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Research Article

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Effect of Aluminum and Zinc Nanoparticles on Improving Wettability Conditions in Situ Oil Recovery in Carbonate and Sandstone Reservoirs

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Abstract

The petroleum is a major source of energy of this era. With daily increase in energy demand, new methodologies are proposed to increase recovery factors in petroleum reservoirs. With increasing cumulative production and pressure drop, the wettability of reservoirs are changed to be oil-wet. Accordingly, one way to increase recovery factor from the reservoirs is to change the wettability of the reservoir rock from oil-wet to water-wet using nanoparticles. In this paper the change in relative permeability due to injection of two Nanoparticles, Zinc and Aluminum, is investigated. Two cases of vertical and horizontal wells are considered and the recovery factors are determined and compared. The tests are performed for a five spot injection-production pattern which is designed for simulation in the Eclipse software. The results indicate that of the injection of the Zinc Nanoparticle in the reservoir will lead to increase in recovery factor in a shorter period of time in comparison with the Aluminum Nanoparticle.

Keywords: Relative Permeability, Nanoparticles, Enhanced Oil Recovery (EOR), Wettability, Carbonate and Sandstone Reservoirs

Introduction

Oil and gas are still considered as the major source of fuel consumption required for the human societies. Considering the limitations of world oil and gas resources and the limited ability to explore, produce and exploit hydrocarbon resources, there is a need to develop new technologies to enhance recovery from petroleum reservoirs. Meanwhile, nanotechnology has the potential to make dramatic changes in recovery factors (RF) of oil and gas fields. In recent years, this subject has been an active area of research and laboratory experiments are a major part of these researches. Laboratory research is coming right next to the theoretical research when a nanoparticle injection plan is going to be conducted in a reservoir.

A major drawback to the laboratory researches that have studied the change in wettability is its infeasibility in the reservoir scale. Surfactants have been used as the main materials for changing wettability in petroleum reservoirs, however, the nanoparticles are received more attentions in recent years. Few of such researches are discussed in the followings.

Menezes et al., have investigated the effects of surfactant on the quartz surface [1].

Skalli et al., have examined the effects of surfactants on wettability of the cores in the presence of oil-based mud. Their study has shown that surfactants change the wettability of the reservoir rock to water-wet [2].

Golabi et al., have applied three types of surfactants, including Nano-surfactants on an Iranian Asmari reservoir, to change the wettability of the reservoir rock. They found out that the performance of each of these surfactants depends on the temperature and specific conditions of the reservoir [3].

Stanely and Firoozabadi, have investigated the effect of clay and several types of surfactants on the rock wettability and observed that non-ionic polymer surfactants are effective in altering sandstones wettability. [4]

Rai Khyiti et al., have provided dimensionless mathematical equations by performing laboratory experiments. The uses of such equations are not solely limited to injection of surfactants and they can be applied to any chemical substances [5].

Qiao et al., have presented a model for wettability change by injecting chemical substances in carbonate reservoirs. Based on their findings, they have categorized the parameters effective of changing wettability under two groups: those who control wettability and those who control the rate of change in wettability. For this latter, in addition to salinity, the amount of acidity should also be taken into account [6].

Golabi et al., have investigated the effect on pH on the alteration of the wettability carbonate reservoirs. Mohammadi et al., have used different surfactants to change the reservoir rock wettability. They found that effective performance of the surfactants is guaranteed under a specific limit for the salinity [3]. Mohammadi et al., have studied the role of aluminum nanoparticle in changing the wettability of a carbonate reservoir in laboratory and found that the absorption of the nanoparticle by the calcite surfactant changes the wettability of the reservoir [7,8].

Esfandyari Bayat et al., have carried out a research on three nanoparticles, including aluminum. Based on their studies, aluminum was the best nanoparticle among others to change the wettability of the reservoir for lowering the petroleum viscosity and its faster penetration through the reservoir [9].

Amirpour et al., have investigated the change in the amount of oil-in-place under Nano-surfactant injection through carbonate and sandstone reservoirs in laboratory scale and found that the use of this particle in carbonate reservoirs is more effective [10].

The changes in the reservoir from oil-wet to partially water-wet or more strongly water-wet by surfactant flooding is an increasingly effective method and many researchers have worked on this area. One of the greatest challenges in injecting surfactants to petroleum reservoirs is the absorption of the surfactants to the surface of the rock. Ahmadi and Shadizadeh have shown through a study that adding silica nanoparticles can increase the absorption [10,11].

Recent research has shown that nanoparticles have a strong effect on heat transfer, wettability, gel structure, formation conditions, and relative permeability.

The necessity of using nanoparticles in EOR has been an active area of research in recent years [12, 13].

Nanoparticles are classified based on surfacial wettability into three types of hydrophilic, hydrophobic, and neutral. The hydrophilic nanoparticles has the ability to change the wettability of a reservoir rock from oil-wet to water-wet, or increase the state of water-wetness of a reservoir rock. The hydrophobic nanoparticles change the wettability of a reservoir rock from water-wet to oil-wet, or increase the state of oil-wetness of a reservoir rock. Nanoparticles can reduce the water-wetness or oil-wetness of a reservoir to a middle estate. Any type of such nanoparticles can be used based on the reservoir condition to change the wettability of the reservoir rock and enhance the recovery factor.

