

Research Article

Acidizing Operation Modelling in Sandstone Formations

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Abstract

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In this paper a survey of modeling and simulation of matrix acidizing in sandstone formations and development of matrix acidizing simulator is investigated. The models used in acidizing of sandstone formation are recognized and one of the most important related models have been coded in such a way that equations covering this model and the stages of making the simulator is explained. In the end, by using simulation software, operations of characterizing of the formation as mineralogy, matrix acidizing, influences and parameters of design such as injection rate is investigated. The most important sandstone acidizing design parameters are acid injection rate, formulation and type of injected acid, volume of injected acid, volume of fluids used in after/before the injection. Computer simulation is performed as a way to investigate the influences of some factors on the result of acidizing operations and injecting fluid behavior and how to fix the damage from the wellbore for different values of these factors, Such as type of damaging material, percentage of formation mineralogy compound, damage intensity and its radius. Developed simulator can be applied to a number of these investigations.

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1. Introduction

Sandstone acidizing with a mixture of Mud Acid (mixture of hydrochloric acid and hydrofluoric acid) has usually been the main technique to fix the damage around the wellbore. Yet many essential and practical questions remain unanswered including live acid penetration and amount of consumed acid,

the initial composition of minerals, the consequences of the deposition of reaction products, acid injection volume and flow optimization.

The main problem in developing an effective design of acidizing is certainly the complexity of natural sand-stones and the complexity of chemistry of aqueous phase [1-3]. Usually the design and test for understanding the outcome of the operation is performed on short cores, which can represent a significant deposition of sediments (which leads to a significant reduction in permeability). So even if the test of injecting acid into the core is provided, by having short cores used, the deposition of sediments cannot be observed in the laboratory and as a result, the acidizing design based on experiments done in the short cores is not proper.

A number of papers have reported that deposition of sediments in experiments conducted in Acidizing long cores is inevitable. Because of its cost and difficulty of such experiments, a suitable design is the effective use of computer simulation.

Common models used in simulation of acidizing operations:

The "two Parameters" Synthetic model that is of developed models among the minerals grouping models to help designing an acidizing operation (lumped mineral models) .

This model, predicts the concentrations of output acid in the short core experiments and flow injection at moderate temperatures precisely, but it doesn't consider the reaction of product deposition and subsequent reaction with the acid. It also doesn't consider the consumed acid inside the formation [4,5].

The four-parameter synthetic models that in this paper called "2acid-3mineral", is showing the failure of two-parameter models in considering the product deposits. However, both of "two-parameters" and "four-parameters" models only consider a small number of chemical compounds of all abundant species and this simplifications probably limits the application of these models [4-9].

Another way to simulate the acidizing operation is Local Equilibrium Assumption (LEA). In this case, a large number of chemical reactions and species can be considered. If only the thermodynamic data are considered, the synthetic data is not necessary to know. This method predicts a critical state, but cannot predict the influence on injection flow and synthetic of mineral reactions and acidizing fluid. This model is of the geochemical models category [10].

Another form of this model was presented in 1995 for the first time. In the newer model, the defects and limitations of all previous models was removed. In here, a large number of reactions include chemical equilibrium, while in the other reactions, the synthetic of reaction is considered. The final

state of the system is Partial Local Equilibrium Assumption. This model includes all the concepts and benefits of the previous models, and can be updated with new data and laboratory results.

Results of simulations with this model, confirms the ability of geochemical modeling, in modeling several mineral species, the acid composition percentage, injection rate and reservoir temperatures [11].

2. Sandstone Acidizing: “2acid - 3mineral” Model

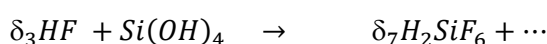
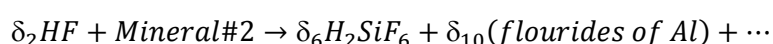
Different models of matrix acidizing process were studied briefly in the previous section. These models try to predict and simulate the reactions between the formation and the acid during the acidizing operation. When an acid system flows in formation it reacts with all or some of the present minerals and by progress of the reaction, the acid concentration and minerals in the formation will change with respect to time and place. But with all these complexities, there have been a lot of progress in acidizing operation modeling.

