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An Experimental Investigation of Magnetized Water Effect on Formation Damage

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ABSTRACT

In oil industries, water injection into oil reservoirs for pressure maintenance, oil displacement, and oil recovery is a common technique. Formation damage during water injection is a major problem in this process. Formation damage from the incompatibility of formation water (FW) and injection water (IW) causes a reduction in the permeability around the injection wells. Therefore, it is necessary that the formation damage be minimized using specific techniques such as the injection of scale inhibitors and water compatible with formation water. It has been proven that moving water through relatively weak magnetic field changes water properties. These changes involve density, electrical conductivity, salts dissolving ability, sedimentation rate of solid particles etc. This study was conducted to investigate the effect of magnetized water injection on the decline in rock permeability. Therefore, a magnetic field device was designed and combined with a formation damage setup. The results indicate that, in the presence of magnetic field, water injection causes less damage to rock, and the permeability reduction in this case is lower than when non-magnetized water is injected. In addition, the results show that a higher magnetic field flux reduces the permeability damage.

Keywords: Formation Damage, Water Injection, Magnetized Water, Scale Precipitation

INTRODUCTION

Experience in oil industries has indicated that many oil wells have flow limitation because of scale deposition in producing formation and equipment. Formation damage induced by oilfield scale is one of the difficult phenomena that occurs during water injection project. Mixing incompatible waters takes place in the reservoir during injection [1-7]. Formation damage due to oilfield scale is the result of precipitation and the accumulation of scale around the well bore [4,7]. This may influence reservoir performance, well bore performance, and deliverability of the reservoir system [8]. Because of the extensive use of water injection for oil displacement and pressure maintenance in oilfields, many reservoirs experience the problem of scale deposition when injection water begins to breakthrough.

In most cases, the scales formed in wells are caused by the formation of sulfate and the carbonate scales of calcium and strontium. Because of their proportionate hardness and low solubility, there are

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restricted processes available for their removal and preventive measures such as the squeeze inhibitor treatment which must be taken. Therefore, It is important to gain a proper understanding of the kinetics of scale formation and its detrimental effects on formation damage in both inhibited and uninhibited conditions [9].

Magnetic treatment methods have been studied for the past few decades as a new alternative for preventing scale, and the magnetic treatment technique is an alternative to the use of scale inhibition chemicals [10-12]. Magnetized water is water that passes through a magnetic field. Magnetizing water is an inexpensive and environmentally friendly method. Nevertheless, the effect of magnetic field on water is a controversial issue. Taking water from a relatively weak magnetized field causes many changes in water properties such as viscosity, pH, ability to dissolve salts, the rate of deposition of solid particles, and so on [12-18].

Many researchers have reported changes in the physical properties of water passed through the magnetic field. Joshi and Kamat [19] reported that the pH of distilled water changed up to 0.4 pH units. Also, Parsons et al. [20] recorded a reduction of 0.5 pH units after passing water through a magnetic field. Iwasaka and Ueno [21] found out that the size of the water clusters altered when they were exposed to a magnetic field. The dissolution rate into water of oxygen is significantly accelerated by the presence of a magnetic field, and the water vaporization rate, an essential process for all biological processes, is significantly affected by the application of a static magnetic field [22]. Chou and Lee [23] studied the effects of the amount of magnetic treatment by a permanent magnet on surface tension and showed that as the number of treatments increased, the surface tension of the sample decreased. Otsuka et al. [16] concluded that no changes in properties of pure water, distilled from ultra-pure water in a vacuum, were observed after magnetic treatment. However, when the same magnetic treatment was carried out after that, the distilled water was exposed to O_2; moreover, properties such as surface tension were changed. Sueda et al. [17] examined the maximum mass and diameter of a dripped water droplet on the tip of a glass capillary, and found out that both of which were affected strongly by magnetic fields.

