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MEASURING SALT WATER PERMEABILITIES

BRIAN D. GOBRAN

ARCO OIL AND GAS COMPANY

Abstract This study investigates flow of saline solutions through sandpacks at elevated temperatures and pressures in the laboratory. The purposes of this work are two-fold. First the experimental apparatus necessary to measure permeability with salt water flow at elevated temperatures must be designed and built. Then, the effect of temperature on absolute permeability to salt water will be compared to the effect with distilled water as the flowing fluid under similar conditions.

Introduction The absolute permeability of a formation occurs as a variable in all fluid flow equations. Since permeability is measured in the laboratory, experimenters have been trying for the last *40* years to simulate reservoir conditions (or at least those conditions thought important) in the laboratory. The first steps in this direction were to subject cores to confining pressures similar to those in the reservoir. This ranged from hydrostatic (Fatt and Davis) to radial (Wyble) to triaxial at a Poisson ratio of 0.33 (Gray, et al.). The results of these studies showed that absolute permeability was a function of confining pressure while relative permeability (Fatt) was not.

The next approximation to reservoir conditions was to investigate the effect of temperature on the measured values of absolute and relative permeabilities. The initial studies (Poston, et al., Weinbrandt) found a reduction in absolute permeability and a shifting of the relative permeability curves when the temperature was increased. Further studies (Casse, Aruna) were initiated with distilled water flow through sandstones and sandpacks to better define the effect of temperature on absolute permeability. These researchers found a reduction in permeability with temperature increase when water (and only water, not mineral oil, gas or 2-octanol) flowed through sandstone (consolidated sandstone or unconsolidated sand but not limestone). This reduction was found to be reversible when this was investigated. Once these results were obtained, explanations were sought from the literature.

Chemical engineering literature was a good source for explaining the observed permeability reductions with temperature increase. During this period (the early 1970's), chemical engineers all over the world were investigating anomalous water (Derjaguin and Churaev). Anomalous water was water condensed in very fine quartz capillaries having properties significantly different (such as fifteen times the viscosity) from normal or bulk water. So, the idea of some unexplained boundary layer phenomenon between quartz and water was used to explain the observed permeability reductions with water flowing through sand.

Although later investigations found no effect of temperature on absolute permeability with distilled water flow (Gobran, Sageev), there were still nagging questions about the quartz/water interface. Perhaps the addition of salt to the water would cause some interfacial forces that would yield a reduction in permeability with temperature increase. To answer these questions and to further simulate actual reservoir conditions in the laboratory, salt water permeabilities were measured in this study.

A similar work presented at this meeting last year (Potter, et al.) and the discussion that followed will be used as a basis of comparison for these results.

Experimental Apparatus and Procedure The experimental apparatus and procedure have been fully described elsewhere (Gobran), however, a brief description is appropriate here for the discussion that follows. A schematic diagram of the apparatus is shown in Figure 1. The fluid flow system begins with a Ruska constant rate pump (with two 403 stainless steel cylinders rated to *4000* psi). The tubing, core holder, differentia1 pressure transducers and other components of the fluid flow system are made of 316 stainless steel.

The procedure for taking permeability measurements is the same as with distilled water (Gobran). At each temperature four different flow rates are used: three high (about one liter per hour) and one low (about 200 milliliters per hour). The value of permeability at each of the high flow rates is the average of the values after five and then ten incremental pore volumes. These values are then averaged to get the permeability at a given temperature. The low flow rate is maintained for only one pore volume and this value is used as a check to be sure there is no flowrate effect.

This system was designed for distilled water flow. It was used to measure the absolute permeability of sandpacks and consolidated sandstone cores as a function of temperature from 100 to 300°F, confining pressure from 2000 to 10,000 psi and pore pressure from 200 to 4000 psi. During the studies with distilled water, no effect of contamination was found on the inlet face of the porous media. Also, except for a settling or re-arrangement of grains, there was no re-duction in permeability caused exclusively by flow.

Results As stated previously, one of the goals of this study was to investigate the effect of temperature on absolute permeability of unconsolidated sandpacks with a 1% NaCl solution as the flowing fluid. The sandpacks were either 100–120 or 120-200 mesh Ottawa sand. The confining pressure and the pore pressure were 2000 and 200 psi, respectively, for all experiments.

During the distilled water experiments and the initial salt water experiment, a 15 micron filter was used in the flow line outside the air bath. During the first salt water experiment this filter plugged badly and there was a 20% reduction in permeability during the first 95 pore volumes of throughput (this is far higher than would be expected merely due to settling as will be seen later). At this point the core was at 150°F and the experiment was stopped. The 15 micron filter outside the air bath was replaced with a 2 micron filter and a second 2 micron filter was installed in the air bath immediately prior to the core holder.

