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EFFECT OF OILFIELD SULPHATE SCALES ON PRODUCTIVITY INDEX

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ABSTRACT

The precipitation and deposition of scale pose serious injectivity and productivity problems. Several models have been developed for predicting oilfield scales formation and their effect on deliverability of the reservoir to aid in planning appropriate injection water programme. In this study an analytical model has been developed for predicting productivity index of reservoir with incidence of scale deposition in the vicinity of the well bore.

NOMENCLATURES

B_o = Oil Formation volume factor, dimensionless
B_w = Water Formation volume factor, dimensionless
C = Concentration, g/m^3
h = Thickness, m
K = Instantaneous permeability, m^2
K_o = Initial permeability, m^2
K_{dep} = Deposition rate constant
r_w = Well bore Radius, m
R = Radial distance, m
S_w = Water saturation, dimensionless
S_{w_c} = Connate water saturation, dimensionless
T = Temperature, K
t = Production time, sec
μ_o = Oil Viscosity, cp

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μ_w =Water Viscosity, cp

ϕ_o =Initial Porosity, dimensionless

ϕ = Instantaneous porosity, dimensionless

ρ = density, g/m^3

INTRODUCTION

The magnitude of flow impairment induced by oilfield sulphates scale deposition around the well bore require description and classification of sulphate scales precipitation, scale build up (saturation), and their corresponding formation damage scenario at different operational and reservoir/brine parameters such as scale concentration in the brine, viscosity of brine, formation volume factor of the brine, solid scale density, injection rate, pressure drawdown, reservoir temperature, reservoir thickness, brine velocity and radial distance from the vicinity of the well bore (Fadairo et al, 2008; Civian, 2001). Major factors that influence the mixing and scale formation have been described in the literature (Fadairo, 2004; Oddo and Tomson, 1991).

The details of how sulphate scales are deposited in different locations in the reservoir near the well bore region and the consequent formation damage has also been presented (Fadairo, 2004, Fadairo et al, 2008).

Mixing of incompatible waters take place in the water contacted portion of the reservoir during water flooding (Fadairo, 2004; Fadairo et al, 2008; Civian, 2001; Bedrikovetsky et al., 2003a, 2004).

For instance, when formation water containing barium ion and seawater containing sulphate ions are mixed together, barium sulphate (precipitate) is formed in the swept zone inside the reservoir and is deposited as scale around the well bore during waterflooding.

In general the water-mixing zone moves from injection wells towards producers and precipitation of scales takes place in the mixing zone. Accumulation of precipitates does not depend upon mixing zone movement. The amount of scale precipitated at any point in the reservoir during such movement does not cause significant reduction in formation permeability (Civian, 2001; Bedrikovetsky et al., 2003a, 2004; Richards, 1968).

Diffusion and intensive mixing increase close to the production well due to increase in fluid velocity which also causes increase in the rate of chemical reaction in this region (Civian, 2001; Bedrikovetsky et al., 2003a, 2004).

These phenomenon lead to a higher rate of sulphate precipitation in the near well bore region than inside the reservoir. The overall effect of the above is that most of the sulphate precipitation and hence permeability reduction occur in the vicinity of the well (Fadairo et al, 2008; Bedrikovetsky et al., 2003b).

Studies (Fadairo et al, 2008; Rosario and Bezerra, 2001; Rocha, 2001) have shown that formation damage caused by sulphate precipitation can be better described as an exponential function of the depositional rate constant, salt concentration and production time rather than by a hyperbolic function of these variables as proposed by Bedrikovetsky et al[7]. Hence, there is the need to develop an expression for estimating the productivity index in wells producing from water-flooded reservoirs with possible incidence of sulphate scale formation based on the exponential function model. The purpose of this paper is to present the mathematical expression for achieving this purpose.

MODEL DEVELOPMENT

Consider the radial two-phase flow of oil and water at constant total flow rate q_t; saturated with solid-state particle at a location r, from the well bore. Assuming an idealized flow equation, the pressure gradient is expressed as follows:

$$\frac{dp}{dr}=\frac{q_t}{2\pi r\,h\,K_s}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right)^{-1} \quad (1)$$

Fadairo et al, 2008, recently expressed the effect of scale builds up on permeability variation based on exponential shape for both porosity and permeability damage function as

$$K_s=K_o[1-\lambda_\phi S_s(1-S_{w_i})]^{3.0} \quad (2)$$

where K_s is define as the instantaneous permeability as a result of solid scale saturation near the well bore region.