Many researchers have studied the effects of magnetic field on reducing scales. Properly installed and configured magnetic treatment devices (MTD’s) have had many successes in reducing the amount of scale build-up in pipes. In an experiment performed by Smith [24], permanent magnets reduced the formation of scale in six out of six hot-water storage tanks with an average of 34%. The maximum reduction was 70% and the minimum reduction was 17%. Brower [14] explains that magnetic systems treat water by passing it through a magnetic field. The dipolar movements of the molecules of dissolved solids and water molecules are affected in such a way that at the instant of crystal formation, the crystal form is divided into thin layers, and the ions align according to a single magnetic axis. The magnetic field then influences the production of a much greater number of nuclei. Hence, the solids precipitate as much finer crystals, which tend to remain separated because of the excess similar charge. Lipusa and Dobersekb [12] attained successful results with the scale on a heating copper-pipe spiral being 2.5 times thinner due to magnetized water treatment compared with untreated water. Busch [25] attained a 22%

reduction in scale, using artificially prepared hard water. Parsons et al. recorded a 48% reduction in scale in his experiment. Tai et al. [26] discovered in their research that the crystal growth rates of calcite were suppressed completely in the presence of the magnetic field at a low pH and in a supersaturating condition. By contrast, the growth rate seemed to increase at a high pH and relative supersaturating. According to Alimi et al. [10], the treatment-pH and the water flow rate of the MTD have an important impact on the nucleation type and on the amount of calcium carbonate.

The purpose of this study was to investigate whether or not magnetic field can affect permeability damage because of scale precipitation in a sandstone rock. A magnetic treatment device was designed using electromagnetic concepts and coupled with a formation damage setup. Finally, two different magnetic field fluxes were used for producing magnetized water, and the decline in rock permeability was examined by injecting magnetized water and non-magnetized water.

EXPERIMENTAL PROCEDURES

Magnetic Device

Magnetic treatment methods have been studied and have been available for the past few decades as an alternative to chemical methods to prevent and control scale formation. Magnetic treatment devices can be based on the electromagnets or permanent magnets. Although electromagnets can produce the magnetic fields of great intensity, many magnetic devices can be used to prevent scale formation. Magnetic devices can be designed to meet the specific requirements such as field strengths, field directions, and uniformity. Depending on the design lines of the magnetic field, it can be parallel or perpendicular to the flow direction [27]. Several authors claim that the important factors which promote magneto–hydrodynamic forces are the conductivity of solution, linear velocity of fluid, and flux density of magnetic field [10, 11, 28-30]. It was found out that even a weak magnetic field (B = 1000 G) influenced aragonite/calcite ratio in precipitated $CaCO_3$ [31]. Gabrielli et al. used a series of pairs of permanent magnets with a uniform magnetic field of 1600 G for investigating the scale reduction of magnetic water treatment [11]. Tombacz et al. have tested both flowing and static systems, and concluded that only in a flowing system, the magnetic effect is observed. The magnetic flux density ranges from 1000 G to 8000 G among those magnetic treatment experiments [32]. Kobe et al. took 5000 G as the magnetic flux density in their experiments to obtain successful treatment results [29].

Therefore, in this study for making magnetized water, a magnetic device was designed by using electromagnetism concepts. The device, which is designed to create a 4500 G magnetic field, consists of an inductor with an air gap and a coil. The magnetic field is created in the inductor and the air gap by applying an electric current to the coil.

Figure 1 shows a simple magnetic circuit with an air gap having in the middle of a length cut (lg) a leg. The winding provides Ni ampere-turn. The magnetic flux generated in the air gap is equal to the magnetomotive force Ni divided by the sum of the reluctances of the core and of the air gap. Supposing that the leakage flux is negligible, by applying the Ampère’s circuital law, one may obtain[33]:

$$Ni = H_g l_g + H_c l_c \tag{1}$$

Hc and *Hg* can be written in terms of the magnetic flux as reads:

$$H_c = \frac{B_c}{\mu_c} = \frac{\phi_c}{\mu_c A_c} \tag{2}$$

$$H_g = \frac{B_g}{\mu_g} = \frac{\phi_g}{\mu_0 A_g} \tag{3}$$

According to Gauss's law of magnetism, the net outward flux of *B* through any closed surface must be equal to zero. Hence, the flux of *B* must be the same over any cross section of the magnetic circuit, which can be written as follows:

$$B_g A_g = B_c A_c \tag{4}$$

By combining the above equations, the magnetic flux is given by:

$$\phi = B_g A_g = \frac{Ni}{\frac{l_c}{\mu_c A} + \frac{l_g}{\mu_g A}} \tag{5}$$

