THERMAL PETROPHYSICAL EFFECTS ON EFFECTIVE PERMEABILITY OF POROUS SANDSTONE

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ABSTRACT

In this paper, the changes in flow and mechanical properties as a result of heating two typical sandstones are presented and discussed. These rocks were heated to several different temperatures from room temperature to reservoir temperature (up to 80°C), and changes in effective permeability were measured. Since the increases in bulk volume were comparatively small, the resultant changes in porosity and permeability were small, too. Porosities increased by 0.45% and permeabilities by 5% to 9%, depending upon the change in porosity during heating. The tests were run at atmospheric pressure and under 100°C, so changes in physical properties of the rocks when subjected to high temperatures may be explained as due to differential thermal expansion of the constituent mineral grains. However, these changes have a small effect on the permeability response to temperature. Therefore, under the effective stress and temperature conditions used in this study, thermal expansion of constituent minerals has negligible impact on porosity, and thus presumably, effective permeability.

INTRODUCTION

It was not until the late 1960s that changes in absolute permeability with temperature were observed. As the essential parameter for core analysis and formation damage evaluation, much attention had been paid to this topic. In 1968, Greenberg *et. al.*[1] reported experiments on the water permeability of nine artificially consolidated porous medium samples for a limited temperature range of 26.7°C to 60°C at no confining pressure. Their results showed that the permeability either decreased slightly or increased with increasing temperature. A year later, Afinogenov[2] reported a large reduction of permeability to oil with increased temperature. He also observed extreme permeability reductions with increasing confining pressure ranging from 2.1 to 103 MPa. By contrast, many studies with sandstones found an increase in permeability with increasing temperature, while other studies found a decrease in permeability, like Weinbrandt *et. al.*[3] Experimental data from Sydansk[4] indicate that brine (3.0% NaCl) absolute permeability in Berea sandstone fired at 450°C does not vary significantly with temperatures between 22 and 85°C. Somerton *et. al.*[5] indicated that no permeability changes were found in the range of 23.9 to 176.7°C. The study by Gobran *et. al.*[6] indicated that effective permeability to distilled water was also found to be temperature independent for both unconsolidated sand and unfired Berea sandstone at temperatures ranging from 37.7 to 148.9°C.

Why are the results of these investigations on the effect of temperature on flow in porous media dissimilar or contradictive? It is probably a consequence of differences in the porous material employed, in the experimental procedures followed, and in the test systems used. Important parameters in formation damage evaluation at reservoir conditions, absolute permeability and/or effective permeability are affected by many factors. In research on the relationship between permeability and temperature, many factors have been considered such as confining pressure, pore pressure, temperature, and wettability, but the thermal petrophysics of the rock skeleton have not yet been investigated.

In recent decades, studies on the changes in effective permeability due to heating are inadequate. In this paper, the changes in flow and mechanical properties of two typical sandstones as a result of heating are presented. It is shown that since increases in bulk volume are comparatively small, the resultant changes in porosity and permeability are small, too. Thus, under the effective stress and temperature conditions used in this study, thermal expansion of constituent minerals has negligible impact on porosity, and thus, presumably effective permeability.

APPARATUS AND EXPERIMENTAL PROCEDURE

Experimental Apparatus

A FDS-641 Formation Damage Evaluation System for reservoir conditions tests was used in this research, which has a maximum pressure of 68.9 MPa and a maximum temperature of 150^{o}C. Quizix-SC2400 controllers with four cylinder piston pumps (rates ranging from 0.001 to 15.0 ml/min) were used as the displacement pumps. A BPR-5 back pressure regulator was mounted downstream of the core in order to prevent water from boiling in the higher temperature tests. A confining control system, consisting of an ACPC-195 Automated Confining Pressure Controller, fluid reservoir, and a pressure transducer, was used to ensure a constant difference between the overburden pressure and pore pressure during the testing process.