The derivation of equation (2) is expressed in appendix A.

Substituting equation (2) into (1) and re-arranging; we obtain

$$\frac{dp}{dr}=\frac{q_t}{2\pi r h\,K_o\left[1-\lambda_\phi S_s\left(1-S_{w_i}\right)\right]^{3.0}}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right)^{-1} \quad (3)$$

$$dp=\frac{q_t}{2\pi r h\,K_o\left[1-\lambda_\phi S_s\left(1-S_{w_i}\right)\right]^{3.0}}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right)^{-1}dr \quad (4)$$

Integrating equation (4); we have

$$\int_{pi}^{p}dp=\frac{q_t}{2\pi h K_o\left[1-\lambda_\phi S_s\left(1-S_{w_i}\right)\right]^{3.0}}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right)^{-1}\int_{\bar{r}_w=r_w\exp(-2s)}^{R}\frac{1}{r}dr \quad (5)$$

$$\Delta p=\frac{q_t}{2\pi h K_o\left[1-\lambda_\phi S_s\left(1-S_{w_i}\right)\right]^{3.0}}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right)^{-1}\mathrm{In}\frac{R}{\bar{r}_w} \quad (6)$$

Therefore

$$\frac{2\pi\, h\, K_o \Delta p}{q_t}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right)\left[1-\lambda_\phi S_s\left(1-S_{w_i}\right)\right]^{3.0} = \text{In}\frac{R}{\bar{r}_w} \tag{7}$$

The productivity index PI in a water-flooded reservoir with possible incidence of sulphate scale deposition around the well bore can be expressed as

$$\text{PI} \Rightarrow \frac{q_t}{\Delta p} = \frac{2\,\pi\, h\, K_o\left[1-\lambda_\phi S_s\left(1-S_{w_i}\right)\right]^{3.0}}{In\dfrac{R}{\bar{r}_w}}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right) \tag{8}$$

At initial production time, when t = 0 and $S_s = 0$ the expression degenerates to the normal Dupui formula for productivity index.

$$\frac{2\pi\, h\, K_o \Delta p^o}{q_t}\left(\frac{k_{rw}}{\mu_w}+\frac{k_{ro}}{\mu_o}\right) = \text{In}\frac{R}{\bar{r}_w} \tag{9}$$

Discussion of Results

The model was validated using the data of Haarberg *et al* (1991) on scale precipitation for given pore volume of sea water injected and fluid/ reservoir properties data[1], (Fadairo, 2004; Fadairo et al, 2008; Richards, 1968) shown below in Tables1 and 2 respectively, as input into the model.

Table 1. Amount of $BaSO_4$ and $SrSO_4$ precipitated as a function of pore volume of seawater injected (after Haarberg *et al* 1991)

Pore volume of seawater injected (%)	$BaSO_4$ Precipitate (g/m^3)	$SrSO_4$ Precipitate (g/m^3)
0	0.0	0.0
10	71.0	0.0
20	65.0	0.0
30	58.0	45.0
40	48.0	68.0
50	42.0	58.0
60	32.0	26.0
70	25.0	0.0
80	18.0	0.0
90	10.0	0.0
100	0.0	0.0

Table 2. Fluid and reservoir base case properties civan (2001) used as input in the scale prediction model

Pay thickness (h)	26m
Initial permeability	0.5922E-13m^2 (60mD)
Initial porosity	0.04
Reservoir pressure	36600kpa
Bottom hole pressure	22060kpa
Reservoir temperature	353K (80C)
Formation volume factor	0.254
Viscosity	0.0007Pa-s
Connate water saturation	0.2

The result of the model show that productivity decline due to scale formation around the well bore is better described when the formation damage function was assumed to be an exponential function of the scale depositional rate constant, salt concentration and time than when hyperbolic shape was assumed as opined by Bedrikovetsky *et al* (2003a). The rate of decline of the productivity of a formation due to sulphate scale deposition may be sharp initially but usually the rate decreases exponentially as the pore volume of the seawater injected water increases (Civian et al 2001; Fadairo, 2004). The productivity decline caused by scale formation around the well bore was over estimated when the formation damage was assumed to be a hyperbolic function (figure 1). The higher the average scale precipitation in the mixing zone along the reservoir, the lower the well productivity index (Table 1).