If the reluctance of core and air gap is written as $R_c = \frac{l_c}{\mu_c A}$ and $R_g = \frac{l_g}{\mu_g A}$ respectively, Equation 5 can be written as follows:

$$Ni = (R_c + R_g)\phi \tag{6}$$

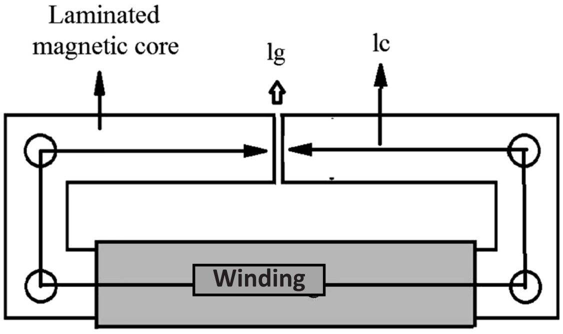

Figure 1: A simple magnetic circuit with an air gap having a length of l_g.

According to the above equations, the magnetic circuit with an air gap can be represented in a series electric circuit shown in Figure 2. The optimum number of winding turns and thickness of magnetic device to produce a magnetic flux of 4500 Gauss in the air gap can be determined by doing a reverse calculation. UI laminated magnetic cores (Figure 3) have been used for designing magnetic device. The calculations were performed for different sizes of UI laminated magnetic cores, and the optimum of winding turns and magnetic device thickness have been determined. Table 1 shows the calculations of different UI laminated magnetic cores. At last, UI-150 magnetic cores were chosen for magnetic device manufacturing, and for them, the calculated N and thickness are 440 turns and 11 cm respectively. This manufactured device is capable of creating a magnetic field with a peak flux density of 4500 Gauss. The air gap in the device is small (5 mm), and the magnetic field influenced the fluid properly. The magnetic field direction is perpendicular to the flow direction. The designed magnetic device is shown in Figure 4.

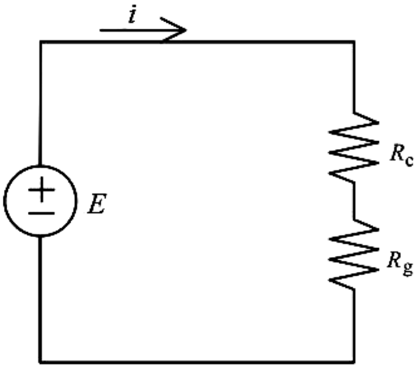

Figure 2: Series electric circuit.

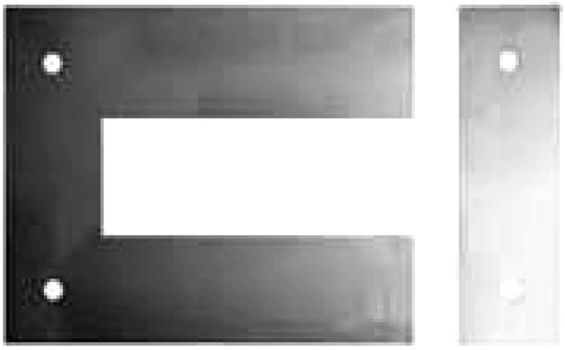

Figure 3: UI laminated magnetic cores.

Figure 4: The magnetic device.

Experimental Section Setup

Here, water injection experiments were conducted by using a core flood system of the FDS350 apparatus [34]. For investigating the effect of magnetized water on rock permeability behavior, the designed magnetic treatment device was coupled with FDS350 apparatus. Figure 5 shows the magnetic treatment device coupled with FDS350.

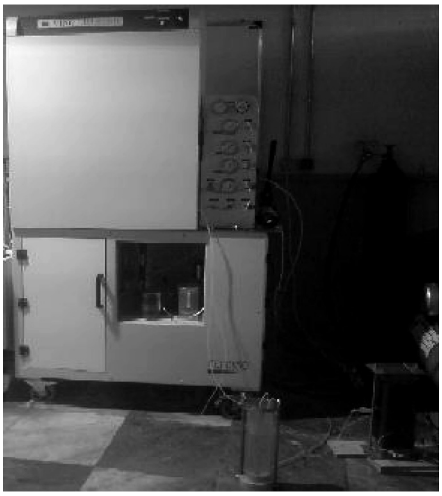

Figure 5: Magnetic device coupled with FDS350.