Nowadays, in the upstream oil industries, optimal management and production of hydrocarbon reservoirs are not possible without anticipating their behavior. Fortunately, with the advances in computer sciences, powerful software programs have been developed to simulate the performance of the reservoirs and to choose the best production scenario. One of these powerful software programs is the Eclipse simulator. This simulator is widely used by various oil companies, including the National Iranian Oil Company, due to its high flexibility and vast facilities.

In this research, following the same path of other researchers, the Brooks-Corey equations have been used to model the relative permeability for two cases of zinc and aluminum nanoparticle injections. The wettability is a function of relative permeability and the relative permeability itself is changing by nanoparticle injection. The relative permeability curves which are modeled by the Brooks-Corey equations are then used into the Eclipse simulation software and the recovery factor curves are obtained. The cases of carbonate and sandstone reservoirs for vertical and horizontal wells are studied. Observing the changes in the recovery factor for all studied cases indicate the considerable impact of zinc and aluminum nanoparticle injection on enhancing the recovery factor.

Methodology

Different methods and models have been presented by various researchers in order to measure and model the relative permeability. One such a method is the Brooks-Corey equations which model the change in relative permeability of the reservoir fluids by fitting equations to measured data in the laboratory. Such modeled permeability curves are used as input to Eclipse software to obtain the production curves and recovery factors.

Brooks-Corey Equations for Carbonate Reservoirs by Injecting Al_2O_3 and ZnO Nanoparticles

In order to overcome the limitations in the Corey models, Brooks and Corey [14], have proposed new modified equations as the followings:

P_e: Initial capillary pressure
λ: Pore size distribution index

$$K_{ro} = K_{ro}(S_{wi}) = (1 - S_w{}^*)^2[1 - (S_w{}^*)^{\frac{2}{\lambda}+1}] \qquad (1)$$

Applying the Brooks-Corey equations to the laboratory measured data will result in an equation tailored for that specific reservoir. For the reservoir under stud the following relation has been derived:

$$S_w{}^* = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{or}}$$

By replacing the parameters of table 1 into equation 1, the equations for different modes of carbonate and sandstone reservoirs are obtained both for the case of aluminum and zinc nanoparticles injection and without injecting the nanoparticles. According to Figures 1 and 2, the fit to the laboratory data is shown to be quite compatible.

Table 1: Coefficients obtained for the Brook-Corey equations

	Carbonate	Al_2O_3 Injected in carbonate	Zno Injected in Carbonate	Sandstone	Al_2O_3 Injected in sandstone	Zno Injected in Sandstone
S_{wi}	0.01	0.01	0.06	0.01	0.01	0.1
S_{or}	0.4	0.24	0.3	0.2	0.02	0.02
K_{rwi}	1.068465858	1.063179178	1.0073554559	0.614239703	0.573394446	055677379
K_{roi}	0.956598689	0.91087013	1.013411115	1.248417906	0.9891140271	1.114751384

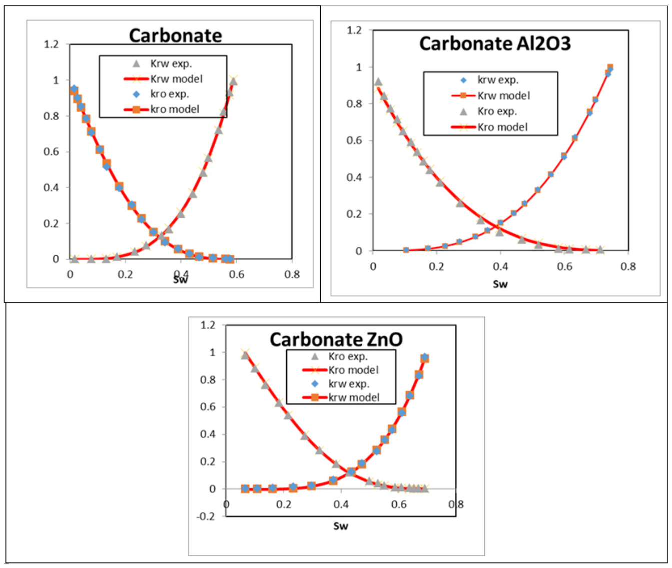

Figure 1: Results obtained from Brooks-Corey equations for carbonate reservoir

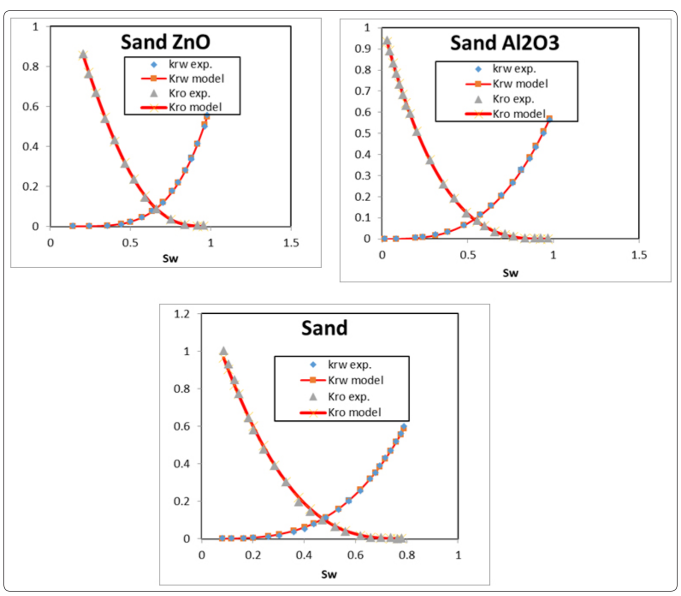

Figure 2: Results obtained from Brooks-Corey equations for sandstone reservoir

Results

The results and data used in the research by Tajmiri et al., were used to calculate the prediction of two nanoparticles of aluminum and zinc on a laboratory scale [15].

