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Modeling the Rate of Mud Invasion in a Permeable Formation

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Abstract**—**The invasion of mud filtrates in to the permeable formation is an inevitable experience during drilling operations. It is usually associated with near-complete formation damage in the immediate vicinity of wellbore and the response of well log tools (especially the low penetration tools) are then greatly influenced by the mud filtrates instead of formation fluids which makes its interpretation more difficult. Hence, it is often necessary to know the possible spatial and time variation of mud filtrate concentrations in the porous media during invasion. This study presents a model technique for the numerical simulation of rate of mud invasion using a pressure transient analogy of mud concentration gradient. The model uses a finite difference element of 1000ft^3 divided into five (5) uniform gridblocks of length, 2ft each. The results of the study showed clearly that from the time and space of invasion process initialisation, the mud concentration diffuses into the porous medium. At early time of invasion, the mud filtrate is continuously diffused into the porous media while at later stage of invasion, mud concentration builds from the inner gridblocks facilitating the formation of filter cake at the wellbore. Further analysis of the results reveals that the displacement of the in-situ formation fluid by the invading mud is not a piston-like phenomenon as shown by the spatial variation of the mud filtrates concentration during the invasion period. However, the concentration gradient can be used to define the extent of mud filtrate invasion into the permeable formation

Keywords—Mud Concentration, Mud Flow rate, Mud invasion,Numerical Simulation, Permeable Formation

I. INTRODUCTION

During overbalanced drilling, a positive pressure differential exists between the mud hydrostatic pressure and the formation pressure. As a result, the adjacent formation is inevitably invaded by mud filtrates during mud filter cake build up. Basically, three types of mud filtration has been identified to be associated with drilling operations- beneath the bit filtration, static filtration and dynamic filtration[1,2].These filtration processes consequently result to three distinct zones of mud invasion into the permeable formation namely: an invaded zone extending to some depth into the formation, the internal filter cake of about few inches into the formation and the external filter cake deposited on the walls of the borehole [3]. The presence of mud filtrates in the immediate vicinity of the wellbore remarkably influences the response of well log tools and its measurements [4]. Since well log tools can only penetrate few inches into the formation, it is almost certain that the depth of invasion may have extended relatively farther. Hence, the logging tool at this point is significantly influenced by the mud filtrate properties instead of the in-situ fluid.This is particularly true for shallow investigation tools such as CNL (Compensated Neutron log), LDT (Litho Density log), MLL (Micro Later log) etc[5]. The implication of this is that there can be misinterpretations in the reservoir rock and fluid properties. Over the years, the idea of mud invasion has made the interpretation of shallow logging tools very critical to interpret. In some cases, deep penetration tools are rather resorted to as a result of its ability to penetrate beyond the invasion zones. However, these tools still do not see clearly enough and therefore still have remarkable uncertainties in the measurements which are relatively compensated for by introducing correction factor terms[6]. The method of interpretation has been based on the assumption that the mud filtrate invasion front advances in a radial piston-like fluid saturation front [7]. However, [8] showed that the piston-like frontal advancement does not hold for low permeability formations.This is also supported by [9] whose study on mud filtrate depth of invasion at the wellbore vicinity revealed that displacement of in-situ fluid by the mud does not conform to the piston-like assumption. Several factors responsible for mud filtrate invasion have been investigated by several works to include dynamic filtration rate; rock petrophysics, fluid properties and capillary pressure; bed geometry; mud properties, cake parameters and time{ [10][11][12][13][14]}. Modeling the rate of the invasion become necessary after identifying the rate as one of the factor responsible for invasion to understand and minimize formation filtrate invasion.

The Rest of the paper is organized as follows, the next Section contains related work and context of study area, Section III contain details of the modelling and essential data used for the work, Section IV describe the results and their discussion and, Section V concludes the research.

II. RELATED WORK

Several numerical approaches has been presented for the evaluation of mud filtrate invasion. In the work of [15] a numerical approach was used to analyze filtrate invasion in deviated wells. The results showed that mud cake build up at static conditions can create a zone of reduced permeability around the wellbore which can be minimized by reducing the solid pressure. Similar studies by [16] for horizontal wells based on approximate analytical solutions also showed that controling the volume of the invading mud filtrate can be achieved by controlling the mud viscosity, specific mud cake volume and other properties on which filtration volume depends. Invasion has been shown to be greatly influenced by well geometry with the underlying principles based on mass conservation and Darcy's law.

During drilling operation, it may be necessary to know the rate at which mud filtrate invades the permeable formation. This can help in remedying the inevitable instances associated with mud filtrate imbibitions into the formation as shown in the literatures above. In this work, a model technique based on finite element analysis is presented for modelling the rate of mud filtrate invasion into the formation by applying a central finite difference approximation to the classical Darcy flow in porous media equation. The model represents a more practical scenario in which the mud filtrates are diffused in the porous media with varying concentration across the grids. The systems of equations generated are resolved using MATLAB and model parameters are presented and discussed accordingly.