Materials

In all of the experiments, three sandstone cores with an average porosity of 16% and an absolute permeability of 3.11 mD were used. The properties of these cores are reported in Table 2. All the cores were washed with toluene and methanol, separately in Soxhlet apparatus, and they were then dried using an oven at 100 °C for four hours before the test. The composition of formation and injected water used for the experiments are listed in Table 3. The formation water was used for the initial saturation of cores and permeability measurements, while the injection water was used for water injection processes in the experiments.

Table1: Calculations of different UI laminated magnetic cores.

Magnetic core	UI-75	UI-85.5	UI-96	UI-108	UI-125	UI-150	UI-180	UI-210	UI-240	UI-360
l_c(m)	0.445	0.508	0.571	0.643	0.746	0.895	1.075	1.255	1.435	2.155
l_g(m)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Ni_{min}	649.2	651	652.8	654.8	657.7	661.9	667	672.1	677.2	697.6
Ni_{max}	1623	1627	1632	1637	1644	1655	1668	1680	1693	1744
x(cm)	22	19.3	17.19	15.28	13.25	11	9.167	7.857	6.875	4.583
N	440	440	440	440	440	440	440	440	440	440
i_{min}	1.465	1.47	1.474	1.478	1.485	1.494	1.506	1.517	1.529	1.575
i_{max}	3.664	3.674	3.684	3.695	3.712	3.736	3.764	3.793	3.822	3.937

Table 2: Core properties.

Core	Length (cm)	Diameter (cm)	Porosity (%)	Absolute Permeability (md)
A	6.39	3.8	12.59	3.1028
B	6.48	3.8	11.62	3.1465
C	6.83	3.8	11.85	3.0484

Table 3: Formation and Injection Water Compositions.

Ion	Formation Water (ppm)	Injection Water (ppm)
Ca^{+2}	6998.41	480.99
K^{+}	1966.68	468.99
Na^{+}	24996.86	12229.97
Mg^{+2}	758.17	1773.99
Cl^{-}	54600.39	23009.02
HCO^{-3}	421.27	0.122
SO_4^{-2}	108.24	3169.24
TDS	82893.28	40872.69
pH	6.7	7.2
Viscosity at 50°C (cP)	1.24	1.18

At first, a dry core was saturated with formation water, and it was then loaded into the core holder of the FDS350 apparatus. The confining pressure was set at 500 psi above the pore pressure during the test. For initial permeability measurement, formation water was injected to the cores at three rates, namely 0.2, 0.3, and 0.4 mL/min. Apparatus records automatically temperature, confining and the pore pressure, flow rates, and differential pressures. Then, it calculates the permeability using the Darcy's law. The pressure differences in the initial permeability measurements at different rates are presented in Figure 6. After permeability measurements, formation water was again injected into the core at the rate of 0.3 mL/min to stabilize the differential pressure proportional to this rate. Then, non-magnetized or magnetized water injection process was started at the same rate (0.3 mL/min), and differential pressure and temperature data were collected by FDS350 program during the test. In this step, damage permeability is calculated by Darcy's law.