In this research, three experiments were carried out on different samples. One sample is taken from an Iranian sandstone reservoir and two other samples are picked from two carbonate reservoirs in Iran. The sample in the first experiment is saturated with crude oil; however, for the samples in the second and third experiments, first nanoparticles are injected and then the samples are saturated by the crude oil and the samples are then placed in the distilled water and the recovery factor has been measured for duration of 30 days. All experiments are carried out using the contact angle method. Each of the samples under studies has been assigned to one the three types of wettability, i.e. oil-wet, water-wet, and neutral. It is worth noting that all samples were washed with methanol and they were kept in Toluene for a week

Comparison of the different Nanoparticles on Carbonate Reservoir Efficiency

Efficiency tests (RF) of different nanoparticles on carbonate reservoir varied from %47 to %63 in the y direction (Figure 3). As can be notice, while the wellbore is vertical, the most effective nanoparticles on carbonate reservoir efficiency are aluminum of course, the impact of zinc nanoparticles was initially greater than that of aluminum, but as time passed, aluminum's impact on the chart starts increasing. As shown, the lowest RF is related to the horizontal wellbore in a carbonate reservoir when the nanoparticles are not injected yet.

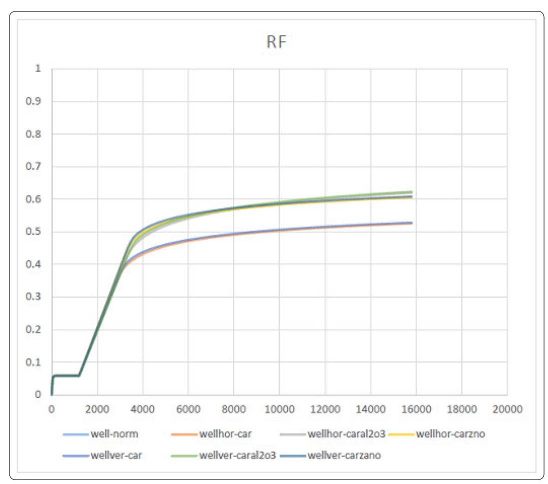

Figure 3: Comparison between the efficiency tests from different Nanoparticles on carbonate reservoir.

Comparison between the efficiency tests from different Nanoparticles on Sandstone Reservoir

According to the Figure 4, generally in sandstone reservoir at the time of nanoparticles injection RF varies from %7 to %87 in the y direction. The most effective nanoparticles on sandstone reservoir are zinc. The RF will decrease in sandstone reservoir while wellbore is horizontal. Though, the Zinc nanoparticles have the higher RF effect on the horizontal wellbore sandstone than Aluminum nanoparticles. The lowest RF in the case of noanoparticles injection was related to horizontal wellbore at the time of injection aluminum.

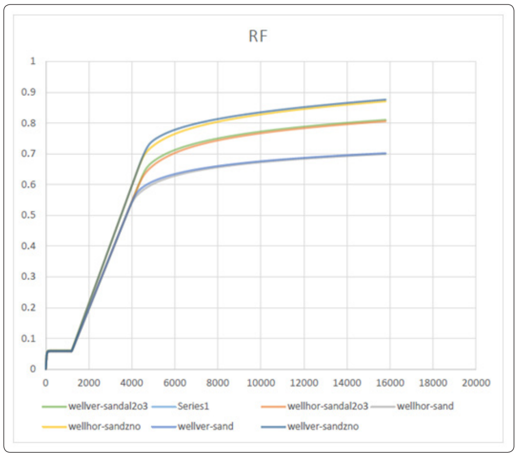

Figure 4: In sandstone reservoir at the time of nanoparticles injection, RF varies from 7% to 87% in the y direction. The most effective nanoparticles on sandstone reservoir's RF are Zinc.

Comparison for the Effect of Aluminum Nanoparticles in Carbonate Reservoir for the Horizontal Well

In Fig. 5, nanoparticle injection increases the recovery factor of the reservoir by 24% comparing to the case where no nanoparticle was injected.

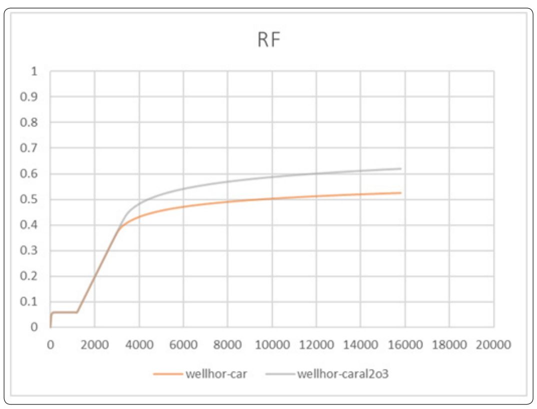

Figure 5: Nanoparticle of Aluminum for a horizontal well in a carbonate reservoir

The Effect of an Injecting Zinc Nanoparticle for a Horizontal Well in a Carbonate Reservoir

The injection of zinc nanoparticle, alike aluminum, increases the recovery factor of the reservoir by 17%.