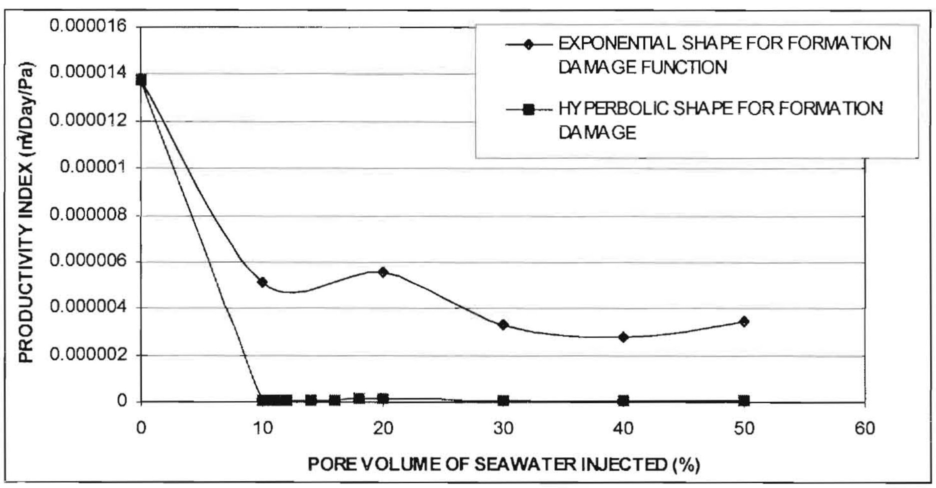

Figure 1. Productivity Index of a Well that Forms Sulphate Scale against Pore Volume of Seawater Injected.

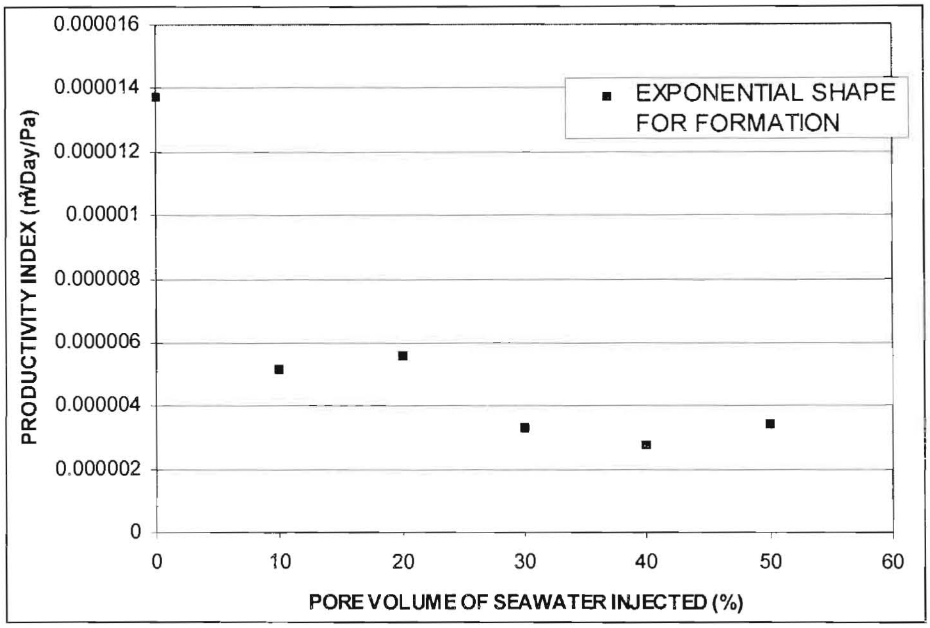

Figure 2. Productivity Index of a Well that Forms Sulphate Scales against Pore Volume of Seawater Injected.

Drastic productivity decline was observed at lower pore volume of seawater-injected ranges from 0% to 10% due to high permeability decline causes by deposited scale at low pore volume of water injected. This is in agreement with the studies reported in the literature ((Fadairo, 2004; Fadairo et al, 2008; Civian, 2001; Bedrikovetsky et al., 2003a, Tomson, 1991, Moghadasi et al., 2006).

This phenomenon might have been caused by heterogeneous nucleation that occurs at the early stage of scale build up around the well bore before re-dissolution of scale begins to take place at higher pore volume of injected water (Crabtee et al., 1999).

