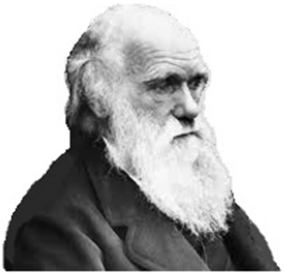
Available online at www.worldnewsnaturalsciences.com



World News of Natural Sciences

An International Scientific Journal

WNOFNS 34 (2021) 98-112 EISSN 2543-5426

Numerical Simulation of Reservoir Formation Damage Due to Mud Filtrate Invasions

T. A. Adeosun[1,*], **F. O. Akinpelu**[2] and **M. A. Adabanija**[3]

[1]Department of Mineral and Petroleum Engineering, Yaba College of Technology, Lagos, Nigeria

[2]Department of Pure and Applied Mathematics, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

[3]Department of Earth Sciences, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

***E-mail address: adebaba2001@yahoo.com**

ABSTRACT

This paper examined the numerical simulation of mud filtrate invasion process quantitatively with finite difference scheme that includes the effects of mudcake growth in oil well damage. Most of the existing models are empirical, experimental or rather complex. Efforts have been made to develop the linear flow model involving the modification of Darcy's equation for determination of mudcake porosity-permeability and thickness through formation pressure near wellbore. The results show the effects of pressure transient on cake buildup over a considerable time intervals. Results also characterized cake parameters and time into low and high permeability zones that are strictly linear with pressure change and supercharging observed during the sensitive formation testing.

***Keywords*: simulation, drilling fluids, formation damage, mud filtrate, mudcake, thikness**

Nomenclature

f_s	Solid fraction,	μ_f	fluid viscosity [cp],	ϕ_o	Initial porosity,
p	Applied filtration pressure [psi]	r_x	Radial direction,	ϕ_{mc}	Mudcake porosity,
p_o	Initial pressure [psi],	a	Adhesion factor,	ϕ_{mco}	Mudcake porosity at 1psi,

(Received 18 November 2020; Accepted 03 December 2020; Date of Publication 04 December 2020)

P_{mc} Pressure across mudcake [psi], a_o Initial adhesion factor, m Exponent defined index,

p_{max1} Maximum pressure [psi], a_g Local specific filtration, n Power law exponent,

p_t Total pressure [psi], c Exponent defined, δ Compressibility multiplier,

p_s Solid pressure [psi], c_t Total compressibility, B Specific cake volume $[ft^3/lb]$,

v Pressure up compressibility exponent, k Permeability [md], Δp Change in pressure [psi],

v_1 Pressure down compressibility expo, k_{mc} Mudcake permeability [md],

Δx Change distance, v_s Volume of solid suspension, k_{mco} Mudcake permeability at 1psi,

X_{mc} Exponent of linearity, v_L Volume of liquid suspension, v_x Flow rate (Darcy law),

T_{mc} Mudcake thicknes.

1. INTRODUCTION

Formation damage in oil wells is any process that causes an undesirable reduction of permeability and also a reduction in the natural inherent productivity of an oil producing formation (Civan, 2007; 2015). It is a condition of spatial distribution of fluids in the near-wellbore region caused by mud filtrate invasion, clay swelling, organic waxes, fine migration, scale formation and emulsions (Abdolreza *et al,* 2013). The adverse effects of these filtrates results in blockage of pore spaces, flow assurance, high viscosity, pipelines corrosion and sweep efficiency (Isehunwa and Falade, 2012). Most of the existing methods to aid mitigation near oil well damages involve experimental and use of empirical models (Windarto *et al,* 2011). Conducting experiments, frequent shot-down of wells for proper well test analysis and pressure maintenance as required in existing analytical and semi-analytical models are highly expensive and time consuming (Civan, 2000, 2007; Dewan and Chenevert, 2001).

Mud filtrate invasion takes place in permeable rock formation penetrated by a well that is hydraulically overbalanced by mud circulation (Jianghui et al, 2005). The loss of drilling muds to the formation does not have immediate serious consequences except if the rate of loss increases or completely lost (Calcada *et al,* 2011); lost circulation is one of the most critical problems that can be encountered in rotary drilling. Furthermore, solid and liquid particles dispersed in the drilling fluid (mud) are trapped by the porosity resulting in permeability reduction and hence formation damage (Civan, 1994). Filtration from drilling fluids arises from the pressure differential between the hydrostatic pressure of the mud column and the formation pressure (Isehunwa and Falade, 2012), since the hydrostatic pressure in the borehole is always greater than the formation pressure, water filters into the porous medium, depositing a porous, permeable and compressible clay swelling or cake of mud particles on the wall of the borehole (Yim and Du Kwon, 2010).

In this paper, a linear flow system is considered involving the modification of Darcy equation for the determination of mudcake porosity and permeability as well as mudcake thickness. The lear flow models depends on the overbalance pressure, formation permeability, mudcake characteristics and invasion time. Numerical simulation has proved to be effective in simulating near wellbore damages which reveal the physical character of invasion profiles taking place under realistic petrophysical conditions (Jianghui *et al,* 2005).

2. STUDY AREA

The validation data sets were obtained from a Brown field in Niger Delta Nigeria situated in the Gulf of Guinea on the coast of West Africa between Latitude $3^{o}N$ and $6^{o}N$ and Longitude $5^{o}E$ and $8^{o}E$ (Aaron, 2005; Anieflok *et al*, 2013). The Niger Delta is a major hydrocarbon producing basin in Nigeria where intensive exploration and exploitation activities have been on since early 1960's owing to the discovery of commercial oil in Oloibiri-1 with well in 1956 (Reijers *et al*, 1996).