Porous Media and Test Fluids

The core samples were all consolidated porous sandstone, either fired outcrop or cleaned core from an oil reservoir. The quartz sandstone outcrop cores are from Sichuan, China, which contain about 1% of nonswelling clays: chlorite and kaolinite. Very little fines material was observed in these outcrop samples with a scanning electron microscope (SEM). There were a few flaky chlorite and kaolinite. The outcrop cores, 2.54 cm in diameter and 5 cm in length, were prepared by firing them in a muffle at 700^{o}C for one week to stabilize any clay minerals present in the rock pore space. This treatment provides an internal rock surface of as near constant properties as possible and prevents other formation damage, except that due to thermal petrophysics. Each core sample was used only once, because thermal shock effects on petrophysical properties of cores are irreversible.

Standard brine and fresh water were filtrated to remove suspended solids. The standard brine contained only chloride ions, which had a high concentration as well as solubility; thus, no inorganic scale developed with changes in temperature, which could interfere with the results of the test, and the water sensitivity of cores containing clay was minimized.

Experimental Procedure

The objectives in this laboratory investigation were:

1) To reproduce the temperature induced permeability changes reported in literature, and
2) To determine thermal petrophysical effects on effective permeability to brine, which is an important parameter for formation damage analysis.

At temperatures higher than 260°C, consideration must be given to other mechanisms, such as decomposition, mineral dissolution, re-precipitation, permanent structural damage caused by thermal stresses, and sometimes, wettability alteration. In China, the temperature of most waterflooded reservoirs is in the range of 40 to 80°C, a few are greater than 80°C but less than 150°C. In addition, measurement errors greatly increase if the temperature exceeds 90°C. Therefore, the temperature ranged from room temperature to 80°C, and the confining pressure was kept about 2.7 MPa higher than the pore pressure. All flow rates were set below the critical velocity of the core samples in order to prevent a rate effect on the thermal petrophysics. The core samples were first saturated with test brine; then, the initial permeability k_0 to water was measured at room temperature as a baseline permeability for comparison. The system was heated with a 5°C grade, and each grade lasted for 30 minutes. When the scheduled temperature was reached, conditions were allowed to stabilize for at least 24 hours before the next measurement.

RESULTS AND DISCUSSION

Results for Quartz Sandstone

The rate damage and water damage for these fired outcrop cores, measured at room temperature, showed that rate and water sensitivity can be neglected (Figures 1 and 2).

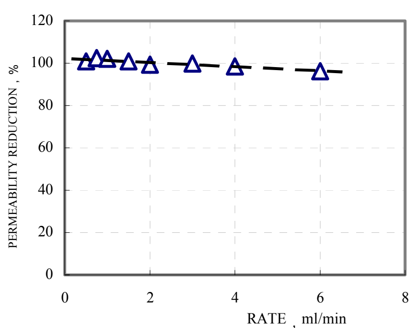

Figure 1. Relationship between permeability reduction and rate for fired outcrop core.

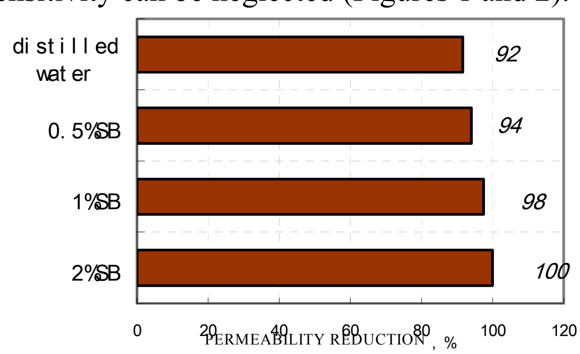

Figure 2. Effect of decreasing concentration of brine on permeability of fired outcrop core.

Then permeability to brine was measured at a variety of temperatures. The results show that the permeability did not change considerably at temperatures up to 70°C. In other words, there was quite a small thermal petrophysical influence on absolute permeability to water for quartz sandstone in our experiments under the used procedures and conditions. The brine permeability increased less than 5% with heating, which is within the experimental error for usual flow tests. It is evident that thermal petrophysics rarely affect brine permeability for consolidated non-clay sandstones at temperatures up to 70°C. When the temperature was higher than 70°C, thermal petrophysics may have some, but not much, effect on brine permeability.