By using these models, it is possible to optimize the acidizing operation to reduce cost, operation time and the total volume that has to be injected. Two models of these, “1acid-2mineral” and “2acid-3mineral” had a high progress in the 90s and has been used till now. In both of these models, the reacting minerals like Clays and Feldspars will be put in a group and treated as a separate component that can be solved. Quartz and the other Silica’s less soluble minerals are put in other group.

It is assumed that Carbonates are soluble in hydrochloric acid and they are not involved in the reaction of hydrofluoric acid. The other assumption is that Carbonates at the end of pre-flushing with hydrochloric acid were completely dissolved. For the simulation performed in this paper, the “2acid-3mineral” model has been used and the implement and the carry out of the simulations will be described in the next section.

2.1 “2acid-3mineral” model [4-7,12]

The chemical reactions model or in a better word the chemical reactions considered in this model as proposed by Da Motta are as follows:



In these equations δ s are the stoichiometry coefficients that defined as the moles of acid necessary to dissolve 1 mole of the mineral.

Mineral#1 indicates fast reacting minerals (clays, sodium feldspar and potassium feldspar) and Mineral#2 indicates the slow reacting minerals. It is assumed that Si(OH)_4 is the silica's gel precipitation. These reactions are having first-degree synthetic in HF concentration and fast-reacting minerals.

2.2 Acid and Mineral Equations

Using the previously mentioned equations synthetics, the mole balance equations can be written in cylindrical coordinates. The differential equations that indicate the change in concentration of HF and H_2SiF_6 are as follows:

$$\frac{\partial(\phi C_1)}{\partial t} + v_i \frac{\partial C_1}{\partial r} = R_{\text{HF}} \quad \text{for acid \#1 which is HF} \quad (1)$$

$$\frac{\partial(\phi C_2)}{\partial t} + v_i \frac{\partial C_2}{\partial r} = R_{\text{H}_2\text{SiF}_6} \quad \text{for acid \#2 which is } \text{H}_2\text{SiF}_6 \quad (2)$$

In these equations the v_i Coefficient is Darcy speed that for incompressible fluid in cylindrical coordinates is as follows:

$$v_i = \frac{q_i}{2\pi r h} \quad (3)$$

In this equation q_i is the injection flow rate in i 'th layer.

R_{HF} and $R_{\text{H}_2\text{SiF}_6}$ are the consumption rate or production rate of these two acids.

The rates of dissolving acid and mineral are connected by the following equation:

$$R_{\text{HF}} = \sum_{j=1}^2 \delta_j R_j + \delta_8 R_3 \quad (4)$$

The index j indicates the reacted minerals with HF.

The differential equation indicating the consumption of mineral is as follows:

$$\frac{\partial((1-\phi)C_{Mj})}{\partial t} = R_j \quad j=1,2,3, \dots \quad (5)$$

The dissolution rate of minerals can be expressed by the rate law that is mainly based on a linear relationship to the concentration of acid and mineral:

$$R_j = -K_{Rj} C_1 (C_{Mj} - C_{MIj}) \quad (6)$$

2.3 Porosity and Permeability Equations

By changing mineral concentrations, the changes in volume and as a result porosity changes can be calculated. The following equation is obtained by using the volumetric balance in a time interval for a specific volumetric element.

$$\Delta\Phi = \frac{(1-\Phi_0)\sum_{j=1}^2(C_{M_j}-C_{MO_j})\frac{M_j}{\rho_j}-\Phi_0(C_{M_3}-C_{MO_3})\frac{M_3}{\rho_3}}{1-\left(\sum_{j=1}^2 C_{M_j}\frac{M_j}{\rho_j}-C_{M_3}\frac{M_3}{\rho_3}\right)} \quad (7)$$

In this equation M_j is the Molecular Weight of j mineral. The permeability amounts are calculated by the empirical equation suggested by Labrid. He observed that for a completely pure silicate sandstone there is a porosity-permeability relationship as follows [13]:

$$\left(\frac{k}{k_0}\right) = \left(\frac{\Phi}{\Phi_0}\right)^n \quad (8)$$

In the equation $n=3$.this equation is used for the acidizing operation blocks.