The section studied falls within the coastal swamp depositional environment of the Agbada Formation. Most of the important hydrocarbon reservoirs in the Niger Delta are within the paradic Agbada Formation (Aaron, 2005). These reservoirs are usually located in zones with structural and stratigraphic complexity (Aki & Ediene, 2018).

3. REVIEW OF LITERATURE

The earliest research efforts on mud filtration were directed at conducting experiments, use of empirical models and formulation of additives to provide properties compliant with API standards. In 2001, Dewan and chenevert carried out extensive filtration measurements which were made on about 100 water-based mud, about 2/3 being laboratory-mixed and 1/3 field muds. With this data base, they arrived at an empirical model which allows for the determination of mudcake parameters and which quantitatively reproduces virtually every aspect of filtration seen in the Laboratory.

Outman (1963) presented an analytic approach to mud filtrate invasion. He described the mechanism of filtration by a theoretical-empirical non-linear equation which was linearized and solved explicitly under certain conditions. The study demonstrated the effects of mud properties like viscosity on filtration rate with a major conclusion that several quantities that affect dynamic filtration have no counterpart in static filtration and therefore static filtration cannot be relied on as a measure of dynamic filtration vice versa.

Jianghui et al, (2005) described in their work a complete model invasion process quatitatively with invasion simulator that includes the dynamically coupled effects of mudcake growth. Specific parametric representation is assumed invasion model based on previously published laboratory experiments on mudcake buildup such as mudcake porosity, mudcake permeability, mud solid content and cross flow between adjacent layers, and gravity segregation.

In recent times, there have been renewed efforts to obtain improved robust models for predicting filtration losses. Tien and Bai (2003) observed that the conventional filtration theory under-predicts parameters and suggested improvements based on better estimation of the average specific cake resistance and the wet cake to dry cake mass ratios. Xu et al, (2008) proposed the equivalent cake filtration modeling to describe filtration in Newtonian and non-Newtonian fluids. Yim and Du Kwon, (2010) suggested improvement in average cake resistance values using the concept of filtration penetration.

Civan, (1998) presented a model to estimate the invasion depth of mud filtrate from water-based mud. The model includes the presence of mudcake layer and irreducible water saturation. The filtration velocity and mudcake thickness model was derived from Darcy law and mass conservation. The invasion depth is obtained from mud filtrate profile in the formation.

The model is verified using experimental data from literature. The invasion depth predicted by the present model was in agreement with the experimental results.

Most of the recent models however have not received widespread filed applications due to their complexities. This study developed a one-dimensional, linear partial differential equation for mud filtrate invasion in a typical Brown field using numerical and simulation approach for improved hydrocarbon recovery. The model proved accurate and simpler to use than many existing formulations.

4. MATHEMATICAL FORMULATION

The assumptions considered in the derivation are: the flow is linear and is governed by Darcy's law, the total pressure which is the sum of fluid and solid particles pressure and is assumed constant for the system, while the isothermal condition exists in the borehole.

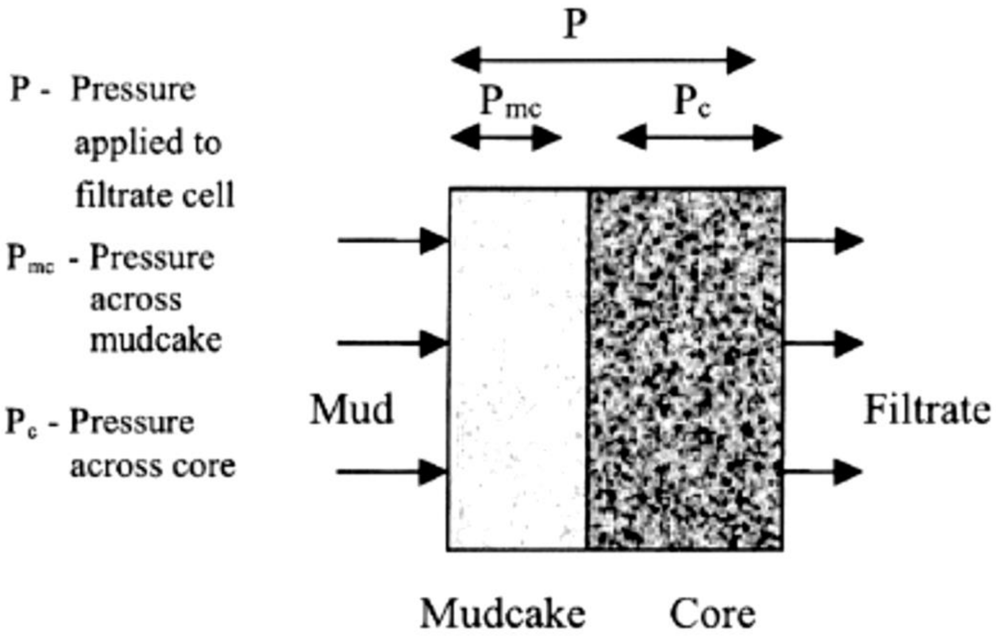


Figure 1. Model Filtration through a rock-core well (Dewan and Chenevert (2001)

Total system pressure = solid particles pressure + fluid pressure

$$p_t = p_s + p \qquad (1)$$

The solid particles pressure, p_s is the measurable effects of stress change while he total pressure, p_t is constant. According to rock-core well model of filtration (**Figure 1**) given by Dewan and Chenevert (2001), Derivative taken over the system gives

$$\frac{\partial p_s}{\partial x} = -\frac{\partial p}{\partial x} \qquad (2)$$

Cake compressibility under an external pressure is defined as:

$$ac = -\frac{1}{dv} \cdot \frac{d(dv)}{dp_s}$$

In terms of change with time, the total compressibility equation

$$ac_t . dv . \frac{dp_s}{dt} = -\frac{d(dv)}{dt} \tag{3}$$

Comparing equation (2) and (3) and the constant to a core $= \phi$, the porosity.

