C_i A_i \right)^2 \right]^{-1/2} \tag{5}$$

Next, let

$$\lambda_S = \sum_{i=1}^{nS} C_i A_i \tag{6}$$

and define an orifice constant, C_i, for each orifice, which is a function of the Reynolds' number, R_e:

$$C_i = f(R_e) \tag{7}$$

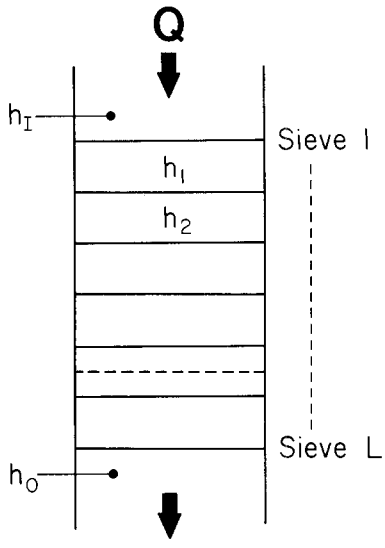

Fig. 1. Hypothetical representation of porous medium as a collection of sieves. Each sieve is considered to be a bundle of orifices.

If the orifices are sharp-edged, a logrithmic approximation may be used to relate C_i to R_e [21]:

$$\ln C_i = a + \ln R_e \tag{8}$$

which yields:

$$C_i = e^a R_e \tag{9}$$

where a is the intercept and is constant. If $a_0 = e^a$, then:

$$R_e = \frac{4}{\pi} \frac{\rho}{\mu} \frac{q_i}{d_i} \tag{10}$$

Substituting Eqn. 10 into Eqn. 9

$$C_i = a_0 \frac{4}{\pi} \frac{\rho}{\mu} \frac{q_i}{d_i} \tag{11}$$

Substituting Eqn. 11 into Eqn. 6

$$\lambda_s = a_0 \frac{\rho}{\mu} \sum_{1=1}^{n} q_i d_i \tag{12}$$

The flow rate through an orifice of diameter d_i is given by q_i, which is defined as:

$$q_i = \frac{\pi}{4} d_i^2 v_i \tag{13}$$

If the velocity through an orifice is constant through the length of the porous medium, then Eqn. 12 can be rewritten as:

$$\lambda_s = a_0 \frac{\rho}{\mu} v \frac{\pi}{4} \sum_{i=1}^{n} d_i^3 \tag{14}$$

Since the porous medium is considered to be a collection of sieves with each sieve composed of a bundle of orifices, then λ_s can be defined as a property of porous medium and is a measure of the capacity of the porous medium to transmit fluids. As shown by Eqn. 14, λ_s is a function of the density and viscosity of the fluid as well as the pore entrance size distribution of the porous medium (d_i).

Substituting Eqn. 14 into Eqn. 5, yields:

$$Q_T = a_0 \frac{\pi}{4} \frac{\rho}{\mu} v (2g (h_1 - h_L))^{1/2} \sum_{s=1} \left[\frac{1}{\left(\sum_{i=1}^{n} d_i^3 \right)^2} \right]^{-1/2} \tag{15}$$

This equation shows that most of the flow through the porous medium will be through the larger pores. Thus, the preferential plugging of large pores will dramatically reduce the total flow rate through the porous medium for a given pressure differential. This implies that the capacity of the porous medium to transmit fluids, i.e., permeability, is reduced by the preferential plugging of large pores.

EXPERIMENTAL PROCEDURE

Core preparation and incubation

Berea sandstone blocks of differing permeabilities were obtained from Cleveland Quarries, Amherst, OH, and were cut into 2.5 cm long by 1.9 cm diameter cores. Each core was steam-cleaned for 2 weeks to remove humic acids, dried for 24 h at 125°C, and cooled in a vacuum desiccator. The outer surface of each core was coated with Conap Easypoxy (Fisher Scientific Co.). Each core was then vacuum saturated with 5% NaCl-0.1 M $CaCl_2$ so-

lution and was flushed with 100 pore volumes of this solution using the permeability apparatus described by Jenneman et al. [16]. The core was then flushed with 15 pore volumes of 5% NaCl solution to reduce the calcium concentration in the cores. The initial permeability of the core was determined. All solutions were bubbled with 100% N_2 gas and filtered through a 0.22 μm membrane filter before being injected into the core.