Skin factor equations and performance: there are three different methods to calculate the average permeability between specific blocks. In this paper, the simple average between the two groups is described. The average layer permeability is calculated from the following equation:

$$k_{layer} = \frac{\ln\left(\frac{r_e}{r_w}\right)}{\frac{\ln\left(\frac{r_e}{r_w}\right)}{k_{und}} + \sum_{j=1}^{Nblocks} \frac{2\ln\left(\frac{r_j}{r_{(j-1)}}\right)}{(k_{d_{j-1}}+k_{d_j})}} \quad (9)$$

In this equation K_d and K_{und} are the amount of permeability of the damaged and undamaged zone respectively.by average amount of permeability of each layer, the skin factor can be calculated from the following equation:

$$s = \left(\frac{k_{und}}{k_{layer}} - 1\right) \ln\left(\frac{r_e}{r_w}\right) \quad (10)$$

And the amount of productivity index is obtained from the following equation:

$$j = \frac{q_i}{\Delta p} = \frac{k_i h}{\mu\{\ln\left(\frac{r_w}{r}\right)+s\}} \quad (11)$$

The non-dimensional boundary and initial conditions are:

$$C_1 = 0 \text{ for } t = 0, r \geq 0$$

$$C_2 = 0 \text{ for } t = 0, r \geq 0$$

$$C_{M_j} = C_{M_{j0}} \text{ for } t = 0, r \geq 0, j=1,2$$

$$C_{M_3} = C_{M_{30}} \text{ for } t = 0, r \geq 0$$

$$C_1 = 1 \text{ for } t \geq 0, r = 0$$

$$C_2 = 0 \text{ for } t \geq 0, r = 0$$

The average permeability of a layer, skin factor and productivity is obtained by use of similar equations of “1-acid 2-mineral” model.

3. Numerical Simulations

This section describes the numerical simulator, finite difference equations of the 2acid-3mineral.

3.1 Algorithm

For modeling acidizing process, the area near the wellbore is divided into several layers, and each layer is divided into radial blocks that are not necessarily the same volume and width. Fig. 1 shows the process of modeling of the system and simulation of interaction of acid and rock in the reservoir.

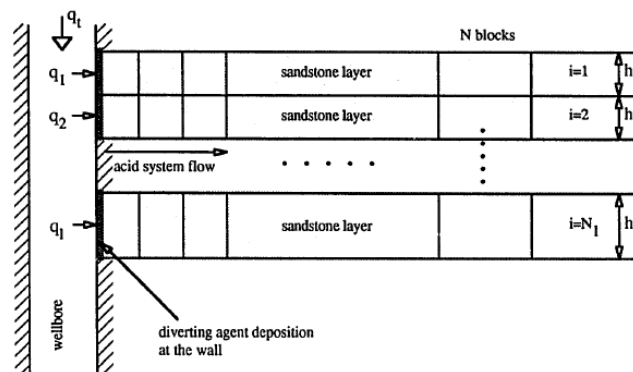


Fig.1: the system modeling and simulation of interaction of acid and rock [5]

The injected acid first contacts with the wall of the well, then enters the closest block to the wellbore and continuously moves to farther blocks. The equations needed to calculate different parameters of the blocks are frequently applied to these blocks [5].

The simulation is done layer by layer. At first, all properties inside the blocks are placed by initial values. Apparent velocity of the fluid is obtained from injection flow rate at wellbore as a function of time and place based on the fluid assumption used in it (compressibility or non-compressibility of the fluid). In a fixed time interval, by using the calculated field velocity and differential equations governed, the change in concentrations of minerals and acid is calculated. At the end of this time interval, by using the change in concentration and density of minerals, the change in volume of minerals can be calculated; therefore the change in porosity can be obtained precisely. Then by using the change in porosity, the change in permeability can be obtained by the mentioned empirical equation. These calculations are then repeated for the next time interval until all the injection volume intended is injected into the formation.

3.2 Simulation Experiments

In this paper the results of several experiments are presented which provide final conclusions based on these simulations and also some that are not mentioned in the paper. The results are presented as three-dimensional graph where the vertical axis is a considered parameter (such as concentration of acid and minerals or porosity and permeability) and the horizontal axis is time (gallon per the injected foot) and place (radial distance from the wellbore). The colors are just to help to identify the parameter amount. In the first simulation experiment almost all the results and in the rest experiments a smaller number of simulation results are presented.