$$\frac{\partial}{\partial x}\left(-\frac{k}{\mu}\frac{\partial p_s}{\partial x}\right) dv = -ac_t dv \frac{\partial p_s}{\partial t} \tag{4}$$

$$\frac{k}{\mu}\frac{\partial^2 p_s}{\partial x^2} = FD . \phi c_t \frac{\partial p_s}{\partial t} \tag{5}$$

From Tiller (1975), we can establish equations (6) to (10)

$$\phi = \phi_o p_s^{-C} \tag{6}$$

$$k = \frac{1}{ax \rho_s (1 - \phi)} \tag{7}$$

$$ax = a_o p_s^n \quad and \quad 1 - \phi = B p_s^m \tag{8}$$

$$\frac{d\left({}^{1}\!/_{1 - \phi}\right)}{dp_s} = a_g \tag{9}$$

$$a_g = \frac{ac}{1 - \phi} \tag{10}$$

From equation (6) to (10) we establish equation (11)

$$k = \frac{1}{a_o \rho_s B p_s^{m+n}} \tag{11}$$

Dewan and Chenevert, (2001) provided a field unit conversion factor that takes into consideration the solid particulates pressure as $FD = 3792.2$ in equation (5). We developed the modified diffusivity equation for linear flow of filtrate through solid particulates which is sensitive to pressure of the formation.

$$\frac{\partial^2 p_s}{\partial x^2} = \frac{\phi \mu c_t}{0.0002637k} \frac{\partial p_s}{\partial t} \qquad (12)$$

Boundary condition: $\frac{\partial p_s}{\partial x}(x,t) = 0\,,\; at \quad \begin{cases} x = 0 \\ x = a \end{cases}, \qquad t > 0$

Initial condition: $p(x,0) = p_o\,, \quad 0 \le x \le a$

5. MUDCAKE POROSITY

The mudcake porosity relation was determined from Dewan and Chenevert, (2001) as a function of the pressure across it. During initial mudcake

$$\phi_{mc}(t) = \frac{\phi_{mco}}{p_{mc}^{\delta v}(t)} \qquad (13)$$

where the reference porosity ϕ_{mco} is an initial reference porosity measured when the mudcake is removed from the cell rather than the extrapolation of line 2 or 3 to1 psi in (**Figure 2**). Note that δ is a multiplier in the range 0.1-0.2, based on porosity-permeability cross plots for shaly sand. Although decompression and recompression to pressures not exceeding p_{max1} will take place along line (2) of Figure 4, whose equation is

$$\phi_{mc} = \frac{\phi_{mco}}{P_{mc}^{\delta v_1} P_{max1}^{\delta(v\, v_1)}} \qquad (14)$$

There is a believe that porosity which is measured when the mudcake is removed from the cell is ϕ_{mco} rather than the extrapolation of line 2 or 3 to 1 psi. The behavior of the line between 10 and 1 psi is immaterial because it is not encountered in practice (Dewan and Chenevert, (2001).

6. MUDCAKE PERMEABILITY

Equation (15 and 16) relate mudcake permeability to the pressure sensitivity across it. Mudcake s are very compressible and various experimenters, including Dewan and Chenevert (1993), have found that the permeability during initial mudcake buildup can be expressed by

$$k_{mc}(t) = \frac{k_{mco}}{p_{mc}^{v}(t)} \qquad (15)$$

where k_{mco} is an initial reference permeability defined at 1 psi differential pressure and v is a "compressibility" exponent. Typical v is in the range of $0.4\ to\ 0.9$. A value of zero would represent a complete in compressible mudcake whereas a value of unity would apply to a mudcake so compressible that its permeability would be inversely proportional to the differential pressure across it. Euqation (15), if used when pressure is sensitive to formation experience a decreasing implies a mudcake is completely elastic, exhibiting no hysteresis in compression and expansion as pressure across it increases or decreases.

However, this is not always true for mudcake to undergo some irreversible compression.

When pressure is reduced the expansion is less than the previous compression, meaning that permeability at a given pressure is lower. This is illustrated in **Figure 2** where the initial compression follows line (1) up to the maximum pressure, P_{max1} experienced by the mudcake. Then the initial expansion follows line (2), down to 10 psi at which point we believe it curves back up to k_{mco} at 1psi.

The equation of the straight portion of the line is

$$k_{mc} = \frac{k_{mco}}{P_{mc}^{v_1} P_{max1}^{(v-v_1)}} \qquad (16)$$

The above explanation applies at any stage of filtration for a more accurately portrayed by **Figure 2: A, B**.