III. METHODOLOGY

A. Model Development

Modeling the rate of mud filtrate invasion as used in this study considers a finite element of mud particle as shown in Figure 1 that is forced into the formation by the pressure overbalance. Invoking the empirical mass conservation law, we will have;

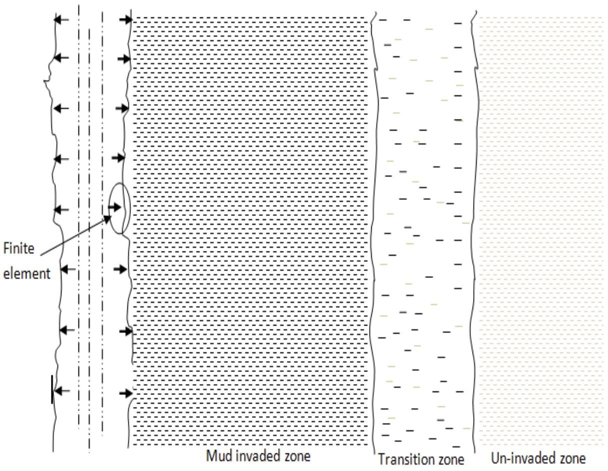

Figure 1: Diagrammatic Representation of Mud Invasion Environs

$$M_i = M_o + L_r \tag{1}$$

Where, Mi= mass of mud filtrate into the permeable ,Mo = mass of mud filtrate out of the permeable, Lr= Mud loss in the permeable formation. The mud loss term, L_r , is in two forms namely: the retention in the rock pores and absorption (common in carbonate rocks) which is assumed negligible in this study. In differential form, Equation (1) can be written as follows.

$$\frac{\partial}{\partial t}M_i = \frac{\partial}{\partial t}[M_o + L_r]$$

$$\frac{\partial}{\partial t}M_i = \frac{\partial}{\partial t}M_o + \frac{\partial}{\partial t}L_r \tag{2}$$

Assuming the mud density to remain constant throughout drilling process, i.e., the mud is void of entrained gases and the effects of bottom-hole temperature and mud contamination by formation fluid is negligible, Equation (2) can be expressed in terms of density as follows:

$$\frac{\partial}{\partial t}M_i - \frac{\partial}{\partial t}M_o = \frac{\partial}{\partial t}L_r$$

$$\rho q\,|_i - \rho q\,|_o = \frac{\partial}{\partial t}L_r$$

$$\triangle(\rho q)\,|_o = \frac{\partial}{\partial t}L_r \tag{3}$$

Where, ρ = mud density and q= mud flow rate which can be evaluated from the Darcy's classical equation given as q = -KA/μ *dP/dL . Applying the Darcy Equation to Equation (3) using a rectangular coordinate system will result to Equation (4).

$$-\triangle\left(\rho\frac{K_xA}{\mu}\frac{dP}{dx}\right) - \triangle\left(\rho\frac{K_yA}{\mu}\frac{dP}{dy}\right) - \triangle\left(\rho\frac{K_zA}{\mu}\frac{dP}{dz}\right) = \frac{\partial}{\partial t}L_r \tag{4}$$

The mud loss term can be evaluated as function of formation V_P reduction due to porosity reduction (caused by mud retention) using Kozeny-Carman equation for porosity alteration given in Equation (5). For a finite element of constant cross-secttional area as shown in Figure .2, the following relationships can be implemented, V_B= A_X△x=A_y△y=A_z△z=△x△y△z

Hence, making these substitutions yields Equation (6) below.

$$\phi = \phi_o(1 - \sigma) \tag{5}$$

Where Φ= altered porosityΦo = original porosity and σ = volumetric concentration of mud particles in the rock pores. Therefore, actual $V_P = \Phi V_B$

$$-\triangle\left(\rho\frac{K_xA}{\mu}\frac{dP}{dx}\right) - \triangle\left(\rho\frac{K_yA}{\mu}\frac{dP}{dy}\right) - \triangle\left(\rho\frac{K_zA}{\mu}\frac{dP}{dz}\right) = \frac{\partial}{\partial t}(\phi \times V_B) \tag{6}$$

$$-\Delta\left(\rho\frac{K_xA}{\mu}\frac{dP}{dx}\right)-\Delta\left(\rho\frac{K_yA}{\mu}\frac{dP}{dy}\right)-\Delta\left(\rho\frac{K_zA}{\mu}\frac{dP}{dz}\right)=\frac{\partial}{\partial t}(\phi\,\Delta x\,\Delta y\,\Delta z) \quad (7)$$