The core was flushed with 3 pore volumes of medium E with 0.1% (w/v) $NaNO_3$ [14] while still attached to the permeability apparatus. Medium E consisted of a sucrose-mineral salts medium with 5.0% (w/v) NaCl [14]. The core was placed in the growth chamber described by Jenneman et al. [16] and 100 ml of sterile medium E with 0.1% $NaNO_3$ were added to each side of the growth chamber as previously described [16]. The growth chamber was incubated at 50°C for 48 h and the permeability of the core was then determined by mounting the core in the permeability apparatus and flushing the core with 5% (w/v) NaCl solution. The above procedure (injecting medium, incubating the core in the growth chamber, and flushing the core with the salt solution) were repeated until the permeability of the core was reduced to a value below 40% of the initial permeability. Since neither the core nor the growth chamber was sterilized, a diverse population of microorganisms that were present in the core or were accidentally introduced into the system grew and reduced the permeability on the core. Microscopic analysis and isolation of the plates of medium E with 0.1% $NaNO_3$ and on plate count agar (Difco Co., Detroit, MI) showed that gram-positive, spore-forming rods similar to *Bacillus* were the dominant organisms [16].

A control experiment (core 4) was simultaneously conducted to determine whether the addition of the nutrient medium E without subsequent growth affected the pore entrance size distribution. The core was flushed with 15 PV of medium E with 0.1% $NaNO_3$ and was incubated at 3°C for 7 days while submerged in a flask containing 100 ml of the above medium. Another core was flushed with 3 PV of medium E with 0.1% $NaNO_3$, mounted in the growth chamber as described above, and autoclaved at 121°C for 20 min. This growth chamber was incubated at 50°C for 4 days. No bacterial growth nor permeability reduction was observed in this core.

Permeability and porosity measurements

The permeability, which is a measure of the fluid conductivity of a porous medium, was calculated from Darcy's law:

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

The permeability apparatus maintained a constant pressure differential across the core. Thus, the permeability of the core calculated by measuring the volumetric flow rate, q. The Reynolds number for every core used was below 10^{-2}; therefore, permeability measurements were in the region of viscous flow, and Darcy's law is valid.

Porosity and dry weight of the core were determined as previously described [16].

Pore entrance size distribution

The pore entry size distribution of each core was determined before and after the treatments described above. The method of Soblod et al. [20] as modified [7], was used. The cores were placed in a Beckman L5-50B Ultracentrifuge and subjected to increasing angular velocities to displace the fluid from the core using air as the displacing fluid. The volume of fluid displaced was measured with a stroboscope attached to the ultracentrifuge. The angular velocity was increased until connate water saturation was reached, which occurs when no more fluid is displaced by increasing angular velocity. The pore entrance size distribution was computed by a FORTRAN program. The dry weight of the core needed to compute the pore entrance size distribution was determined after centrifugation for cores plugged by microbial growth.

RESULTS

The addition of nutrients to the cores and incubation of the cores at 50°C resulted in large de-

Table 1

Effect of microbial growth on the permeability of Berea sandstone cores

Core No.[b]	Porosity (%)	Permeability (mdarcys)		Permeability reduction factor[a]	$(\lambda/\lambda_0) \times 100^c$
		initial	final		
1	20.0	308	117	38.1	5.5
2	19.1	282	24	8.5	6.9
3	17.6	175	2.6	1.5	9.1
4	17.6	130	119	91.5	ND[d]

[a] Final permeability divided by initial permeability times 100.
[b] Cores 1 through 3 were incubated at 50°C while core 4 was incubated at 3°C.
[c] Calculated from the pore entrance size distribution of the core according to the model.
[d] ND, not determined.

creases in the permeability of the cores (Table 1). Growth chambers incubated at 50°C contained large numbers of microorganisms. The addition of nutrients and incubation at 3°C (core 4) did not result in a large reduction of the permeability of the core. No growth of microorganisms was observed in the flask containing core 4 after 7 days of incubation at this low temperature. Thus, we concluded that the observed changes in permeability were the result of microbial growth and metabolism, and not caused by the addition of the nutrients themselves.