The results of the second experiment are shown in Figure 2. Here permeability is graphed versus temperature. There was a loose wire to one of the air bath heating elements and the maximum attainable tempera-ture was 284°F. These results show no significant reduction in absolute permea-bility during the heating portion of the experiment. There was, however, a large loss in permeability during the cooling cycle. The experiment was stopped before the usual four flowrate measurements could be made at 100°F.

Figure 3 shows permeability graphed versus throughput for this experiment. The results of this experiment with salt water can be compared with the results for distilled water flow shown in Figures 4 and 5. Figure 4 shows permeability as a function of throughput at 100°F. This shows the reduction in permeability that can be expected merely due to flow. Clearly, the reduction in permeability (20% in 95 pore volumes) in the first salt water experiment was excessive as was the reduction during the cooling cycle of the second experiment.

Figure 5 shows permeability as a function of temperature for distilled water flow. This compares very well with the heating cycle in the second salt water experiment with both showing no temperature dependence. Examina-tion of the core and the two filters at the conclusion of the second salt water experi-ment showed that the filters were plugged with a brown particulate and that this same material coated the inlet face of the core.

The results of this experiment indicated that permeability was not dependent on temperature with salt water as the flowing fluid. It also showed that both the flow lines inside the air bath and the pump itself were corroding with the salt water flow. The progress of the corrosion-produced particulate cold be delayed by use of filters but there would still be permanent damage to the pump and flow lines.

At this point a solution (instead of a delaying approach) was sought. After phone calls to numerous major oil company research laboratories, it was determined that 100 parts per million of sodium sulfite (Na_2SO_3) would remove the dissolved oxygen from the salt water. Alternate materials such as titanium and mnel were considered as replacements for the 316 stainless steel tubing, but, due to time and cost limitations, were not used.

A system of check valves and cylinders which allowed flow of mercury in the pump and water in the system was implemented. This design is shown schematically in Figure 6. After several abortive experiments in which mercury leaked into the flow system, this design seemed to work successfully.

During the final experiment there was a continued decrease in permeability with throughput (although not of the magnitude that would be caused by mercury in the core). The low flowrate measurements yielded permeability values significantly lower than the high rate values. This experiment was stopped while heating to 250°F when the differential pressure across the core kept increasing. This is indicative of flow of the confining oil into the core.

Discussion In his work, Mr. Potter found corrosion of his system (316 and 304 stainless steel) with distilled water flow at elevated temperatures. This was due to oxidation which produced Fe^{+3} ions. When the system was changed to titanium, no more corrosion problems were encountered. During the discussion following his presentation, it was suggested that the 304 stainless steel components caused the problems and that the 316 stainless would have no problems. This has been borne out by two recent studies (Gobran, Sageev). However, systems constructed of 316 stainless steel cannot be used with salt water flow at elevated temperatures. Baaed on the results of this work and other studies on stainless steel (Gordon), stainless steel and salt water are not compatible above 170°F. Therefore materials such as inconel, titanium or mnel are needed for such systems.

Conclusions Two conclusions can be made from this study: 1) Absolute permeability of sandpacks to salt water is not a function of temperature. 2) Materials other than 316 stainless steel must be used for salt water systems at elevated temperatures.

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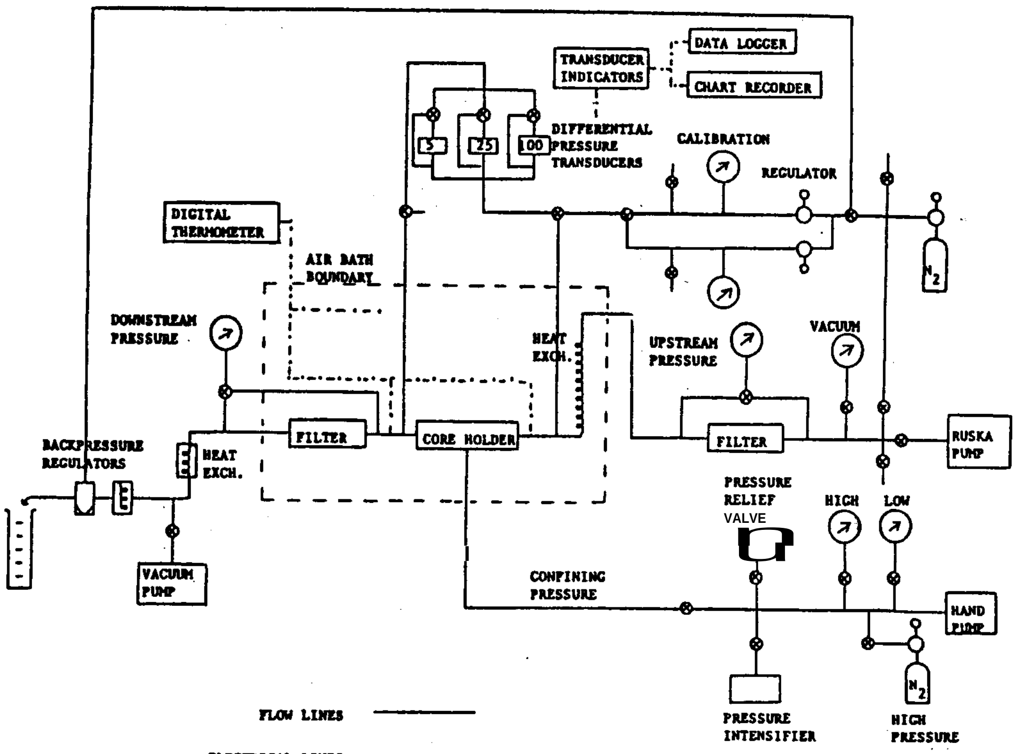

Figure 1. Schematic diagram of the experimental apparatus.