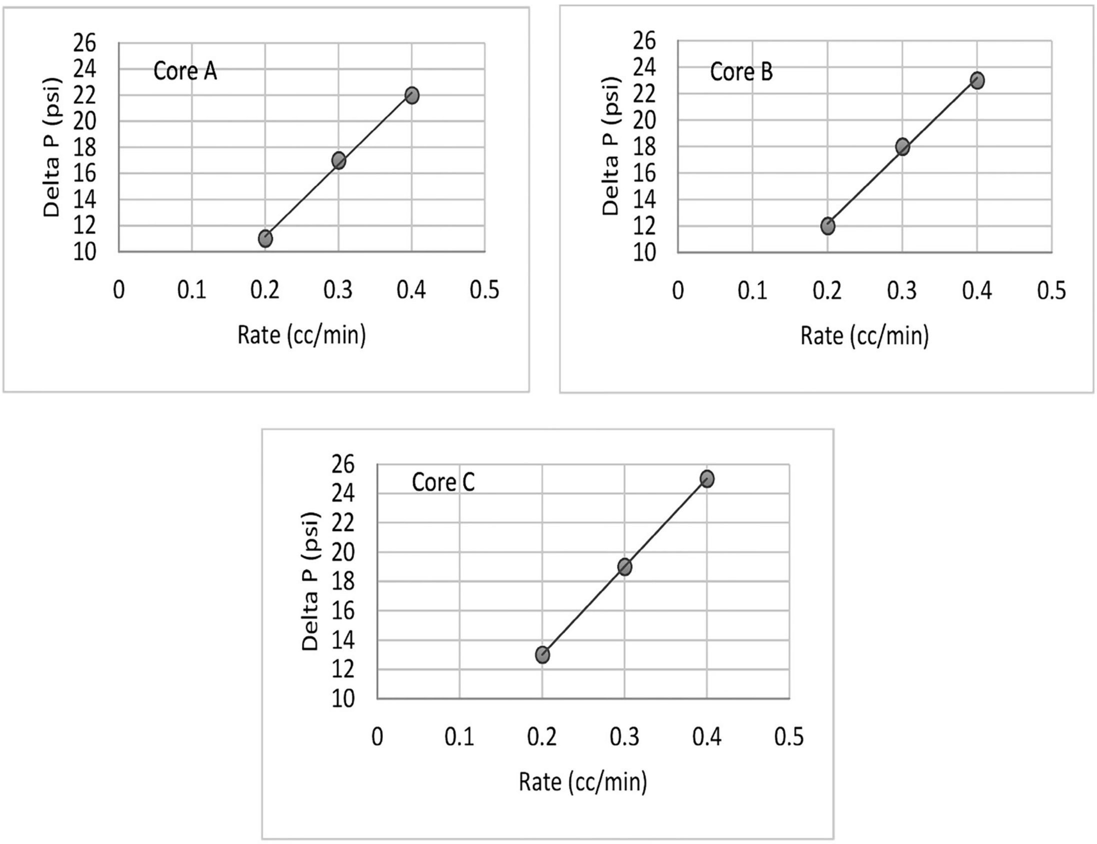

Figure 6: Differential pressure of cores at initial permeability measurement.

For producing magnetized water, a pump of FDS350 was coupled with the magnetic treatment device. Injection water was circulated through the magnetic treatment device by using the pump about one hour for each test.

In this study, three main experiments were considered, as listed below:

1. Injecting non magnetized injection water;
2. Injecting magnetized formation water (magnetic field =3000 G);
3. And injecting magnetized injection water (magnetic field = 4500 G).

The experiments were performed at a temperature of 50 °C, and the confining pressure during each test was 500 psi above inlet pressure (i.e. the effective stress is 500 psi).

RESULTS AND DISCUSSION

The main purpose of this part of investigation is to study rock permeability decline caused by scale deposition during magnetized water injection. As described before, three experiments conducted include non-magnetized water and two different magnetized water injections. All the experiments were conducted by using sandstone cores, which were initially saturated with formation water.

Figures 7-9 present the differential pressure variations versus injection time. These figures were plotted just after injection water was started to be injected at the flow rate of 0.3 mL/min into the core samples. The differential pressure was stabilized to a constant pressure before injecting injection water by the injection of formation water at a rate of 0.3 mL/min.

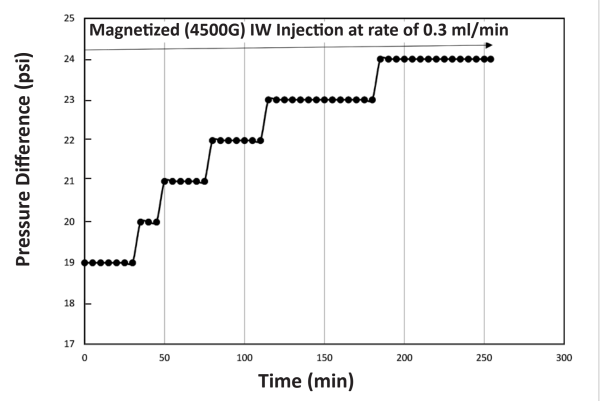

Figure 7: Pressure difference of non-magnetized water injection.

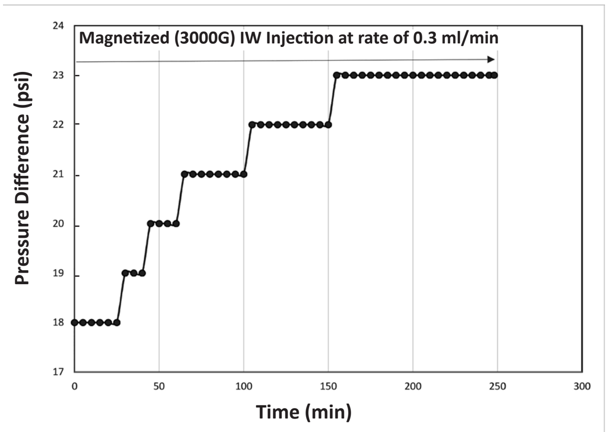

Figure 8: Pressure difference of magnetized water (magnetic field=3000 G) injection.