The pore entrance size distribution of the cores before and after microbial plugging is shown in Fig. 2. The pore entrance size distribution of the unplugged cores was similar to that found by Donaldson et al. [8] for Berea sandstone. The data show that the large pores were preferentially plugged by microbial action and that the pore entrance size distribution is shifted to the smaller pore entrance sizes. The largest pore entrance size in the unplugged cores was 59, 69 and 62 μm for cores 1, 2 and 3, respectively. After plugging, the largest pore

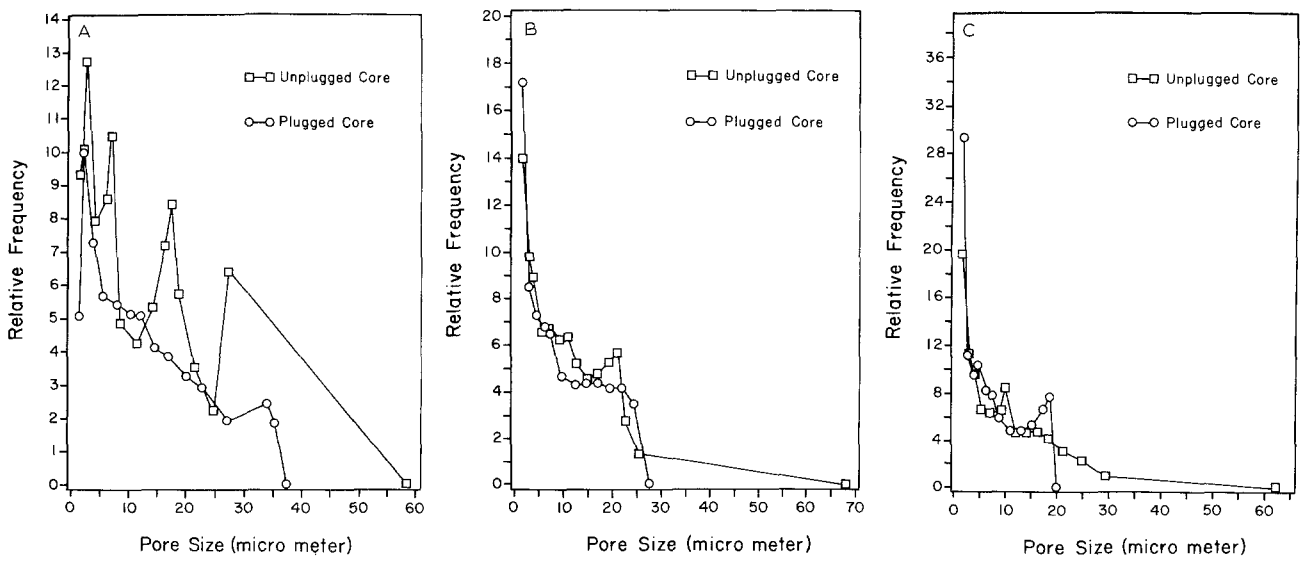

Fig. 2. Pore entrance size distribution of Berea sandstone cores before and after plugging. A, core 1; B, core 2; C, core 3.

entrance size was 38, 28 and 20 μm for cores 1, 2 and 3, respectively. In some cases (core 1), the microbial plugging reduced the heterogeneity of the core. The multiple peaks present in the pore entrance size distribution were reduced and the distribution curve was much smoother after microbial plugging.

The pore entrance size distribution of core 4 was not markedly changed after incubation of the core at 3°C to prevent significant microbial activity (Fig. 3). Thus, the addition of nutrients without microbial growth and metabolism did not affect the pore entrance size distribution of the core. These results also show that consistent pore entrance size distributions are obtained for the same core.

