Evaluation and Modeling of Steam Drive in Diatomite under Reservoir Conditions

[Reza Cheraghi Kootiani, Soroush Chehrehgosha, Sasan Mirali and Ariffin Bin Samsuri]

Abstract---**There are large petroleum deposits in low permeability diatomaceous rocks. These oil deposits form a substantial part of original oil trapped in the San Joaquin Valley, California. Water flooding and steam drive with hydraulically fractured injectors and producers are possible ways of recovering oil from such deposits. Water flooding in diatomaceous rocks has not been widely effective, primarily due to the low mechanical strength of the rock. The brittle formation fractures easily and fracturing leads to injector/ producer linkage. Steam injection on the other hand shows better prospects of performance in these reservoirs. Since diatomite is primarily silica, steam injection into a diatomite reservoir could cause some changes in reservoir rock characteristics due to dissolution, transport and re-precipitation of silica. This study is aimed at modeling mathematically this dissolution process and predicting the dissolution and precipitation rates by developing a simulator code that predicts the physics of these processes. The simulator results will be compared with available experimental results. The mathematical model will then be updated to include the effect of this dissolution mechanism on the reservoir properties, such as permeability with duration of steam injection.**

Keywords---**Permeability, Water flooding, Steam injection, Simulator code, Dissolution mechanism**

Reza Cheraghi Kootiani
Universiti Teknologi Malaysia (UTM)
Malaysia

Soroush Chehrehgosha
Universiti Teknologi Malaysia (UTM)
Malaysia

Sasan Mirali
Islamic Azad University of Omideyeh
Iran

Ariffin Bin Samsuri
Universiti Teknologi Malaysia (UTM)
Malaysia

I.   Introduction

A large number of diatomaceous petroleum reservoirs are found in Kern County, California. For example, these fields include South Belridge, North Belridge , Cymric, Midway Sunset and Lost Hills diatomite. Collectively they contain an estimated 10 billion barrels of original oil in place (OOIP). This figure is roughly comparable to the OOIP for Prudhoe Bay, Alaska (Kovscek "et al."1996).

Diatomite is a hydrous, non-crystalline form of silica or opal composed of microscopic shells of diatoms. Diatoms are the remains of single celled microscopic aquatic plankton. The diatomite reservoirs are typically of high porosity (25-65%) and high internal surface area, but have very low permeability ranging from 0.01 mD to 10 mD (Stosur, 1976). In addition, diatomaceous rocks have low mechanical strength. The low mechanical strength and low permeability of these rocks has resulted, generally, in low primary recovery and unpredictable performance of water flooding even with hydraulically fractured injectors and producers. Steam flooding pilots have been more successful, and in general, thermal methods hold great promise. But, steam injection into diatomite has its own complications. One factor influencing this process is the reactivity of diatomite with steam. During steam injection the hot aqueous condensate might dissolve the diatomite which is principally SiO_2, and this dissolved silica could be carried forward by the moving water condensate.

As the condensate travels, its temperature drops, and thus, the dissolved silica tends to precipitate at other places within the reservoir. This process can cause permeability redistribution within the reservoir, which is already relatively impermeable. Likewise, silica dissolution might cause cavities in the formation around injection wells. Thus, the understanding of kinetics of silica dissolution and precipitation will form an important facet of planning a good steam recovery project in diatomite reservoirs.

II. Literature Survey

Many reports are available in the literature regarding silica dissolution in alkaline flooding. Most studies have focused on dissolution mechanisms and rates. One notable reference relates particularly to diatomite. Koh "et al." (1996) have studied the problem of permeability damage in diatomaceous reservoirs due to condensate flow. They performed experiments to find the behavior of a diatomite core as hot saturated silica solution was injected into it. They compared their experimental results with a mathematical model that assumed silica dissolution and precipitation both follow a first- order kinetic equation. While modeling permeability damage, they also assumed a simple empirical model of permeability decrease due to porosity decrease,

$$k(x,t) = k_0 \left(\frac{\emptyset}{\emptyset_0}\right)^{\gamma} \qquad (1)$$

Where k_0 and k are permeabilities at porosities $\emptyset_0$ and $\emptyset$ respectively; g is assumed to be a constant. They evaluated g to be 9.0 for the conditions of their experiment. The model assumed by et al. for kinetics of silica dissolution and precipitation is simplistic. The following aspects possibly need to be investigated in order to successfully model diatomite dissolution and precipitation and their effect on permeability.