3.2.1 Simulation Experiment #1

Table 1 presents the parameters used in the simulations of experiment #1. Fig. 2 – 7 show different parameters with respect to radial distance. Fig. 8 illustrates the changes in skin factor by time.

Table 1: Parameters used in simulation of experiment #1

Parameter	Amount
Sandface Acid Injection Rate	0.2 bbl/(min.ft)
Thickness of Formation	30 ft
Damage Radius	10 in
Simulation Radius	16 in
External radius	660 ft
Wellbore Radius	4 inch
Injected HF Concentration	3 % by weight
Initial Damaged Permeability	100 md
Initial Virgin Permeability	800 md
Initial fast- reacting- mineral (Clays such as Albite, Mica, ..) volume fraction	0.1
Initial Slow Reacting Mineral Concentration (Mainly Quartz)	0.9
Number of Grid blocks	17
Correlation Used for Updating Permeability from Porosity Change	Labrid Correlation with $m= 3.3$
Blocks Outside Simulation Radius	Considered to Have Small Effect on Results ($m=1$)

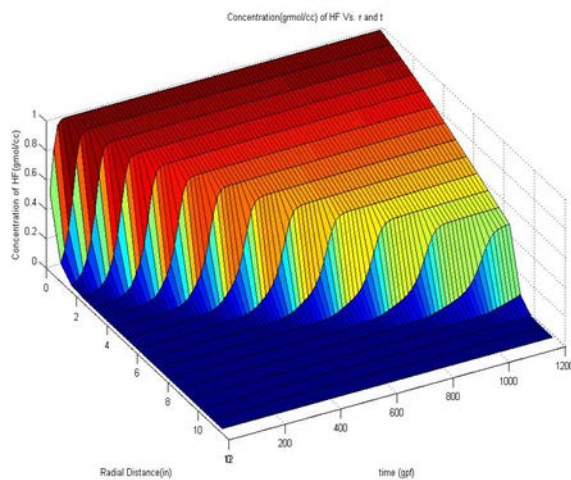


Fig. 2: Concentration of hydrofluoric acid in different time intervals and radial distances

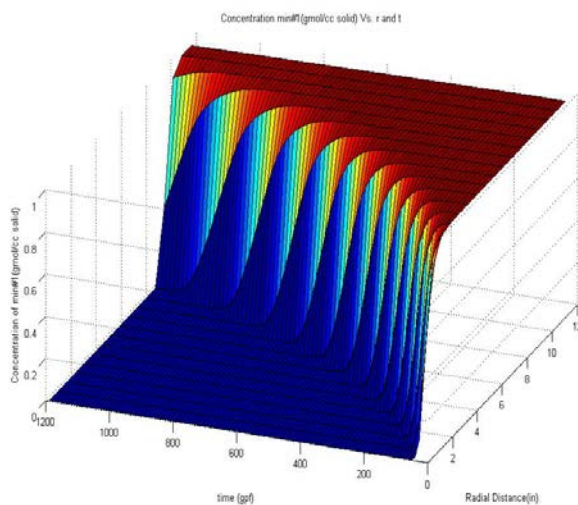


Fig. 3: Non-dimensional concentration of fast reacting minerals in different time intervals and radial distances

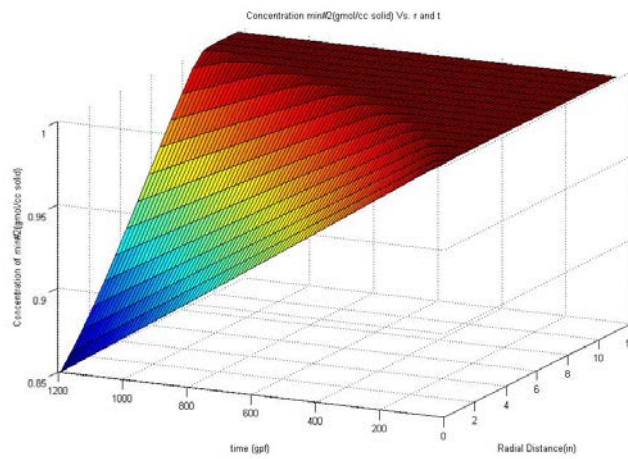


Fig. 4: Non-dimensional concentration of slow reacting minerals (Quartz) in different time intervals and radial distances