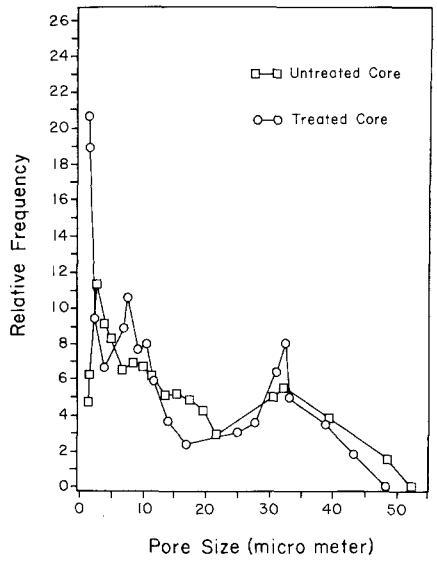

Fig. 3. Pore entrance size distribution of a Berea sandstone core (core 4) before and after the addition of nutrients and incubation for 7 days at 3°C.

DISCUSSION

The in situ microbial growth and metabolism preferentially plugs the larger pores in Berea sandstone. Microbial plugging reduces the magnitude and number of peaks observed in the distribution (Fig. 2), resulting in a more homogeneous distribution of pore entrance sizes. Some increase in the relative frequency of smaller pores is often observed after treatment, indicating the partial plugging of larger pores. The production of biomass in the growth chambers during the experiments conducted under growth conditions (i.e., 50°C), the lack of biomass during the experiment conducted under non-growth conditions (i.e., 3°C), and the decrease in permeability with increasing amounts of nutrient injected indicate that the permeability reductions were the result of microbial growth. Thus, the shift in the pore entrance size distribution curve to the smaller pore entry sizes was the result of the metabolism and growth of indigenous bacteria in the core.

The experimentally obtained permeability reduction factors and the pore entrance size distribution were used to verify the model. The values for a_0, μ, ρ, and v in Eqn. 15 were assumed to be constant and equal for both the plugged and unplugged core. The ratio of λ (after plugging) to λ_0 (before plugging) was calculated from the pore size distribution (Table 1). The permeability reductions predicted by the model (λ/λ_0) were close to the experimentally obtained values when the permeability was reduced to 10% of its original value. In core 1, where the permeability reduction was less than the other cores, the model prediction deviated greatly from the experimentally determined value. We believe that this was due to the inability to accurately determine the pore entrance size distribution of the core beyond 40–50 μm by the centrifuge method. The largest pore entrances are evacuated at the slowest centrifuge velocities, where accurate readings are not always possible.

That microorganisms preferentially plug the larger pores rather than the smaller pores, as was indicated in earlier work [10], has important implications for microbially enhanced oil recovery. After waterflooding, much oil still remains in the smaller pores which were not contacted by the waterflood. By plugging the larger pores, the flowing fluid will now contact a larger percentage of pores within a given elemental volume of the reservoir and displace the oil that was previously bypassed. Since smaller pores comprise most of the pore space in

an elemental volume of the porous medium, this will increase the microscopic sweep efficiency, defined as that fraction of the elemental volume contacted by the recovery fluid [3]. This may explain why additional oil (10–35% of the original oil in place) was recovered from Berea sandstone cores waterflooded to residual oil saturation by the in situ growth of microorganism in the cores [18].

The proposed mathemathical model qualitatively predicts the observed changes in permeability caused by microbial growth in the core. The model predicts that plugging the larger pores rather than the smaller pores will have a much greater effect on the permeability. The in situ growth of microorganisms did plug the larger pores and the permeability of these cores was greatly reduced. However, the model did not accurately predict the degree of permeability reduction. This was particularly true for core 1 where the permeability reduction was much greater than the other two cores. When the permeability reduction is not large, some of the larger pores are not completely plugged. The pore entrance size of these pores was difficult to accurately determine with the method used and a linear approximation of these pore entrances sizes was used. This may have affected the accuracy of the model's prediction in this case.

The reason why the in situ growth of microorganisms preferentially plugged the larger pores may be explained as follows. Since the larger pores transmit most of the fluid, most of the injected nutrients will pass through these pores. Thus, the microorganisms that are present in the larger pores will be able to grow at a faster rate and to higher densities than the organisms in the smaller pores, since the larger pores contain higher nutrient concentrations.

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