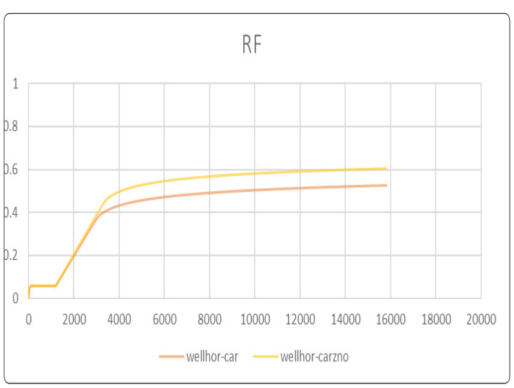

Figure 6: Nano-scale for a horizontal well in a carbonate reservoir

The Effect of Injecting Aluminum Nanoparticles on Vertical Carbonate Reservoir

For a vertical carbonate reservoir, even without Nano injection, the recovery factor is 0.51. The injection of aluminum nanoparticle increases the recovery factor in such a reservoir up to 19%.

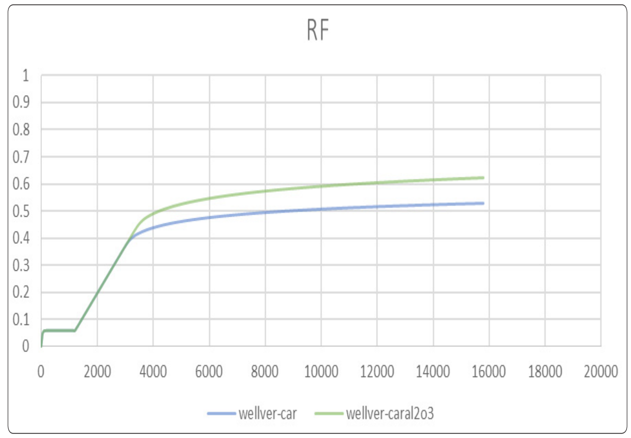

Figure 7: Nanoparticle of Aluminum in a carbonate vertical reservoir

The Effect of Zinc Nanoparticles on Vertical Carbonate Reservoir

In Figure 8, the effect of injecting zinc for a vertical well in a carbonate reservoir is similar to its effect for a horizontal well.

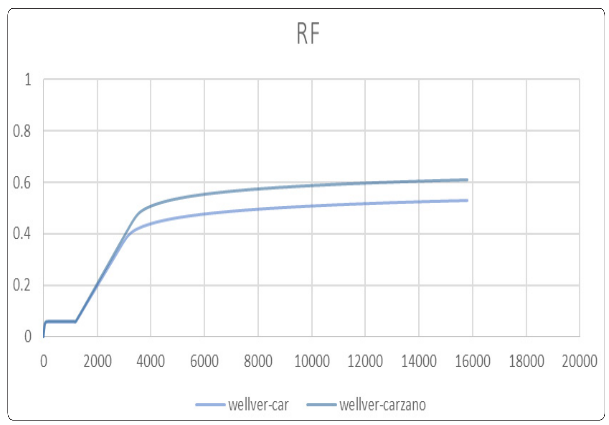

Figure 8: Nanoparticle of Zinc in a carbonate vertical reservoir

Influence of Aluminum Nanoparticle Injection for a Horizontal Well in Sandstone Reservoirs

Injection aluminum nanoparticle for a horizontal well in a sandstone reservoir will lead to 14% increase in recovery factor. For early stages of production there is almost no change in the recovery factor (RF).

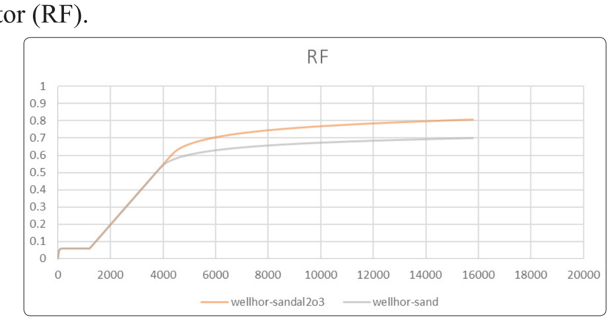

Figure 9: Nanoparticle of Aluminum for a horizontal well in a sandstone reservoir

Influence of Aluminum Nanoparticle Injection for Horizontal and Vertical Wells in Sandstone Reservoir

The injection of aluminum nanoparticle in a sandstone reservoir will lead to an increase of 24% in recovery factor which is even observable at early stages of production. For this type of reservoir, the effect of the nanoparticles is similar for both cases of horizontal and vertical wells.