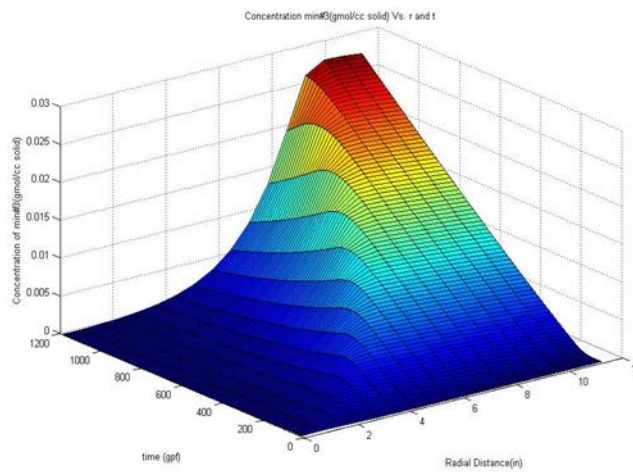


Fig. 5: Non-dimensional concentration of silica gel precipitation in different time intervals and radial distances

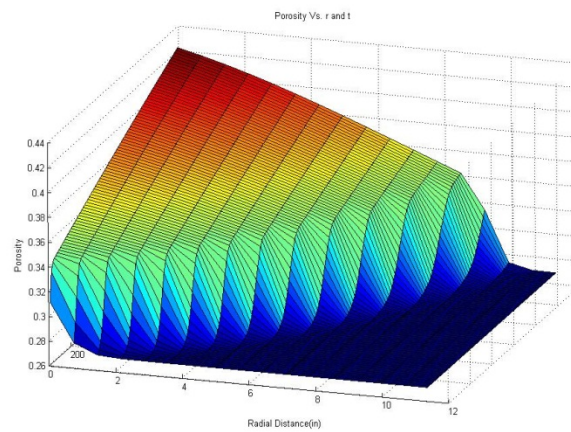


Fig. 6: Porosity change in different time and radial distances

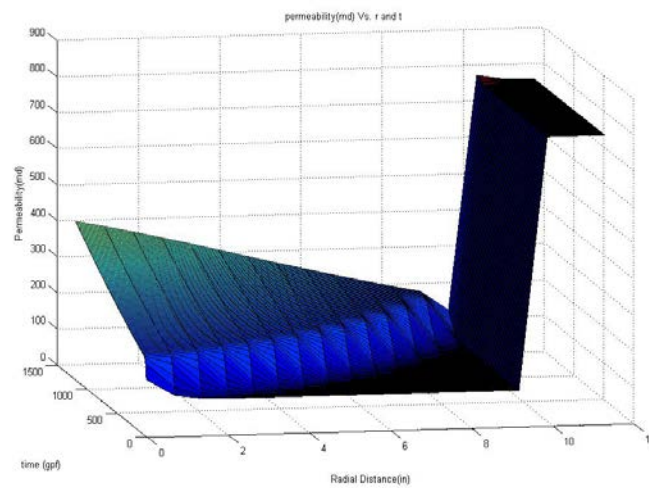


Fig. 7: Permeability change in different time and radial distances

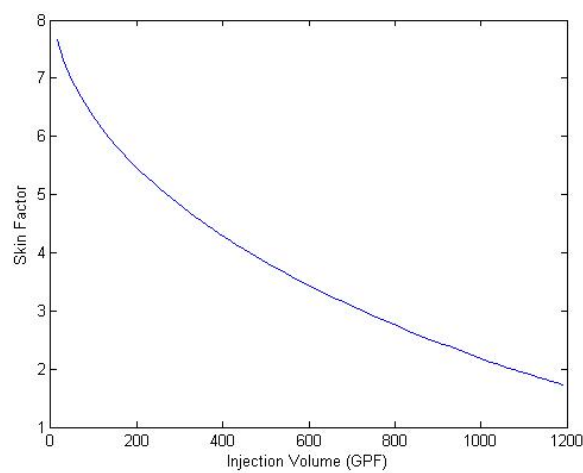


Fig. 8: Change of skin factor by time (Gallons per foot of injected acid)

3.2.2 Simulation Experiment #2: Damage Radius

In this experiment, the parameters of simulation are the same as last experiment, but the damage radius is 6 inches so that the effect of this parameter on the operation is investigated. Fig. 9 and Fig. 10 show the changes in permeability and porosity respectively.