The kinetics of silica dissolution and precipitation reactions at high temperatures,

the factors that influence these reactions, and ultimately their effect on the solubility of diatomite in water. The relationship between permeability, porosity, and particle size distribution of a porous medium. The change of porosity and particle size distribution with diatomite dissolution and precipitation, and consequently, the evolution of

permeability with throughput and temperature history. The impact of high temperature and pressure conditions on the permeability of diatomite. The system that we are examining is at a high temperature and is slightly alkaline (pH in the range of 7.5-8.0). Various people have tried experimentally to model silica dissolution and precipitation kinetics. Bunge "et al."(1982) proposed kinetic models based on an irreversible first order reaction in an alkaline medium. Deghani (1983), based on experiments with sandstone, concluded that the dissolution of silica can be represented as a first order reaction only for pH's in the range of 8. Similar conclusions were reached by Mohnot (1984). Thornton (1985) et al later showed that silica dissolution rate decreases as the solubility limit of silica at the prevailing temperature is reached. These findings rule out first order kinetics for silica dissolution in an alkaline

atmosphere near the solubility limit of silica in water.

Secondly, the effect of high temperatures on permeability of siliceous reservoirs has been studied experimentally. Weinbrandt "et al."(1975), Aruna (1976), Danesh (1978) all performed experiments that suggest that there is a considerable permeability decrease at high temperatures and pressures in porous media comprised mainly of silica, whereas non-siliceous porous media, like limestone, show no permeability decrease. Udell "et al." (1989) postulated that this decrease in permeability of siliceous porous media is due to stress-induced silica dissolution. They argued that there is a linear relationship between surface chemical potential and surface stress. The surface stress is highest at contact points in a porous medium under pressure. Thus, the surface chemical potential too is highest at these points. This high potential causes the solubility of silica in water to be higher at these location compared to locations with lower stresses, like the main pore body. The difference in solubility causes a silica concentration gradient between high stress locations and the rest of the medium. Due to the concentration gradient, silica migrates from contact points to the main pore fluid by diffusion along the surface. The pore fluid is already saturated at a level consistent with surface potential of unstressed pore surface. The addition of silica by diffusion, results in super saturation of silica in the main pore body. This results in precipitation of silica on the unstressed pore body surface. This phenomenon causes permeability reduction.

III. Modeling

Our effort is to model mathematically a system undergoing the process of silica dissolution and precipitation with associated impact on permeability, and then compare the results of the model with the experimental data generated by Koh "et al." (1996), for hot water flow through diatomite. Our modeling study will consists of two parts. The first is flow modeling, and the second is to model how dissolving and precipitating silica alters the rock porosity and permeability.

A. *Flow Modeling*

The flow modeling is essentially the mass conservation principle. Initially, a model for single-phase flow (hot water) through diatomite is considered. Once our model accurately describes the dissolution process and the permeability alterations for condensate flow through diatomite, we will update this model to multiphase (steam) flow. The equations used for flow modeling are the following. Silica Mass Balance Equation is:

$$-\frac{\partial(C_{si}u_w p_w)}{\partial x} + q_{si} = \frac{\partial(C_{si}\emptyset\, p_w)}{\partial t} \qquad (2)$$