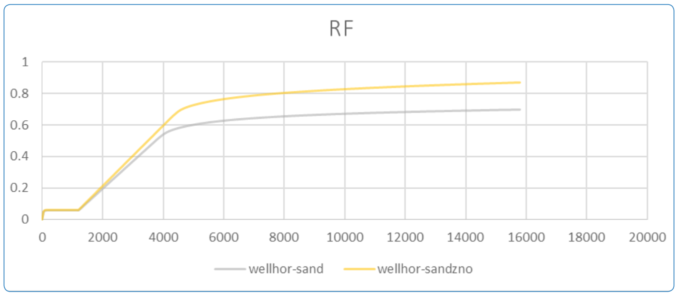

Figure 10: ZnO Nanoparticle for a horizontal well in a sandstone reservoir.

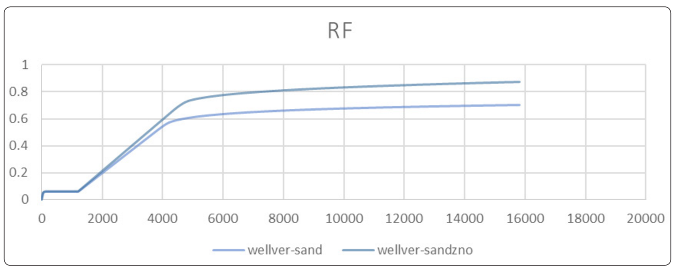

Figure 11: ZnO Nanoparticles for a vertical well in a sandstone reservoir

The Effect of Reservoir Properties (Permeability and Porosity) and Type of Nanoparticles on the Recovery Factor Curve for a Carbonate Reservoir

The effect of permeability change on the recovery factor curves for a carbonate reservoir is sketched in Figures 12, 13, and 14. Under such situation, the case of horizontal well in the carbonate reservoir results in the least recovery factor whereas the case of vertical well will result in the highest recovery factor.

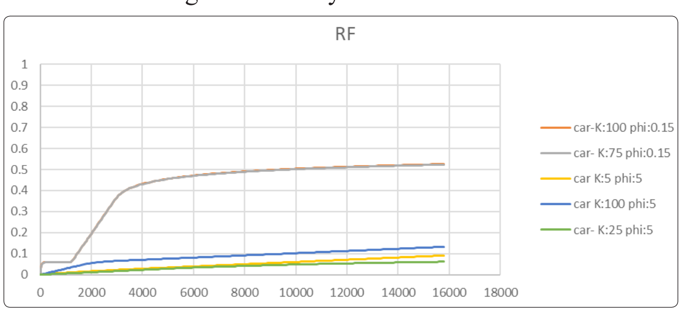

Figure 12: The effect of change in porosity and permeability for a carbonate reservoir

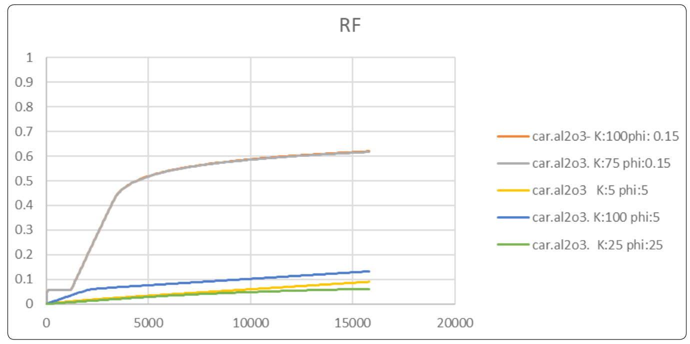

Figure 13: The effect of change in porosity and permeability for a carbonate reservoir with Nano-Aluminum injection

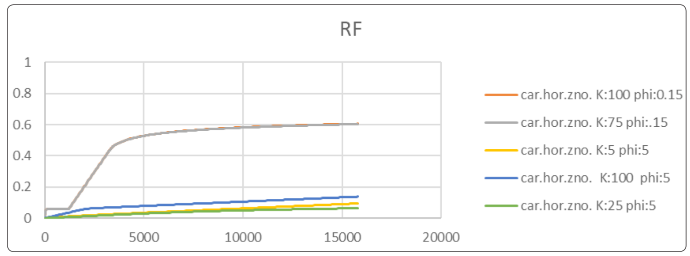

Figure 14: The effect of change in porosity and permeability for a horizontal well in a carbonate reservoir with Nano-Zinc injection

The Effect of Reservoir Properties (Permeability and Porosity) and Type of Nanoparticles on the Recovery Factor Curve for a Sandstone Reservoir

The effect of permeability change on the recovery factor curves for a sandstone reservoir is sketched in Figures 15, 16, and 17. For this case, the permeability is fallen from 100 to 75md. Under such circumstances, the recovery factor has been declines by 42%.

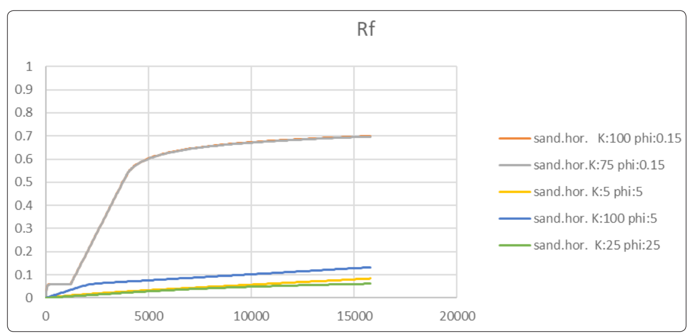

Figure 15: The effect of change in porosity and permeability for a sandstone reservoir