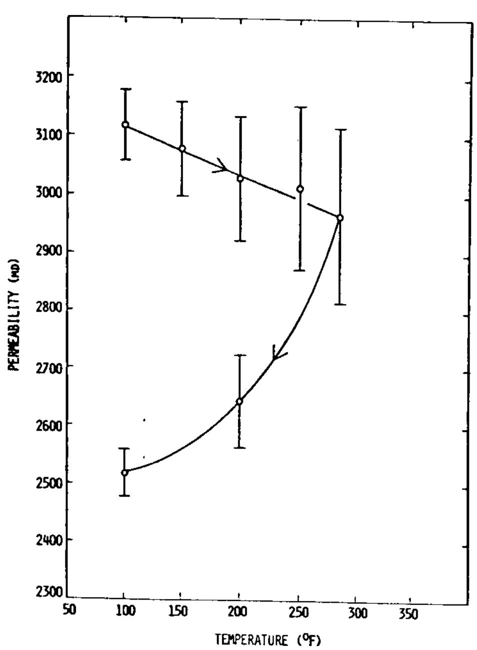

Figure 2. Salt water permeability versus temperature.

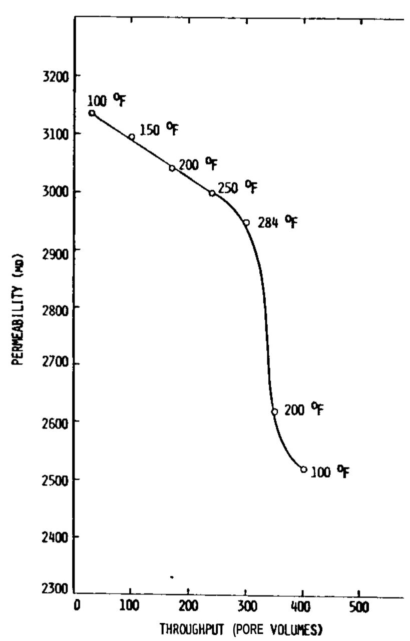

Figure 3. Salt water permeability versus throughput.

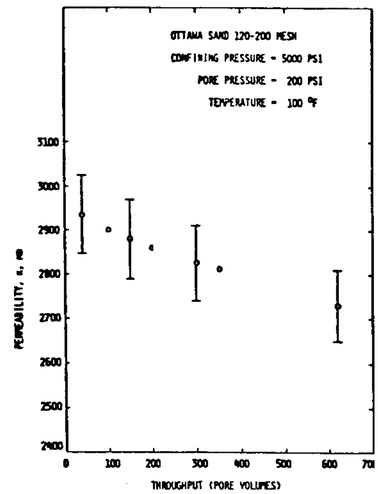

Figure 4. Distilled water permeability versus throughput.

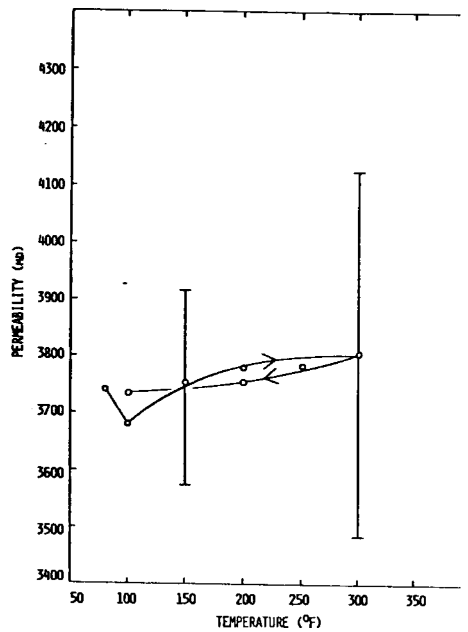

Figure 5. Distilled water permeability versus temperature.

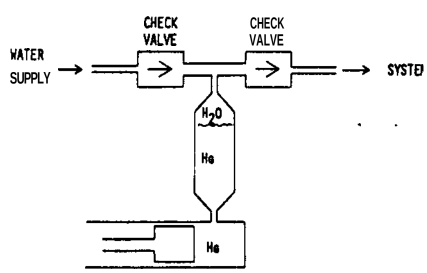

Figure 6. Mercury flow modifications.