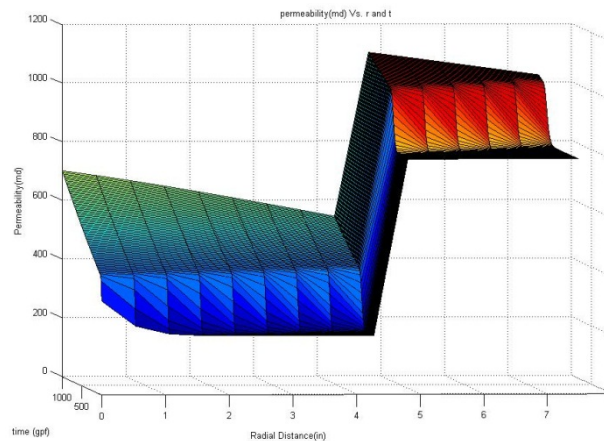


Fig. 9: Permeability in different time and radial distances

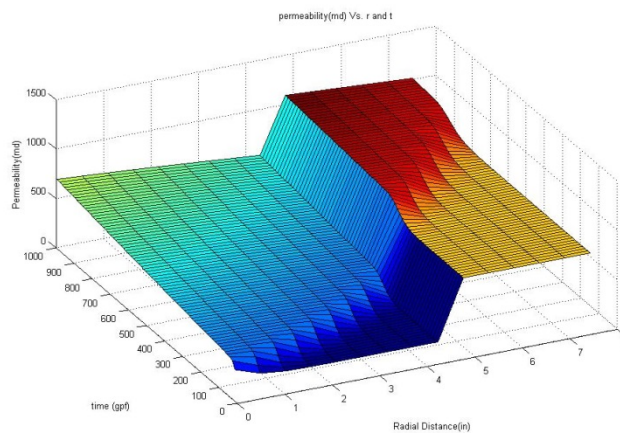


Fig. 10: Porosity change in different time and radial distances

3.2.3 Simulation Experiment #3: Damage Severity

The parameters in this experiment are the same as experiment #2 but the damage severity is more and permeability of the damaged area is 100 md and the amount of exponent n in Labrid equation is 3.3 in order to amplify the influence of mineral dissolution in this area on the increase in permeability. Fig. 11 shows the concentration of acid and Fig. 12 illustrates the skin factor changes based on this experiment.

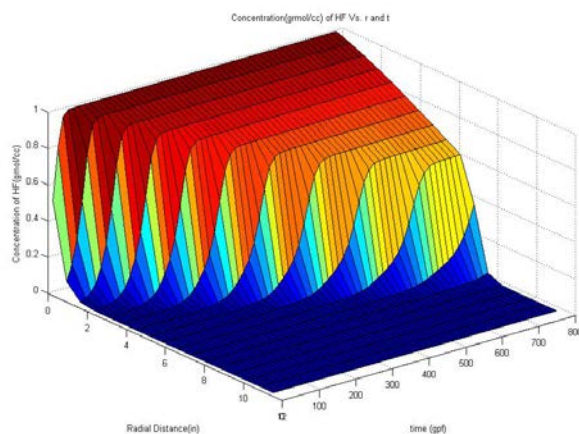


Fig. 11: Acid hydrofluoric Concentration in different time and radial distances

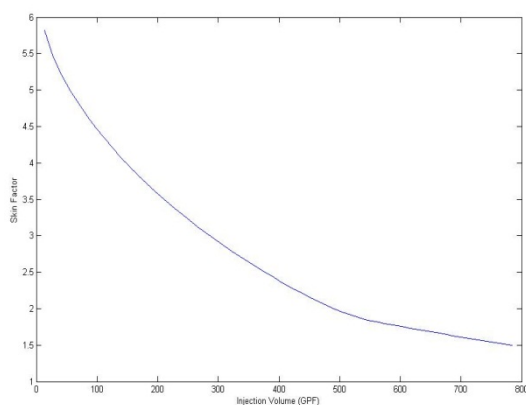


Fig. 12: Skin Factor Change with Time (Injected Volume)