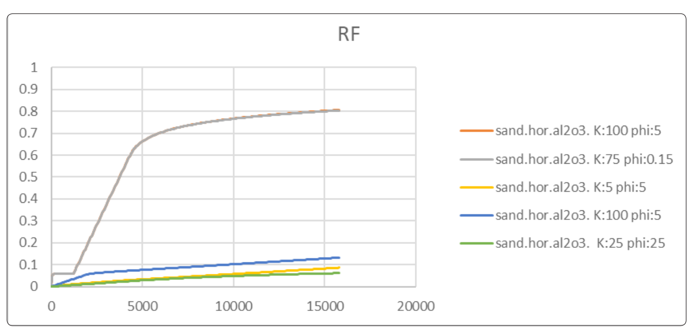

Figure 16: The effect of change in porosity and permeability for a horizontal well in a sandstone reservoir with Nano-Aluminum injection

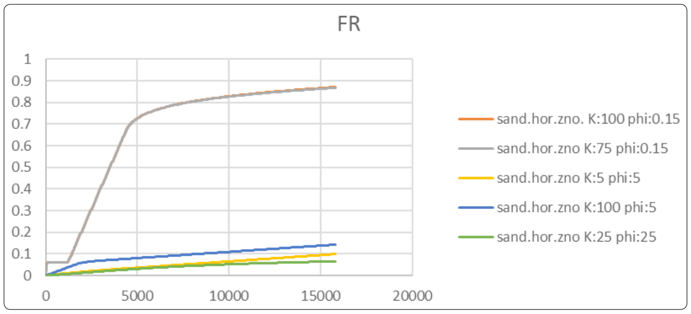

Figure 17: The effect of change in porosity and permeability for a horizontal well in a sandstone reservoir with Nano-Zinc injection

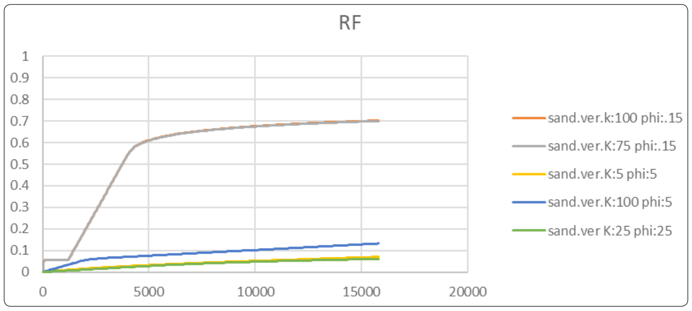

Figure 18: The effect of change in porosity and permeability for a vertical well in a sandstone reservoir

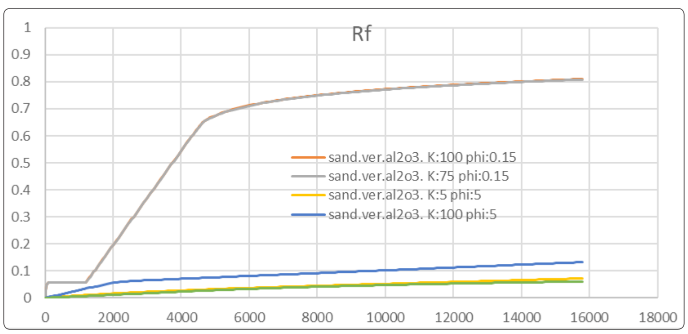

Figure 19: The effect of change in porosity and permeability for a vertical well in a sandstone reservoir with Nano-Aluminum injection

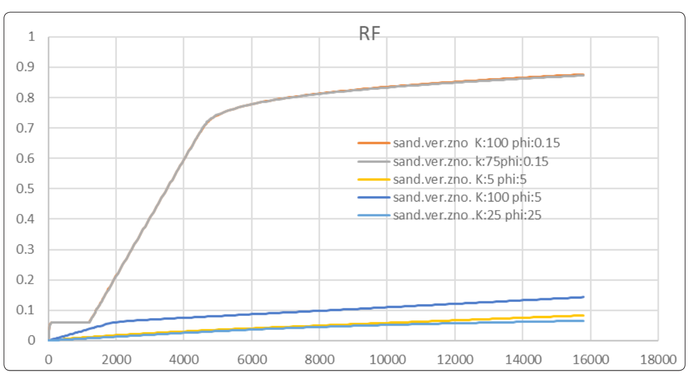

Figure 20: The effect of change in porosity and permeability for a vertical well in a sandstone reservoir with Nano-Zinc injection

Recovery Factor curves for different permeability and porosity of a carbonate reservoir

For the case of a carbonate reservoir, by reducing the permeability from 100 to 75 md while the porosity is fixed, the recovery factor does not change whereas in the case of observing an increment in porosity, the recovery factor curve declines sharply.