The increase in productivity index observed between 45% to 100% pore volume of water injected might have been due to scale re-dissolution (figure 2)

CONCLUSION

The following conclusions were drawn from the result of this study:

- At every given pore volume of sea water injected, the decline in productivity index for oil wells in water flooded reservoirs due to sulphate scale deposition depends upon oilfield solid scale saturation in the porous media.
- The rate of decline in productivity index due to sulphate scale deposition is the function of operational and reservoir/brine parameters such as scale concentration in the brine, viscosity of brine, formation volume factor of the brine, solid scale density, injection rate, pressure drawdown, reservoir temperature, reservoir thickness, brine velocity and radial distance from the well bore.

- The developed model is capable of predicting productivity index decline due to scale deposition around the well bore in water-flooded reservoirs.

APPENDIX A. INSTANTANEOUS PERMEABILITY AS A RESULT OF SOLID SCALE SATURATION NEAR THE WELL BORE REGION

Instantaneous local porosity can be defined as the difference between the initial porosity and damaged fraction of the pore spaces (Fadairo et al, 2008; Moghadasi et al., 2006).

That is $\phi_s = \phi_0 - \phi_d$ (A1)

Therefore

$$\phi_s = \phi_o - \frac{q^2 \left(\frac{dC}{dP} \right)_T . B . \mu . t . \lambda_k}{4 \pi^2 r_s^2 h^2 K_o \rho} \quad \text{(A2)}$$

Damage fraction of the pore spaces ϕ_d can be defined as the ratio of the volume of scale deposited to bulk volume of the porous media or the fraction of minerals scale that occupied the total volume of porous media (Fadairo et al, 2008; Moghadasi et al., 2006).

That is $\phi_d = \dfrac{\text{volume of minerals scale deposited}}{\text{bulk volume of the porous media}}$

Also Fadairo (2004); recently expressed the fraction of mineral scale that occupied the pore spaces at different radial distance from the well bore as follows:

$$S_s = \frac{q^2 \left[\frac{dC}{dP} \right]_T . B_w . \mu_w . t . \lambda_k}{4\pi^2 . r_s^2 . h^2 . \phi_o \lambda_\phi K_o \rho (1 - S_{w_i})} \quad \text{(A3)}$$

Re-arranging equation (A3), we have:

$$\phi_o \lambda_\phi S_s \left(1 - S_{w_i}\right) = \frac{q^2 \left(\frac{dC}{dP} \right)_T . B_w . \mu_w . t . \lambda_k}{4\pi^2 . r_s^2 . h^2 K_o \rho} \quad \text{(A4)}$$

where λ_ϕ and λ_k can be defined as porosity damage coefficient and permeability damage coefficient respectively.

That is $\lambda_\phi = \exp(-K_{dep}.Ct)$ and $\lambda_k = \exp(3K_{dep}.Ct)$ (A5)

Substituting equation (A3) in equation (A2), we have

$$\phi = \phi_o - \phi_o \lambda_\phi S_s (1 - S_{w_i}) \quad \text{(A6)}$$

Dividing both side of equation (A6) by ϕ_o, we have

$$\frac{\phi_s}{\phi_o} = 1 - \lambda_\phi S_s (1 - S_{w_i}) \quad \text{(A7)}$$

Considering the relationship between the initial permeability and instantaneous permeability as a function of altered porosity and initial porosity defined by Frank et al (1991) as:

$$\frac{K_s}{K_o} = \left(\frac{\phi}{\phi_o}\right)^3 \quad \text{(A8)}$$

Instantaneous permeability can be expressed as Fadairo, (2004):

$$K_s = K_o[1 - \lambda_\phi S_s (1 - S_{w_i})]^{3.0} \quad \text{(A9)}$$

Equation (A9) expresses the effect of scale build up on permeability variation at different operational parameters and reservoir/brine parameters such as scale concentration in the brine, viscosity of brine, formation volume factor of the brine, solid scale density, injection rate, pressure drawdown, reservoir temperature, reservoir thickness, connate water saturation against injection time and radial distance from the well bore vicinity.

APPENDIX B. PIRSON'S CORRELATION

Average relative permeability was expressed as a function of average water saturation was given below as follows (Ahmed, 1989):

$$S_w^* = \frac{S_w - S_{w_c}}{1 - S_{w_c}} \quad \text{(B-1)}$$

$$K_{r_w} = \sqrt{S_w^*}\ S_w^3 \tag{B-2}$$

$$K_{r_o} = (1 - S_w^*)\left[1 - \left(S_w^*\right)^{0.25}\sqrt{S_w}\right]^{0.5} \tag{B-3}$$

REFERENCES

Ahmed, T. (1989) *Introduction to Petroleum Reservoir Analysis*, Gulf Publishing Company. Houston TX.