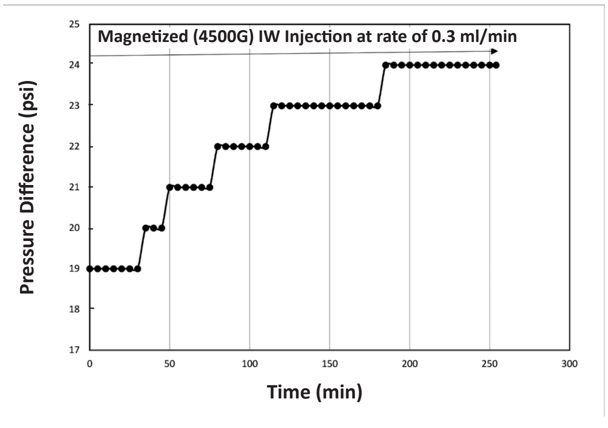

Figure 9: Pressure difference of magnetized water (magnetic field=4500 G) injection.

As shown in Figure 7, at the beginning of non-magnetized water injection into the core samples, the differential pressure was 17 psi; as the injection was consumed, the differential pressure across the core started to build up due to formation water and injection water interaction. This pressure build-up was because of the scale precipitation in the core. As injection process continued, the formation water tends to exist from the core. The interaction of formation water and non-magnetized water in the core was also reduced. Therefore, at the end of the process, the differential pressure was slowly increased. Magnetized water injection also caused damage due to scale precipitation. As shown in Figures 7 and 9, the differential pressure of injection water which was treated with 3000 and 4500 G magnetic field was increased during the process. The effect of magnetized water injection on formation damage cannot be explained by pressure drop curves properly; therefore, for its explanation, permeability damage curves are used in the next part.

The Effect of Magnetized Water Injection on Formation Damage

To investigate the effect of injection water injection on permeability reduction, the variation of permeability ratio was plotted as a function of time. Figure 10 shows the permeability declining trend versus the injection time of the 3000 G magnetized against non-magnetized water injection. At the beginning of flowing period, because of incompatibility of formation water and injection water, a sharp decline in permeability value was observed. The permeability decline rate was decreased during time. The reason for this behavior may be due to the fact that rate of plugging increases as the interaction of more injection water with formation water. This phenomenon was observed in both tests; however, in the presence of a magnetic field, the permeability decline rate was less than the other one. The growth rate of scale crystals is suppressed completely in the presence of a magnetic field. In addition, when water is treated with magnetic fields, the available dipole molecules affect crystals, and crystal growth is limited. When scales cannot grow enough, they may not flocculate and can pass the pore throats, which results in reducing formation damage.

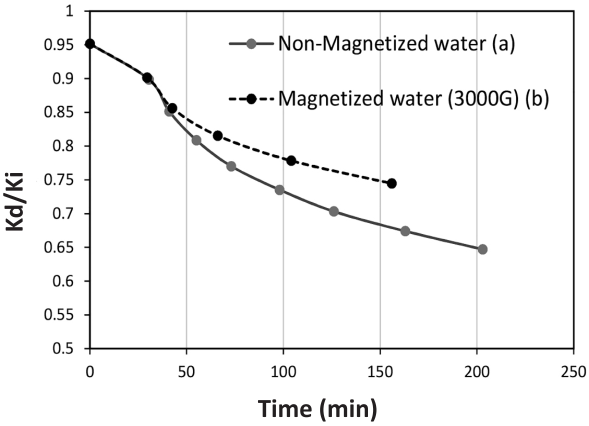

Figure 10: Effect of 3000 Guess magnetized water on formation damage.