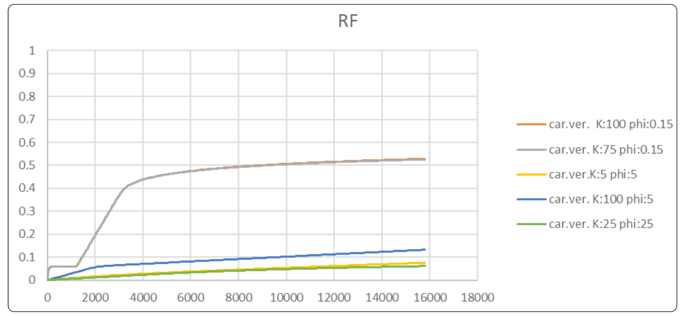

Figure 21: The effect of change in porosity and permeability for a vertical in a carbonate reservoir

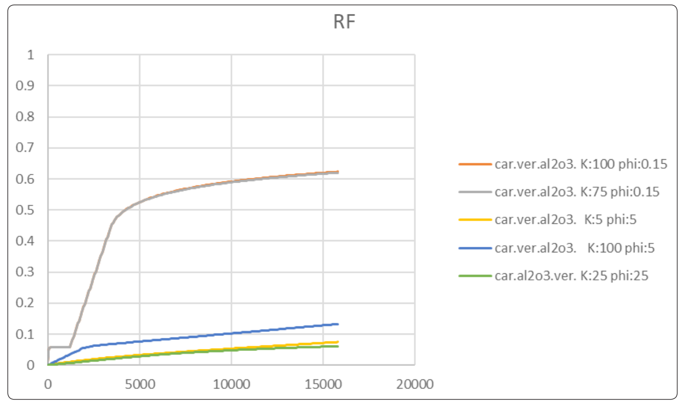

Figure 22: The effect of change in porosity and permeability for a vertical well in a carbonate reservoir with Nano-Aluminum injection

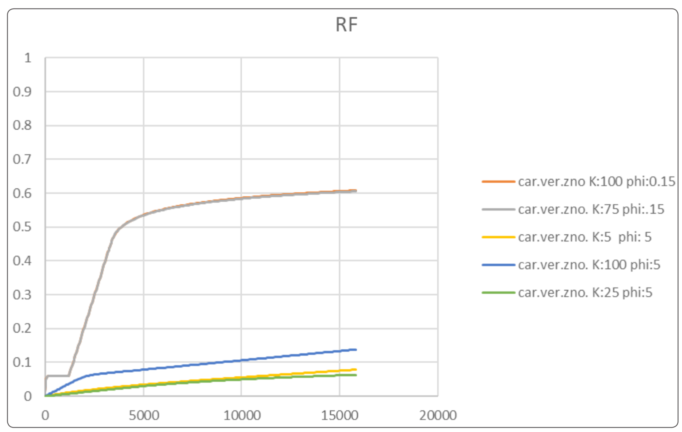

Figure 23: The effect of change in porosity and permeability for a vertical well in a carbonate reservoir with Nano-Zinc injection

Results and Discussions

Nanoparticles Effect on Carbonate Reservoirs

Fluids containing different nanoparticles have the potential to change the nature of the reservoirs with different ratios. The two nanoparticles which are used in this study have shown different effects on carbonate reservoirs. As it was stated, the injection of nanoparticles changes the status of wettability in reservoirs from oil-wet to water-wet and hence increases the recovery factor. The change in wettability will lead to change in other reservoir properties, the most important of which is the reservoir's relative permeability.

In this study, the effect of Zinc and aluminum nanoparticles injection on the reservoir was investigated. In general, the injection of nanoscale particles in the sandstone reservoir will lead to a further increase in the recovery of the reservoir.

The results obtained from the aluminum nanoparticle injection into a carbonate reservoir indicated that the effect of injection for a vertical well is greater comparing to other situations. However, when a short period of time is considered, the injection of zinc nanoparticle proves to be more effective.

Studying the Effect of Contacting Time in Carbonate Reservoirs

For early stages of production, the following situations indicate greater recovery factors, respectively:

a) Vertical well in a carbonate reservoir with zinc nanoparticle.
b) Vertical well in a carbonate reservoir with zinc nanoparticle.
c) Vertical well in a carbonate reservoir with injecting aluminum nanoparticle.
d) Horizontal well in a carbonate reservoir with injection aluminum nanoparticle.
e) Vertical well in a carbonate reservoir without injection.
f) Horizontal well in a carbonate reservoir without injection.

And for a long period of time, the following cases result in the highest recovery in carbonate reservoir, respectively:

a) Vertical well in a carbonate reservoir with the injection of aluminum nanoparticles.
b) Horizontal well in a carbonate reservoir with aluminum nanoparticle injection.
c) Vertical well in a carbonate reservoir with zinc nanoparticle injection.
d) Horizontal well in a carbonate reservoir with zinc nanoparticle injection.

At the end of this queue and with a large decrease, the cases of vertical well in a carbonate reservoir without injection, and horizontal well in a carbonate reservoir without injection, are placed.

According to Figure 23, if the increment in recovery factor for a short period of time is delighted, the zinc nanoparticle injection is suggested. However, with increasing production and prevailing pressure drop in the reservoir, the injection of aluminum nanoparticle is suggested in order to increase the recovery factor for a vertical well drilled in a carbonate reservoir.

The Recovery Factor of the reservoir is the lowest in the case of a horizontal well in a carbonate reservoir with no injections; meanwhile, the injection of aluminum nanoparticles increases the recovery factor. In a horizontal well of carbonate reservoirs, alike the vertical wells, the effect of nanoscale aluminum injection on the relative permeability and hence the recovery factor of the reservoir (in long term) is greater than that of nanoparticles of zinc. However, in horizontal wells, the effect of zinc nanoparticles is much more pronounced than the aluminum.