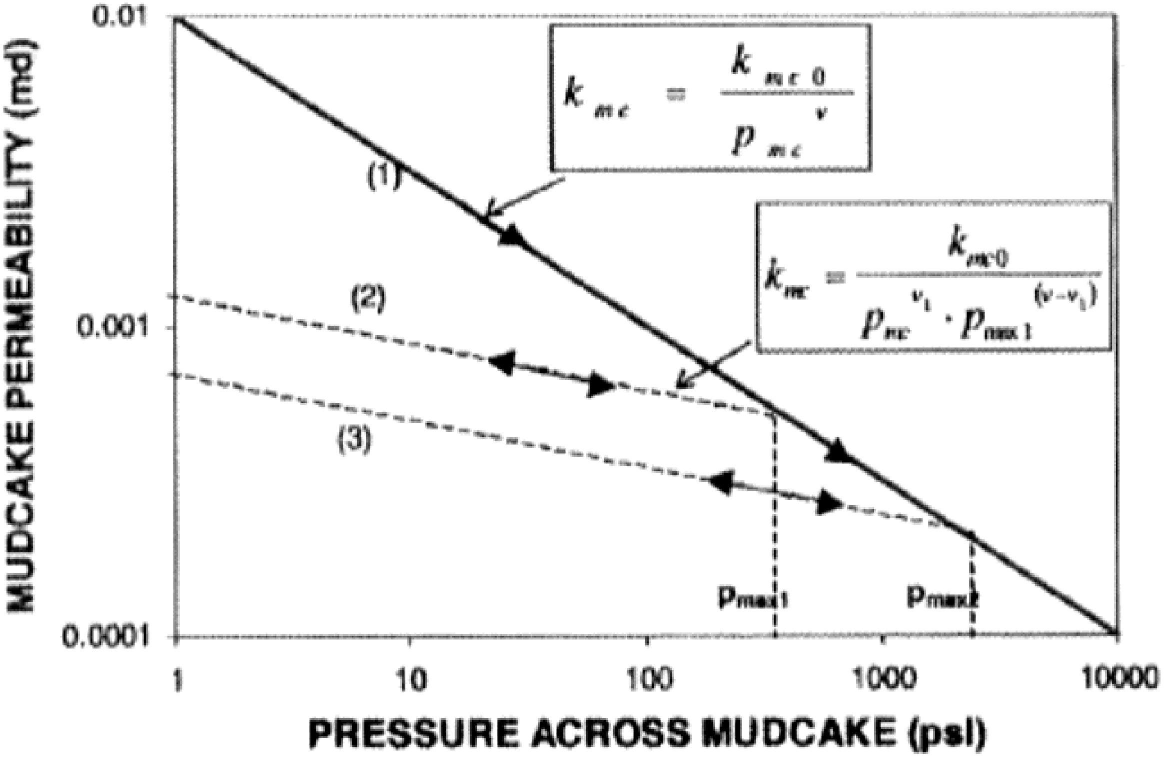


Figure 2(A). Illustration of porosity and Permeability hysteresis (Dewan and Chenevert, 2001)

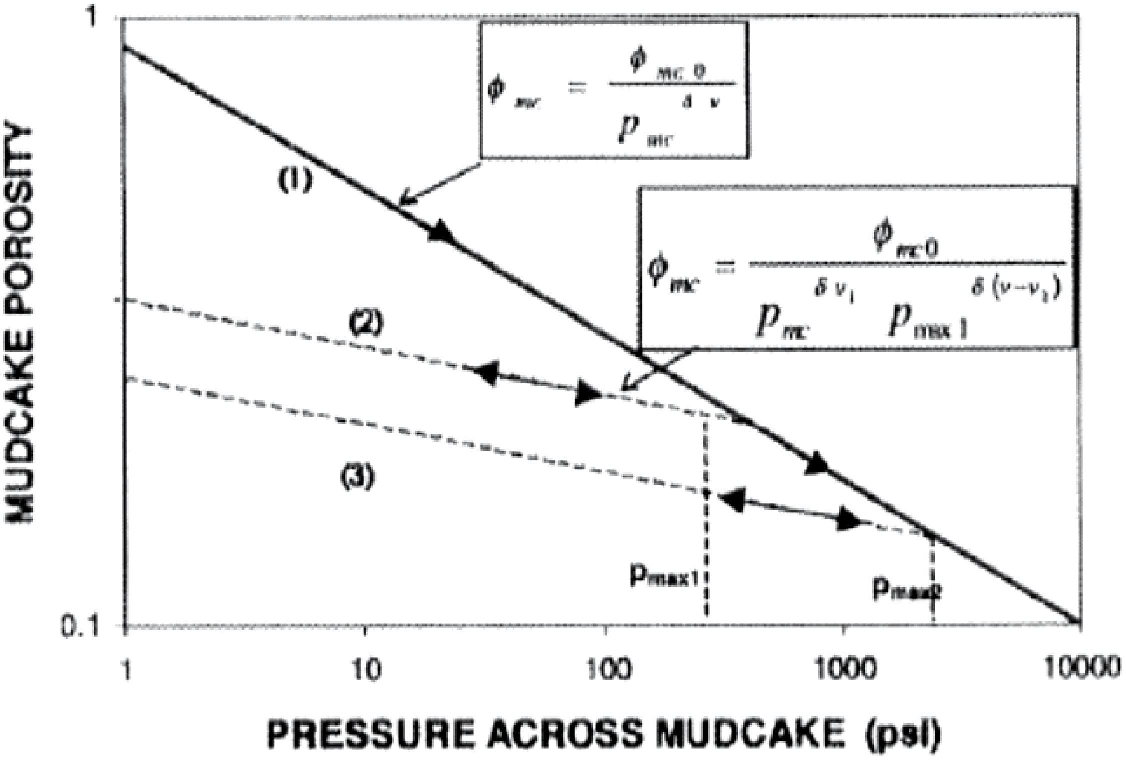


Figure 2(B). Illustration of porosity and Permeability hysteresis (Dewan and Chenevert, 2001)

7. MUDCAKE THICKNESS

The filtrate of a fluid suspension of solid particles can be constructed from first principle. Let $T_{mc}(t) > 0$ represent mudcake thickness as a function of time, where $x_{mc}(0) = 0$ indicates zero initial thickness. Let V_s and V_L denote the volume solid and liquid in the mud suspension respectively. Let f_s denote the solid fraction defined as

$$f_s = \frac{V_s}{V_s + V_L} \qquad (17)$$

If the solid particles do not enter the formation, Ferguson (1954) shows that the time of evolution of mudcake thickness $T_{mc}(t)$ satisfies the ordinary differential equation

$$\frac{dT_{mc}}{dt} = \frac{f_s}{(1 - f_s)(1 - \phi)} |V_x| \qquad (18)$$

Let V_x be the Darcy velocity of the filtrate through the mudcake. From equation (4) above, the corresponding Darcy velocity is given by

$$V_x = -\frac{k_{mc}}{\mu_f} \cdot \frac{\Delta p}{T_{mc}} \qquad (19)$$

Substituting equation (19) into equation (18), we have

$$\frac{dT_{mc}}{dt} = \frac{f_s}{(1-f_s)(1-\phi)} \cdot \frac{k_{mc}}{\mu_f} \cdot \frac{\Delta p}{T_{mc}} \qquad (20)$$