The Effect of Magnetic Field Strengths

Herein, the magnetic field flux was increased from 3000 G to 4500 G, while the other conditions were kept constant to eliminate the effect of other parameters. The permeability decline trend was similar to the other tests as shown in Figure 11. Curve “a” in Figure 11 illustrates the permeability decline for 4500 G magnetized water. A decrease in permeability was also observed in this case, which is because of the scale precipitation in core samples due to the incompatibility of formation water and injection water, but this reduction is less than other cases. This result shows that by increasing magnetic field strength, the permeability damage due to scale precipitation is preferentially decreased. The effect of magnetic field strength was obvious in these experiments, and by injecting magnetized injection water to a core, which was saturated with formation water, the permeability improvement was about 10%. As discussed in literature, magnetic field has an effect on the scale precipitation, and numerous mechanisms have been investigated by researchers in this context. For example, Chibowski et al. or Barrett and Parsons have observed that a magnetic treatment applied to hard water decreased the quantity of scale deposited in the well [31, 35]. The principle of the phenomenon is still not well understood, and various contradictory hypotheses have been proposed. Two different approaches, namely magnetohydrodynamic (MHD) phenomena or hydration effects, were reported by Knez and Pohar [36]. MHD phenomena depend on the flow of the magnetized treated water. Busch et al. have assumed that the Lorenz forces $\vec{F}=q.\vec{v}\times\vec{B}$ exerted on charged species induce local convection movements in the liquid which could contribute to accelerating associations among ions [25]. MHD phenomena could also concern the electrical double layer near the charged surface of particles. This interpretation seems receivable for many experimental results of the literature where highly supersaturated waters were treated by a magnetic field. The aggregation of the colloidal particles under the influence of electrostatic phenomena would contribute to the acceleration of the crystal growth and the precipitation process [35].

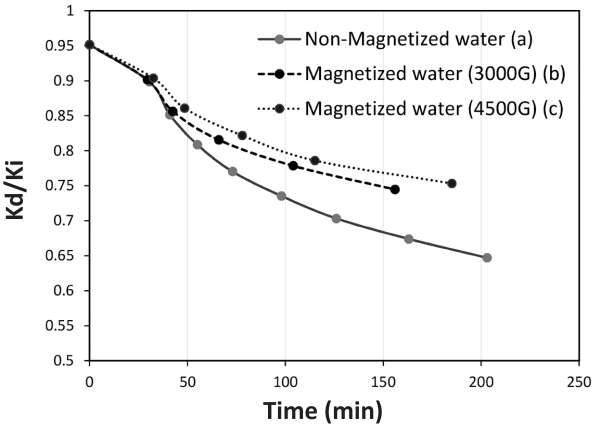

Figure 11: Effect of increasing the magnetic field fluxon formation damage.

There are many researches on the effect of magnetic field on water and scale precipitation, and some theories have been considered for interpreting this phenomenon as discussed. Therefore, the only goal of the researcher was to distribute and investigate this phenomenon in porous media. The results of the experiments confirm the positive effect of magnetized water injection on the permeability improvement when incompatible waters are contacted to each other. However, such research needs more investigation to align this phenomenon with considered theories.

CONCLUSIONS

A magnetic treatment device was used for the laboratory determination of the effect of magnetized water injection on formation damage. The designed magnetic treatment device was easily coupled with the formation damage setup. This device can be used to treat water with different magnetic field fluxes up to 4500 G. Laboratory core flooding experiments were conducted in which two different magnetized water (treated with 3000 and 4500 G magnetic field flux) and non-magnetized water were injected into sandstone core samples. The experiment results confirm that:

- The permeability decline trend of magnetized water injection was similar to that of non-magnetized water injection.
- The permeability reduction of core samples was lower in the presence of a magnetic field.
- It was observed that the injected water, which was treated at a higher magnetic field flux, produced a less decline in permeability, but it was not so significant.
- Increasing magnetic field flux from 3000 G to 4500 G improved permeability by about 2%, while this improvement for 3000 G magnetized water was about 10%.

NOMENCLATURES

μ : Permeability of magnet (H/m)
$\mu_0 = 4\pi \times 10^{-7}$: Permeability of free space (H/m)
A : Cross sectional area of the core (m^2)
B : Magnetic flux density (Gauss)
c : Subscript to the core
FW : Formation Water
g : Subscript to the air gap
H : Magnetic field strength (Ampere/m)
i : Eclectic current (Ampere)
IW : Injection water
Kd/ Ki : Formation damage (damaged permeability to Initial permeability)
l : Length (m)
ϕ : Magnetic flux (Wb)
N : Number of turns in winding
R : Reluctance (ohm)
x : Device thickness (cm)

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