Atkinson, G., Raju, K. and Howell, R.D. (1991) *"The Thermodynamics of Scale Prediction"*, SPE 21021, pp.209–215, presented at the Society of Petroleum Engineers international Symposium on Oilfield chemistry Anaheim, Canada.

Bedrikovetsky, P.G., Gladstone, P.M., Lope, Jr., Rosario, F.F., Silva, M.F., Bezerra, M.C. and Lima, E.A. (2003) *Oilfield Scaling Part I: Mathematical and Laboratory Modeling*, SPE 81127, presented in SPE American and Caribbean Petroleum Engineering Conference in Port of Spain Trinidad West Indies.

Bedrikovetsky, P.G., Gladstone, P.M., Lope, Jr., Rosario, F.F., Silva, M.F., Bezerra, M.C. and Lima, E.A. (2003b) *Oilfield scaling part II: Productivity Index Theory*, SPE 81128, SPE Latin American and Caribbean Petroleum Engineering Conference, Port-of-Spain, Trinidad and Tobago.

Bedrikovetsky, P.G., Gladstone, P.M., Lope, Jr., Rosario, F.F., Silva, M.F., Bezerra, M.C. and Lima, E.A. (2004) *Barium Sulphate Oilfield Scaling: Mathematical and Laboratory Modeling*, SPE 87457, SPE International Symposium on Oilfield Scale, Aberdeen, United Kingdom.

Civan, F. (2001) *Modeling Well Performance under Non Equilibrium Deposition Condition*, SPE 67234, presented at SPE production and Operations Symposium Oklahoma, USA.

Crabtee, M., Eshinger, D., Fletches, P., Johnson, A. and King, G (1999) Fighting Scale – Removal and Prevention, Oilfield Review, Schlumberger Autumn.

Fadairo, A.S.A. (2004) Prediction Scale Build Up Rate around the Well Bore, MSc Thesis, Department of Petroleum Engineering, University of Ibadan, Nigeria.

Fadairo, A.S.A. Omole, O. and Falode O. (2008) 'Effect of Oilfield Scale on Mobility Ratio', SPE 114488 Gas Technology Symposium 2008 Joint Conference held in Calgary, Alberta, Canada, 16–19 June 2008.

Frank, F., Chang and Civan, F. (1991) *Modeling of Formation Damage Due to Physical and Chemical Interaction between Fluid and Reservoir Rock*, SPE 22856. SPE Annual Technical Conference and Exhibition, Dallas, Texasn

Haarberg, T., Selm, I., Granbakken, D.B., Østvold, T., Read, P. and Schmidt, T. (1992) Scale Formation in Reservoir and Production Equipment during Oil Recovery II" equilibrium Model, *SPE Journal Production Engineering*, Volume 7, Number 1n

Moghadasi, J., Sharif, A., Kalantari, A.M. and Motaie, E. (2006a) *A New Model to Describe Particle Movement and Deposition in Porous Media,* SPE 99391, presented at 15th SPE Europe Conference and Exhibition, Vienna, Austria.

Oddo, J.E. and Tomson, M.B. (1994) 'Why scale forms in the oilfield and method of predict it', SPE 21710, *SPE Journal Production and Facilities*, Volume 9, Number 1n

Richards, S.G. (1968) Effect of Brine Concentration and Pressure Drop Gypsum Scaling in Oil Well, SPE 1830, *Journal of Petroleum Technology*, Volume 20, Number 6n

Robert, B.E (1997) Effect of Sulphur Deposition on Gas Well Performance, SPE 36707, *SPE Annual Technical Conference and Exhibition in Denver*, Colorado.

Rocha, A.A., Frydman, M., Fontoura, S.A.B., Rosario, F.F. and Bezzarra, M.C. (2001) *Numerical Modelling of Salt Precipitation During Produced Water Re-injection, SPE 68336*, International Symposium on Oilfield Scale, Aberdeen, United Kingdomn

Rosario, F.F. and Bezerra (2001) *Scale Potential of a Deep Water Field Water Characterization and Scaling Assessment,* SPE 68332, International Symposium on Oilfield Scale, Aberdeen, United Kingdom.