If mudcake thickness is infinitesimally thin at initial condition with time $t = 0$ and $T_{mc}(0)$. Equation (20) can be integrated to yield

$$T_{mc}(t) = \sqrt{\frac{2t\Delta p f_s}{(1-f_s)(1-\phi)} \cdot \frac{k_{mc}}{\mu_f}} \qquad (21)$$

This solution demonstrates that mudcake thickness in a linear flow grows with time in proportion to $\sqrt{t}$. Equation (21) is valid only when k_{mc} , ϕ_{mc} and Δp are constants and k_{mc} , ϕ_{mc} and Δp are function of time.

8. METHOD OF SOLUTION

The mechanism of mud filtrate invasion through any compressible cake medium described by linear flow of filtrate through of solid particulates that is sensitive to pressure of the formation given in equation (12) was resolved by finite forward difference method for x-direction with initial condition: $p(x, y, t = 0) = 5000\ psi$ = initial pressure in the well. Using finite forward difference, equation (12) can be written as

$$\left(\frac{p_{i+1,j}^{k+1} - 2p_{i,j}^{k+1} + p_{i-1,j}^{k+1}}{\Delta x^2}\right) = \frac{\phi\mu c_t}{\lambda k}\left(\frac{p_{i,j}^{k+2} - p_{i,j}^{k+1}}{\Delta t}\right) \qquad (22)$$

$$\frac{\Delta t}{\Delta x^2}\left(p_{i+1,j}^{k+2} - 2p_{i,j}^{k+2} + p_{i-1,j}^{k+2}\right) = \frac{\phi\mu c_t}{\lambda k}\left(p_{i,j}^{k+2} - p_{i,j}^{k+1}\right)$$

$$r_x\left(p_{i+1,j}^{k+2} - 2p_{i,j}^{k+2} + p_{i-1,j}^{k+2}\right) - \frac{\phi\mu c_t}{\lambda k} p_{i,j}^{k+2} = -\frac{\phi\mu c_t}{\lambda k} p_{i,j}^{k+1}$$

$$\left(r_x p_{i+1,j}^{k+2} - \left(2r_x + \frac{\phi\mu c_t}{\lambda k}\right) P_{i,j}^{k+2} + r_x p_{i-1,j}^{k+2}\right) = -\frac{\phi\mu c_t}{\lambda k} p_{i,j}^{k+1} \qquad (23)$$

$$r_x = \frac{\Delta t}{(\Delta x)^2}; \quad \lambda = 0.000264 \quad \Delta t = \frac{T}{N}; \quad \Delta x = \left(x_f - x_0\right)$$

The distance between the wellbore radius and the formation's outer –boundary is 0.635 cm to march the thickness of the filtration medium invaded with a constant sensitivity pressure condition at the outer boundary. The initial and boundary conditions for equations (12) and (21) are given as:

Boundary condition: $\frac{\partial p_s}{\partial x}(x,t) = 0\,, \;\; at \;\; \begin{cases} x = 0 \\ x = a \end{cases}, \qquad t > 0$

Initial condition: $p(x, 0) = p_o\,, \quad 0 \leq x \leq a$

Initial condition: $p(x, y, t = 0) = 5000\,psi$

Initial condition with time $t = 0$ and $T_{mc}(0)$

9. MODEL VALIDATION

The numerical simulator was implemented on Matlab and validated using real field data sets. Gaussian noise of $\mp$ 10% was introduced into the field data sets to obtain the synthetic data sets. In this particular case, mud properties are as follows: mudcake reference permeability $k_{mco} = 0.03\,md$, mudcake reference porosity $\phi_{mco} = 0.8$, solid fraction $f_s = 0.231$, formation porosity $\phi_{mc} = 0.25$, compressibility exponent for mudcake permeability $v = 0.63$, and exponent multiplier for mudcake porosity $\delta = 0.1$. water viscosity $\mu = 1cp$, wellbore (length) radius = $10.00\,cm$, Initial formation pressure $p = 5000\,psi$ and the recording continues for $1hr$ time step intervals. The field data sets were obtained from one of the NNPC joint venture operator.

10. RESULTS AND DISCUSSION

Mud filtrate invasion model was developed for one dimensional linear flow equation (12 and 21). The discretized solution equations (22 and 23) were used for the result in **Figure 3**. The result shows the pressure across the formation with time for various permeability values. The effect of this was that mud filtrate contained solid suspension and when these suspensions were allowed for few minutes, mudcake began to build up on the wellbore thereby restricting oil flow near wellbore. Another effect is that mudcake continue to thicken until $1cm$ thickness is reached at constant increase over time. At this point, the pressure has reduced to initial value when sandface pressure has reached its steady-state.

Figure 4 shows pressure loss due to mudecake buildup over time. Pressure across mudcake was highly sensitive to mudcake permeability over time. The pressure across mudcake increases with reference to permeability and became constant over a long period of time. **Figure 5** is the plot of mudcake porosity with time for various initial mudcake across the formation. This effect also has influence on mudcake growth and buildup over constant time with increasing mudcake porosity, knowing that the total amount of solid deposition decreases with increasing porosity.

Figure 6 shows the sensitivity analysis of mudcake reference permeability and mudcake permeability. Time evolution of mudcake across the formation is very important. The fect of this was that mudcake permeability decreases with increasing pressure across the mudcake and that the solid line ($k_{mc} = 0.03md$) in **Figure 7** revealed that mudcake permeability was stabilized at $0.8 \times 10^{-3}md$ after $1hr\;\;25mins$.