3.2.4 Simulation Experiment #4 : Injection Flow Rate

The parameters are the same as experiment #1 but the injection flow rate has been changed to its half value and the concentration is shown in Fig. 13.

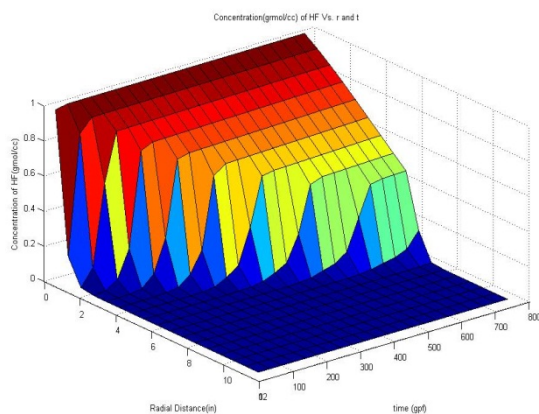


Fig. 13: Acid hydrofluoric Concentration in different time and radial distances

4. Conclusion

Based on simulations performed and comparing the results of changing parameters in the simulation, the following results were obtained while for field-scale usage, calibration of the some model parameters is needed and due to the lack of field data, the possibility to confirm was not possible.

1. Presence of fast reacting minerals that rapidly react to HF causes the front of acid in low injection flow rate not to be enough to penetrate into the formation, and all of the acid is used to dissolve the reactant minerals near the wellbore. But with increasing injection flow rate, the rate of transport of acid by bulk flow will be more than surface reaction rate and then greater penetration of acid into the formation will be observed. In this case the limiting factor for the increase in flow injection rate is injection pressure, which should not be more than breakthrough pressure of the formation or well head equipment safety pressure.

2. Increasing in porosity and consequently increasing in permeability is largely due to the dissolution of high soluble minerals behind the front HF. Also, the role of the dissolution of quartz is not very impressive in increase of porosity and permeability due to its slow response to high reaction rate.

3. Percentage of fast reacting minerals in the solid part of the rock is effective on the front location and depth of penetration of live acid. The more the percentage, the less the front advancing, but the increase in porosity and permeability in back of the front is more and depends on the damaged depth.

4. The concentration of injection acid also impacts on acid front and concentration of fast reacting minerals and porosity and permeability profiles. With increasing the concentration of injected acid, the penetration of live acid is more. In all previous simulations, the injected acid concentration was 3 wt% HF.

5. With increase in flow rate of injected acid, the acid penetration for a specific time is increasing and more damaged sectors of formation are being exposed to acid that can improve the operation. But ultimately the volume of acid being used is high. By knowing the rapid reaction of hydrofluoric acid with fast reacting mineral, it seems that acid front will not reach there until all the fast reacting minerals to a particular distance are solved, and Increase in injection flow rate has effective influence in removing away of potential sediments from the area near the well.

6. The more intense of the damage, the better performance of the hydrofluoric acid injection in a particular injection volume, and the influence of the acid is more in performance of the reservoir. The reason is that there is a small amount of damaging substances that can cause blockage of the holes and as a result there will be a significant reduction in permeability. To solve this small amount of these damaging materials we need a small volume of acid, while by solving them the permeability can increase significantly.

7. When the radius of damaged area is decreased, the amount of acid needed to improve the productivity in the desired reservoir is less. The cause is the nature of the acid front in the presence of fast reacting minerals that eventually will reach the desired radius sooner.

Acknowledgement:

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Nomenclatures:

C = concentration of acid in reservoir

C_M = concentration of minerals

K = factor proportional to permeability of porous medium

p = pressure

q = volumetric flow rate

t = time

Greek Letters

μ = fluid viscosity

ϕ = porosity

ρ = density

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