Where C_{si} is the silica concentration in moles of silica per unit mass of water, u_w is Darcy velocity of water in length per unit time, p_w is the liquid density at the location x, and time, t. The term q_{si} is silica generation at location x, and time t, in moles of silica per unit time per unit rock volume and $\emptyset$ is the porosity. Rock Mass Balance Equation is:

$$q_r = \frac{\partial[(1-\emptyset)p_r]}{\partial t} \qquad (3)$$

Where q_r is rock generation in mass per unit time per unit rock bulk volume and p_r is the rock density. The rock generation term in the mass balance equation will be due to silica dissolution/ precipitation. Energy Balance Equation is:

$$-\frac{\partial(u_w p_w C_{Pw}T)}{\partial x} + q_h = \frac{\partial[(\emptyset p_w C_{Pw}+(1-\emptyset)p_r C_{Pr})T]}{\partial t} \quad (4)$$

Where T is temperature change from base temperature, and C_{Pw} and C_{Pr} stand for specific heat capacity of liquid and rock respectively. The term q_h is the term for any heat source or sink. Darcy's Law equation is:

$$u_l = \frac{k}{\mu}\frac{dP}{dx} \qquad (5)$$

Where k is permeability, μ is viscosity and P is the pressure, and water balance equation is:

$$-\frac{\partial(u_w p_w)}{\partial x} = \frac{\partial(\emptyset p_w)}{\partial t} \qquad (6)$$

Where it is assumed that there is no water generation.

B. *Silica Kinetics Modeling*

The second term on the left hand side of Eq. 2 and on the right hand side of Eq. 3 is the term for net silica dissolution. Initially we assume that Darcy velocities are low and hence the residence times are large such that silica dissolution and precipitation attain equilibrium. The equilibrium silica concentration attained as a function of temperature is given by a polynomial of the form (Bruton, 1996),

$$C_{si} = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 \qquad (7)$$

Where a_i are constants and T is the temperature in °C. In case the assumption of local equilibrium proves to be invalid, (i.e., the dissolution process is not able to attain equilibrium), we will derive a kinetic model for silica dissolution. The model would rely on the fact that silica which is primarily SiO2 is like any other mineral oxide. So, its dissolution would occur via hydrolysis of active sites on the surface through the formation of an intermediate complex (Saneie "et al."1986). This complex exists in equilibrium with silicic acid in the solution. The dissolution of the silica can be represented as a first-order reaction only for sufficiently low alkali concentrations and low temperatures. The reaction is not decidedly first order at moderately high pH and high temperatures. Most importantly, the dissolution phenomenon is a surface reaction. Experiments (Saneie "et al."1986) suggest that silica solubility in terms of total dissolved silica, increases with temperature only for moderate initial pH (less than 10) and it is practically insensitive to temperature changes for high initial pH values (in the range of 11 onwards). The silica dissolution mechanism is a two-step process.

- Formation of the intermediate complex
- Dissolution (desorption) by bond breaking.

The first step is a rapid step while the second step is slow, and thus rate limiting. There are experimental instances to prove the existence and formation of such a complex in the silica dissolution process (Saneie "et al."1986).

An alkaline environment has effects on the silica dissolution rate and equilibrium concentration since it is hydrolysis of a mineral oxide. In an alkaline environment, there exist ionic silicic species other than $Si(OH)_4$ and none of these participate in the back reaction of Step b, (i.e. precipitating back on the surface). For a given amount of silica leaving the surface, the formation of ionic species other than $Si(OH)_4$ causes lower concentration of $Si(OH)_4$ in the solution and therefore tends to shift equilibrium (between the dissolution from surface and deposition on the surface) more towards dissolution. This leads to a higher reaction rate. Thus higher pH enhances the dissolution rate. There is also an effect of the ionic species present in the system (like NaCl). Since the sites available for silica complex formation are also sites available for ion exchange, there is a competition between these sites and this fact must be taken into account when formulating the rate equation.