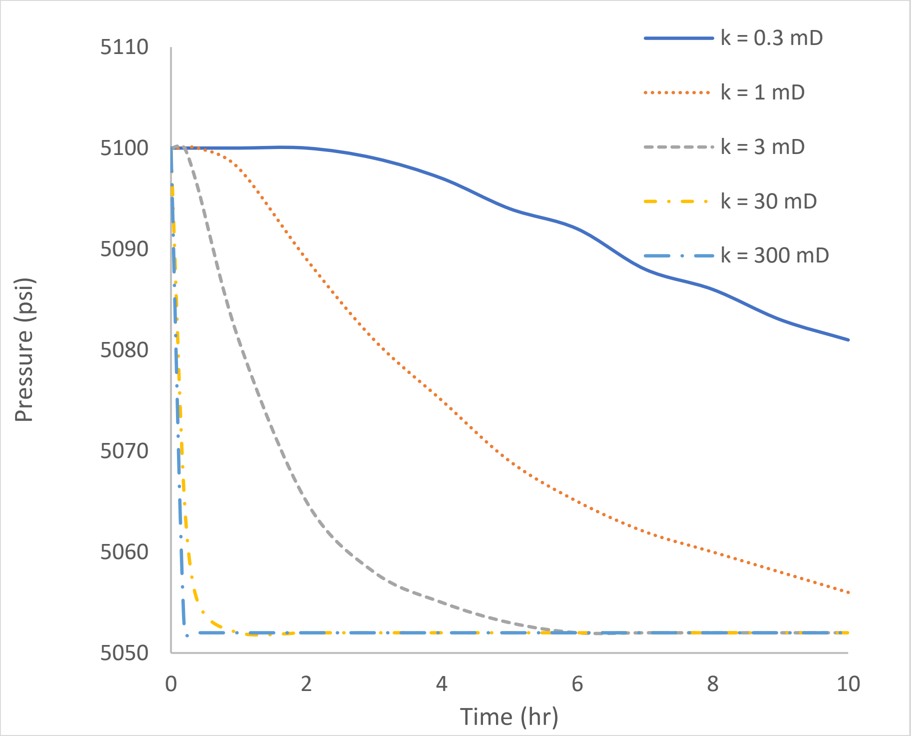


Figure 3. Pressure versus time evolution in rock-core permeability.

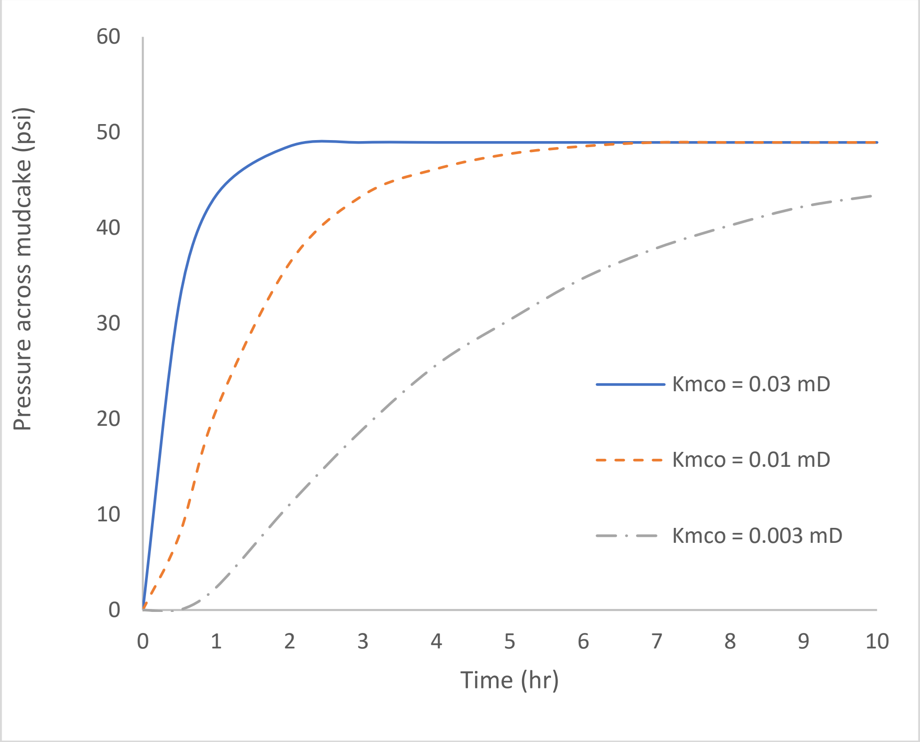


Figure 4. Pressure across mudcake versus time evolution in rock-core permeability.