Result for Sandstones Containing Swelling Clays

However, this ideal porous medium does not exist in real reservoirs, even under most laboratory research conditions. Thus, several sandstones containing swelling clays were used to investigate thermal petrophysical effects. The permeabilities of these sandstones were between 5 and 80 md. The permeability damage can be between 30 and 60% due to water and rate sensitivity. Higher concentration brine was used at the critical rate in order to minimize this possible formation damage during the test.

These results also indicated a slight reduction in brine permeability with heating (Figure 3). The reduction was less than 10%. It can be concluded that absolute permeability or effective permeability to water is a decreasing function of heating; sometimes, it may be ignored due to other factors.

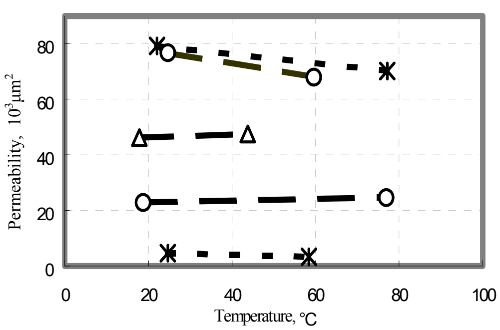

Figure 3. Relationship between effective permeability and temperature for reservoir rock.

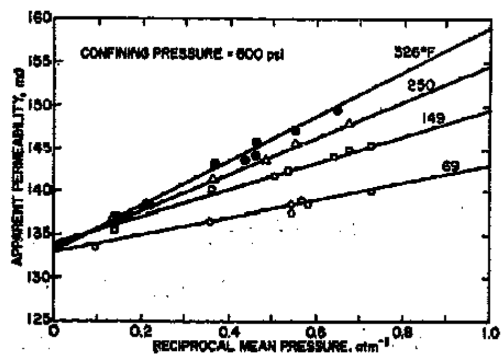

Figure 4. Relationship between gas permeability and the reciprocal of average permeability for Berea sandstone.[7]

Results for Pore Volume

While measuring gas (nitrogen) permeability for fired Berea core at five different temperatures, Casse and Ramey[7] found that the effective permeability was dependent on temperature, while the extrapolated permeability at infinite mean pressure was unchanged. We know that this extrapolated permeability represents the fluid independent absolute permeability of the rock. Therefore, it appeared that absolute permeability did not change with temperature (Figure 4).

In Casse and Ramey's work, the pore volume change with temperature was not considered. In fact, thermal expansion must result in a change in pore volume, while effective permeability may change with pore volume. The porosity-permeability relationship for reservoir rock can be represented by the Carman-Kozeny equation given as

$$k = \frac{d_p^2 \phi^3}{72\tau(1-\phi)^2} \tag{1}$$

where, d_p is the mean grain size and τ is the tortuosity of the reservoir rock. Tortuosity is related to the mean pore-channel length (L_p) of the reservoir and the sample length (L_{REV}) as[10]

$$\tau = \left(\frac{L_P}{L_{REV}} \right)^2 \tag{2}$$

When the temperature is increased from reference temperature (T_0) to temperature (T), the coefficient of volumetric expansion for the grain matrix is given by

$$\beta_{gv} = \frac{1}{V_g} \left(\frac{\partial V_g}{\partial T} \right) \tag{3}$$

where, V_g is the grain volume. Then, the grain-matrix coefficient of linear expansion is given by

$$\beta_{gl} \approx \beta_{gv}/3 \tag{4}$$

Mean grain diameter d_p at temperature T is related to the particle diameter at reference temperature T_0 according to

$$(d_p)_T = (d_p)_{T_0} \exp\left[\beta_{gl}(T - T_0)\right] \tag{5}$$

and the average length of a pore channel in a representative elemental volume is given by

$$\left(\frac{L_P}{L_{REV}} \right)_T = \left(\frac{L_P}{L_{REV}} \right)_{To} \times \exp\left[\beta_{gl}(T - To)\right] \tag{6}$$

Substitution of Eq.5 and Eq.6 into Eq.1 leads to the following expression for the dependence of permeability ratio on temperature

$$\left(\frac{k_T}{k_{T_0}} \right) = \frac{\phi_T^3}{(1-\phi_T)^2} \cdot \frac{(1-\phi_{T_0})^2}{\phi_{T_0}^3} = \left(\frac{\phi_T}{\phi_{T_0}} \right)^3 \cdot \left(\frac{1-\phi_{T_0}}{1-\phi_T} \right)^2 \tag{7}$$