C. *Permeability Modeling*

For modeling permeability, instead of the simple power-law permeability-porosity relationship illustrated in Eq. (1), we will use a permeability relationship depending additionally on the particle size distribution. The permeability of an unconsolidated medium depends on porosity $\emptyset$, tortuosity τ, mean grain size $D_{P,m}$, standard deviation s, and skewness γ of the pore size distribution. For unconsolidated sands, for example, the permeability expressed in these terms is (Panda and Lake, 1994),

$$k = \frac{D_{P,m}{}^2 \emptyset^3}{72\tau\,(1-\emptyset)^2}\left[\frac{\left(\gamma V_{DP}{}^3 + 3V_{DP}{}^2 + 1\right)^2}{\left(1 + V_{DP}{}^2\right)}\right] \qquad (8)$$

Where $V_{DP}=$ s and $D_{P,m}$ is the coefficient of variation of pore size distribution. For homogeneous media V_{DP} is zero.

This model of permeability and porosity is good for a medium having permeability up to 1 mD. For media having permeability lower than 1 mD, this equation predicts results which are higher than observed. Since diatomite permeability falls below 1 mD limit, certain type of a suitable equation would be needed ultimately. Based on the formulated mathematical model and the equations developed, we are solving the equations numerically using standard reservoir simulation techniques.

IV. Conclusions

We are in the first stages of simulating a steam drive process for diatomite reservoirs. The system is currently, for single-phase flow with the assumption, that residence times are low enough, such that equilibrium is reached in the dissolution mechanism. If our assumptions are correct, the model would agree with the available experimental data. In case it is not, we will modify the flow model to take into account non equilibrium of the dissolution mechanism. After a dissolution model is validated, the simulation model will be updated to include permeability changes. Ultimately, we will attempt to model three phase flow under reservoir conditions which would also include effects on permeability.

References

[1] Aruna M.: "The Effect of Temperature and Pressure on Absolute Permeability of Sandstone," (1976).

[2] Aziz K. and Settari A.: "Petroleum Reservoir Simulation," (1979).

[3] Bunge A. L., Radke, C. J.: "Migration of Alkaline Pulses in Reservoir Sands," (1982).

[4] Bruton, C.: Private Communication, Lawrence Livermore National Laboratory (1996).

[5] Danesh A., Ehling-Economides, C., and Ramey, H. J., Jr.: " Effect of Temperature Level on Absolute Permeability of Unconsolidated Silica and Stainless Steel," (1978).

[6] Deghani K.: "Caustic Consumption by Reservoir Rock at Elevated Temperatures," (1983).

[7] Koh, C. J., Dagenais, P. C., Larson D. C., and Murer A. S. : "Permeability Damage in Diatomite Due to In-situ Silica Dissolution/ Precipitation," (1996).

[8] Kovscek, A. R., Johnston R. M., and Patzek T. W.: "Interpretation of Hydrofracture Geometry During Steam Injection Using Temperature Transients I. Model and Verifications (1996).

[9] Stosur J. J.: "Petrophysical Evaluation of the Diatomite Formation of the Lost Hills Field, California," (1976).

[10] Mohnot, S. M., Bae, J. H. and Foley L.: "A Study of Mineral Alkali Reactions. (1984).

[11] Panda, M. and Lake, L. W.: "Estimation of Single Phase Permeability from Parameters of Particle Size Distribution," (1994).

[12] Saneie, S. and Yortsos, Y.C.: "Kinetics of Silica Dissolution and Hydroxyl Ion Consumption in Alkaline flooding," (1986).

[13] Thornton, S. D.: "Dissolution and Condensation Kinetics of Crystalline and Amorphous Silica in Alkaline Solutions," (1985).

[14] Udell, K. S. and Lofy J. D.: "Permeability Reduction of Unconsolidated Media Caused by Stress Induced Silica Dissolution," (1989).

[15] Weinbrandt, R. M., Ramey H. J., Jr., and Casse F.J.: "The Effect of Temperature on Relative and Absolute Permeability of Sandstones," (1975).