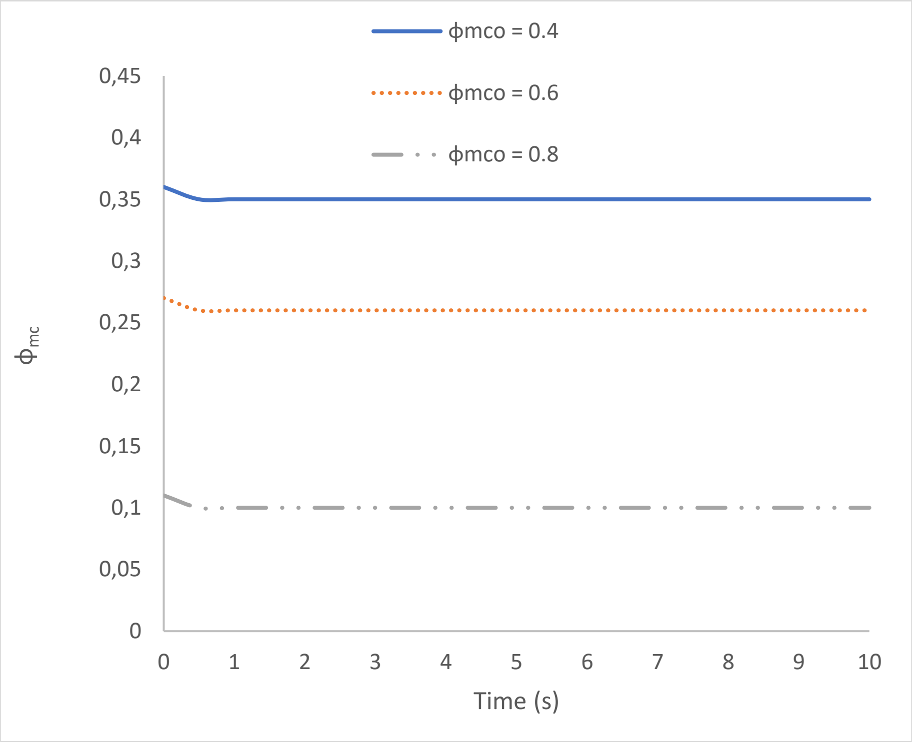


Figure 5. Mudcake porosity versus time evolution for different mudcake porosity.

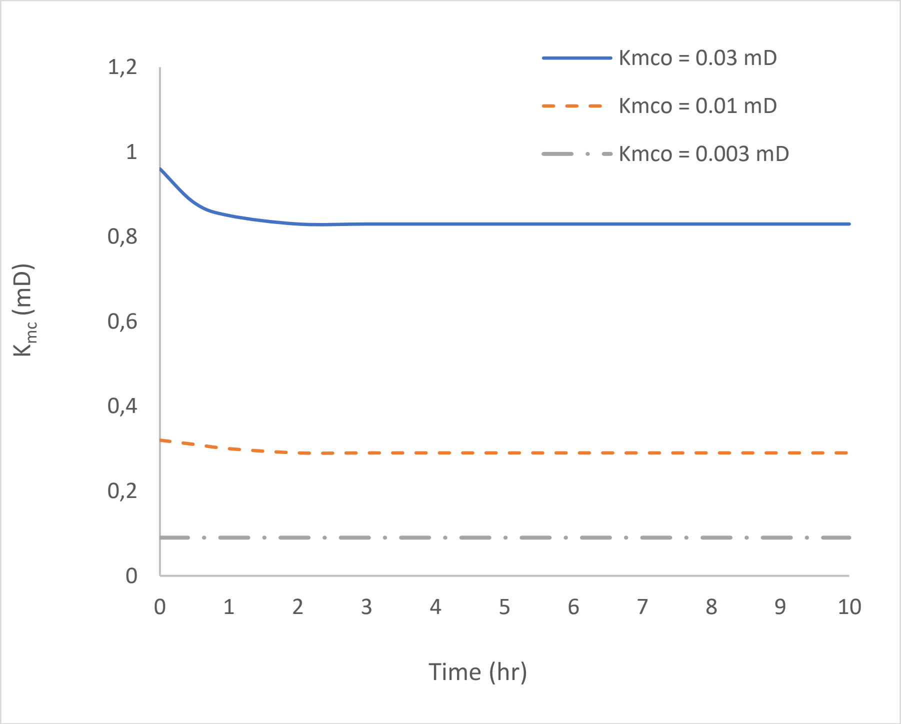


Figure 6. Mudcake permeability versus time evolution for different mudcake permeability.

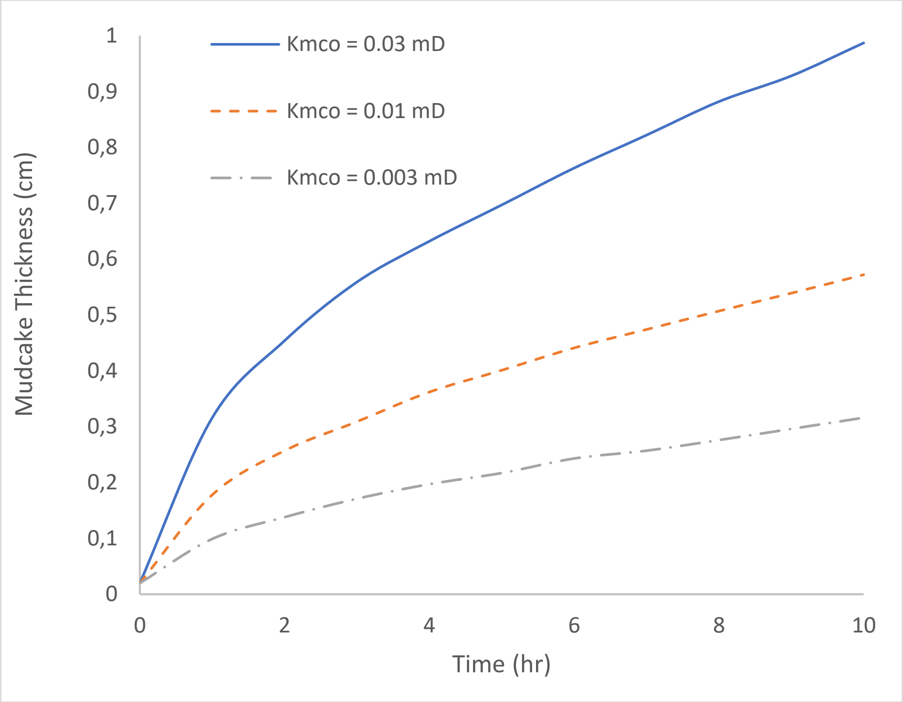


Figure 7. Mudcake Thickness versus time evolution for different mudcake permeability.