Effect of Injecting Nanoparticles in Sandstone Reservoirs

In sandstone reservoirs, by injecting zinc nanoparticles within the reservoir, the recovery factor of a vertical well is most affected such that the change in recovery factor reaches op to 87%. Furthermore, injecting zinc nanoparticle within a horizontal well in a sandstone reservoir results in the least recovery factor.

The highest recovery factors for sandstone reservoirs are related to the following states, respectively:

a) Case of injecting zinc nanoparticle through a vertical well.
b) Case of injecting zinc nanoparticle through a horizontal well.
c) Case of injecting aluminum nanoparticle through a vertical well.
d) Case of injecting zinc nanoparticle through a horizontal well.
e) Case of a vertical well without nanoparticle injection.
f) Case of a horizontal well without nanoparticle injection.

The Effect of Injecting Time in Sandstone Reservoir

In Sandstone reservoirs unlike the carbonate reservoirs, the effect of injecting nanoparticles in the reservoir dos not changes with time. However, for a vertical well drilled in a sandstone reservoir, the effect of injecting zinc nanoparticle on the recovery factor is considerably greater than the effect of injecting aluminum nanoparticle.

For carbonate reservoirs, the aluminum nanoparticle injection is proposed when a long-term production period is considered. However, the injection of zinc nanoparticle within sandstone reservoir has indicated a greater increase in the recovery factor. Extraction petroleum from horizontal wells has always been a riskier and more difficult task to do comparing with the vertical wells, however by injecting appropriate nanoparticles into the reservoirs, especially the sandstone reservoirs, the challenges can be surprisingly reduced. Performing such a task in carbonate reservoirs appear to be more troublesome as the effect of injecting nanoparticles is changing over time.

The Effect of Reservoir Properties (Porosity and Permeability) and Nanoparticles on Recovery Factor of the Carbonate Reservoirs

The recovery factor curves are plotted for the two cases when the permeability drops from 100 to 75 md (Figures 13, 14, and 15). The lowest recovery factor is related to the case of injecting aluminum into a horizontal well within a carbonate reservoir and the highest recovery factor relates to a vertical well in such condition. For the case of injecting zinc nanoparticle, the effect on recovery factor happens in a shorter time comparing to injecting the aluminum nanoparticle. The effect of dropping the permeability when the zinc nanoparticle injection is considered, does not lead to a greater change in recovery factor curves.

The Effect of Reservoir Properties (Porosity and Permeability) and Nanoparticles on Recovery Factor of the Sandstone Reservoirs

In sandstone reservoirs, as depicted in Figs. 16, 17 and 18, for the case of a permeability of 75 md, the recovery factor experiences a broader range of variations from 0.61 to 0.87and the change in recovery factor in the y-direction is about 42%. For the case when permeability is 100 md, the changes in recovery factor ranges from 0.6 to 0.87 and the change in the y-direction is about 45%.

For the case of horizontal wells through sandstone reservoirs, the effect of injecting nanoparticles for low porosity and high permeability is more tangible, but as the permeability decreases and porosity increases, the recovery factor curves approach the y-axis and possess lower slopes. It is worth noting that the effect of zinc Nanoparticle injection on the reservoir is less comparing to the case of injecting aluminum and the effect of injecting the Nanoparticles for cases of vertical and horizontal wells does not differ.

In order to better understand the effect of the porosity on the recovery factor curves with a constant permeability, i.e. 100 md, the porosities for the were increased to 5%as depicted in Figures 19, 20, and 21. It is evident that the change in recovery factor is slight and hence we can conclude that the injection of nanoparticle in high porosity reservoirs is ineffective.

Recovery Factor Curves For Different Permeability and Porosity

In the carbonate reservoir, the recovery factor curve does not change for the case when the permeability drops from 100 to 75 md, however, if the porosity increases then the recovery factors drops considerably.

Accordingly, it can be stated that in Figures 22, 23, and 24, the slope of the recovery factor's curves is strongly dependent on the porosity. In the case of injecting nanoparticles the curves will be similar, however, the recovery factor will be generally higher. As the permeability increase and porosity decrease the recovery factor increases.

Comparing the case of a vertical well with a horizontal well within a carbonate reservoir, the nanoparticle injection has a higher effect on the vertical well. As the porosity increases and permeability decreases the slope of the recovery factor curves decreases and the effect of nanoparticle injection will be minor.

Conclusions

Laboratory experiments indicate that by injecting nanoparticles within a reservoir the relative permeability changes. A reservoir simulator software can be used to relate the changes in relative permeability with the changes in recovery factor of the reservoir. According to the laboratory data, injecting both zinc and aluminum nanoparticles will lead to an increase in the recovery factor of the reservoir however the effect of aluminum injection is more lasting. The case of zinc injecting into a reservoir concerns a shorter period of time.

In a carbonate reservoir for the case of a vertical well, the injection of aluminum particle be most effective. For a sandstone reservoir and the case of vertical well, the zinc nanoparticle will be most effective. If the increase in recovery factor within a short period of time is considered, the zinc nanoparticle is considered.

Under constant porosity, the higher the permeability the higher is the recovery factor; however, for a constant permeability, as the porosity increases the recovery factor decreases.

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