Under actual reservoir conditions, the total volume of porous rock is approximately constant. The pore volume decreases with increasing temperature when the solid volume increases by thermal expansion. In addition, the thermal petrophysical effects on absolute permeability to water are dependent on the porosity change and the coefficient of thermal expansion for the grain matrix. The coefficient of thermal expansion for the grain matrix is always greater than 1; it is about 6 for quartz and 3 for carbonates. From Eq.7 both terms being multiplied are less than 1, if the pore volume decreases with heating ($\phi_{T_0} \geq \phi_T$). Therefore, $\frac{k_T}{k_{T_0}} \leq 1$ ($T_0 < T$), *i.e.* thermal expansion results in a reduction of the absolute permeability to water with heating. On the other hand, the thermal expansion of grains can be partially into the annular space around the core sample in the coreholder, because the annular space is very large compared to the pore volume. As a result, thermal expansion of the pore fluid and grain matrix is limited under this condition. The maximum volume change for quartz sandstone due to thermal expansion was measured in order to determine the thermal petrophysical effect on volume. This measured volume change was between 0.4% and 0.5 % of pore volume. It is clear that the reduction in pore volume due to thermal expansion is very small. The measured values of volume and thermal expansion for core samples used in this experiment were used in Eq.7, obtaining a reduction in absolute permeability in the range of 5% to 9%, which less than or near the experimental error.

CONCLUSIONS

1. The results from experiments and theoretical analysis show that thermal petrophysics may affect the absolute permeability to water for porous sandstone. They show that the permeability tends to decrease with increasing temperature.
2. Thermal petrophysics is relevant to the change in pore volume; the greater the change in pore volume, the greater the thermal sensitivity. The pore volume variation is very small, so that the changes in the absolute permeability to water are near the allowable experimental error under typical experimental conditions.
3. If a smooth heating process is maintained in order to avoid thermal shock, for cores of slight water and rate sensitivity, a thermal petrophysical effect on the absolute permeability to water is small and can be neglected.

REFERENCES

1. Greenberg, D.B., Cresap, R.S., and Malone, T.A., "Intrinsic Permeability of Hydrological Porous Medium: Variation with Temperature," *Water Resources Research*, (Aug.1968), **4**, No.4, 791.
2. Afinogenov, Y.A., "How the Liquid Permeability of Rocks Is Affected by Pressure and Temperature," *SNIIGIMS,* (1969), No.6, 34-42.
3. Weinbrandt, R.M., Ramey, Jr., H.J., and Casse, F.J., "The Effect of Temperature on Relative and Absolute Permeability of Sandstones," *SPEJ,* (Oct.1975), 376-384.
4. Sydansk, R.D., "Discussion of the Effect of Temperature and Confining Pressure on Single-Phase Flow in Consolidated Rocks," *JPT,* (August 1980), 1329.
5. Somerton, W.H., Mehta, M.M., and Dean, G.W., "Thermal Alteration of Sandstones," *JPT,* (May 1965), 589-593.
6. Gobran, B.D., Brigham, W.E., and Ramey, Jr., H.J., "Absolute Permeability as a Function of Confining Pressure, Pore Pressure, and Temperature," *SPEFE*, (March 1987), 77.
7. Casse, F.J. and Ramey, Jr., H.J., "The Effect of Temperature and Confining Pressure on Single-Phase Flow in Consolidated Rocks," *JPT,* (August 1979), 1051.
8. Gupta, A. and Civan, F., "Temperature Sensitivity of Formation Damage in Petroleum Reservoirs," SPE27368, (1994).
9. Sydansk, R.D., "Discussion of the Effect of Temperature and Confining Pressure on Single-Phase Flow in Consolidated Rocks," SPE9087, (1980).
10. Lake, L.W., *Enhanced Oil Recovery,* Prentice Hall, New Jersey (1989).
11. Cohen, E.S., Elzinga, Jr., E.R., and Smith, L.W., "Effects of Temperature and Fluid Saturation On Thermal Conductivity of Sands," SPE1448-G, (January 14, 1960).