11. CONCLUSIONS

Numerical simulation has therefore proved to be effective tool in simulating near wellbore damages and transient sensitivity effect has been applied to the mud filtrate invasions. The study shows that:

a) Mud properties, cake parameters and time are major factors that are sensitive to control mud filtrate invasions.

b) Sensitivity analysis was performed using base case as referencing by varying the selected parameters in validating the simulator.

c) Mudcake properties, particularly permeability have a significant influence on the invasion process. Particulates solid fraction also has a considerable influence on mudcake growth.

d) For high permeability zones, both mudcake growth rate and mud filtrate invasion rate are controlled primarily by mud properties (i.e., mudcake permeability, mudcake porosity and mud solid fraction).

e) For low permeability zones, both mudcake growth rate and mud filtrate invasion rate will be influenced by formation properties (i.e., formation permeability endpoint).

f) Filtration invasion are sensitive to formation pressure and the factor of linearity in filtration equation and so the filtration equation has to be treated as strictly linear with mud thickness equation.

References

[1] Aaron, K. K. (2005): Perspective: big oil, rural poverty, and environmental degradation in the Niger Delta region of Nigeria; *Journal of Agricultural Safety and Health*, 11 (2) 127-134

[2] Abdolreza Dabiri, Mohammed Afkhami, and Hooman Fallah ((2013): Reservoir Fomation Damage due to Mud Filtration; Department of Petroleum Engineering Iran. *International Journal of Oil, Gas and Coal Engineering* Vol. 1, No. 1, pp. 1-5

[3] Aki E. E., V. E. Ediene, Characteristics and classification of soils derived from Awi sandstone formation in Awi, Akamkpa local government area of Cross River State, Nigeria. *World Scientific News* 112 (2018) 142-152

[4] Aniefiok E. Ite, Udo J. Ibok, Margaret U. Ite, and Sunday W. Petters, Petroleum Exploration and Production: Past and Present Environmental Issues in the Nigeria's Niger Delta. *American Journal of Environmental Protection* 1, no. 4 (2013): 78-90. doi: 10.12691/env-1-4-2

[5] Calcada, L. A., Scheid, C. M., De Araujo, C.A.O., Waldmann, A. T. A. and Martins, A.L (2011): Anaylsis of Dynamic and Static Filtration and Determination of Mudcake Parameters. *Brazilian Journal of Petroleum and Gas*, Vol. 5, No. 3, pp. 159-170

[6] Civan, Faruk (1994): Drilling Mud Filtrate Invasion – Improved Model and Solution; *Journal of Petroleum Science and Engineering*, Vol. 11, pp. 183-193

[7] Civan, Faruk (1998): Practical Model for Compressive Cake Filtration including Fine Particle Invasion. *AICHE Journal*, Vol. 44, No. 11 pp. 2398

[8] Civan, Faruk (2000): Reservoir Formation Damage-Fundamentals, Modeling, Assessment, and Mitigation; 2nd Ed., Gulf Professional Pub., Elsevier, 11-14.

[9] Civan, Faruk (2007): Formation Damage Mechanisms and Their Phenomenological Modeling. SPE-107875, 2-12.

[10] Civan, Faruk (2015): Reservoir Formation Damage; 3td Ed. ISBN: 978-0-12-801898-9. Gulf Professional Pub., Elsevier, pp. 11-14.

[11] Dewan, J. T. and Chenevert, M. E. (1993): Mudcake buildup and Invasion in low permeability Formations: Application to Permeability Determination by Measurement while Drilling; SPWLA/CWLS Symposium, June13-14, Calgary Alberta.

[12] Dewan, J. T. and Chenevert, M. E. (2001): a Model for Filtration of Water-Based Mud during Drilling: Determination of Mudcake Parameters. *Petropyhsics*, Vol. 42, No. 3, pp. 237-250

[13] Ferguson, C. K. and Klotz, (1954): Filtration of Mud during Drilling. *Petroleum Transactions of AIME*, Vol. 201, pp. 29

[14] Isehunwa, S. O. and Falade, G. K. (2012): An Approximate Theory of Static Filtration of Drilling Muds in Vertical Wells; Department of Petroleum Engineering, University of Ibadan, *ARPN Journal of Engineering and Applied Sciences*, Vol. 7, No. 1, pp. 26-31

[15] Jianghui, Wu, Carlois, Toress-Verdin, Kamy, Sepehrnoori and Mark A. Proett (2005): The Influence of Water-Based Mud Properties and Petrophysical parameters on Mudcake Growth, Filtrate Invasion, and Formation Pressure. *Petropyhsics*, Vol. 40, No. 1, pp. 14-32

[16] Outmans, H. (1963): Mechanics of Static and Dynamic Filtration in the Borehole; *SPE-491*, pp. 236-244

[17] Reijers, T. J. A., Petters, S.W., Nwajide, C. S. (1996): The Niger Delta Basin in: T.J.A. Reijers (Ed) Selected Chapters on Geology; SPDC Corporate Reprographic Service, Warri, Nigeria, pp.103-144.

[18] Tien C and Bai R. (2003): An Assessment of the Conventional Cake Filtration Theory. *Chem. Eng. Sci.* Vol. 58, pp. 1323-1336.

[19] Tiller F.M. (1975): Compressible Cake Filtration; In Scientific Basis of Filtration. K Ives (Ed). Noordhoff, London, U.K. pp. 315-397

[20] Xu T et al (2008): Equivalent Cake Filtration Model. *Chinese J. of Chem. Eng.* 16(2), 214-217

[21] Windarto, A., Yodi, G., Pudjo, S. and Edy, S. (2011): Modeling of Mud Filtrate Invasion and Damage Zone Formation. *Journal of Petroleum Science and Engineering*, Vol. 77, Issue 3-4, pp. 259-364