$$\left[-\Delta\left(\rho\frac{K_x\,\Delta y\,\Delta z}{\mu}\frac{dP}{dx}\right)-\Delta\left(\rho\frac{K_y\,\Delta x\,\Delta z}{\mu}\frac{dP}{dy}\right)-\Delta\left(\rho\frac{K_z\,\Delta x\,\Delta y}{\mu}\frac{dP}{dz}\right)\right]\frac{1}{\Delta x\,\Delta y\,\Delta z}=\frac{\partial}{\partial t}\phi \quad (8)$$

$$-\frac{\Delta}{\Delta x}\left(\rho\frac{K_x}{\mu}\frac{dP}{dx}\right)-\frac{\Delta}{\Delta y}\left(\rho\frac{K_y}{\mu}\frac{dP}{dy}\right)-\frac{\Delta}{\Delta z}\left(\rho\frac{K_z}{\mu}\frac{dP}{dz}\right)=\frac{\partial}{\partial t}\phi \quad (9)$$

Taking limits and considering an isotopic system, Equation (9) reduces to Equation (10)

$$\frac{\rho K}{\mu}\left[\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}\right]=-\frac{\partial}{\partial t}\phi \quad (10)$$

Or

$$\frac{\rho K}{\mu}\nabla^2 P=-\frac{\partial}{\partial t}\phi \quad (11)$$

Since the gradient responsible for mud filtrate invasion is the mud concentration in the porous media, the V^2P gradient term can be replaced by the concentration gradient term, V^2C in Equation (12) below.

$$\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}=-\frac{\mu}{\rho K}\frac{\partial}{\partial t}(\phi_0-\phi_0\sigma) \quad (12)$$

$$\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}=-\frac{\mu}{\rho K}\left[\frac{\partial}{\partial t}\phi_0-\frac{\partial}{\partial t}\phi_0\sigma\right] \quad (13)$$

Since ϕ_0 is constant, $\partial/\partial t\ \phi_0 = 0$ which reduces Equation (13) to Equation (14)

$$\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}=\frac{\mu}{\rho K}\frac{\partial}{\partial t}\phi_0\sigma \quad (14)$$

Recall, $\sigma = V_m/V_p$ and $\phi_0 = V_p/V_B$ $\Longrightarrow \phi_0\,\sigma = V_p/V_B \times V_m/V_p = V_m/V_B$ .Introducing these relationships into Equation (14) simplifies to Equation (15).

$$\nabla^2 C=\frac{\mu}{\rho K V_B}\frac{\partial}{\partial t}(V_m) \quad (15)$$

But $q_m=(\partial V_m)/\partial t$ such that at any time during mud invasion process, the mud entering the entering the system is evaluated as follows:

$$q_m=\frac{\partial V_m}{\partial t}\Big|_n=\frac{V_n-V_{n-1}}{t_n-t_{n-1}}=\frac{V_{n+1}-V_n}{t_{n+1}-t_n}$$

Hence,

$$q_{m,n}=\frac{V_n-V_0}{t_n-t_0}$$

for invasion process between time t_0 to t_n.

Therefore, Equation (15) becomes;

$$\nabla^2 C=\frac{\mu}{\rho KBV}q_{m,n} \quad (16)$$

Equation (16) is the mathematical model for the invasion process and filter cake formation which shall be numerically resolved in the preceding section using MATLAB.

B. Numerical Implementation

Considering the gridblocks of the porous medium in Figure 2 with 2ft grid blocks of 10ft in x, y and z-directions, assigned inner and outer boundary conditions. The mud in the borehole that is ready for invasion initialization has a concentration value C_o and as the process progress, the concentration of the mud in the porous medium changes from grid to grid (i.e. from point to point) until a certain length is reached where the concentration gradient is zero. At such point the invasion can no longer continue. This point marks the end of the invaded zone.

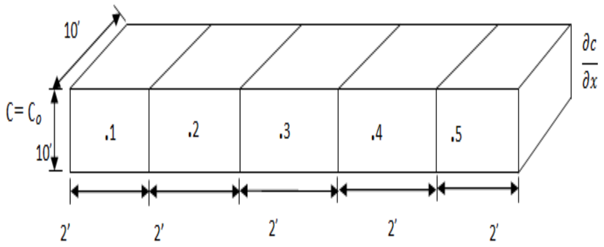

Figure 2: Gridblock System used for the Implementation of the Numerical Simulation

Since the LHS of Equation (16) is in second order, a central finite difference can be used to approximate with approximately zero truncation error as follows.

$$\frac{\partial^2 C}{\partial x^2}=\frac{C_{i+1}-2C_i+C_{i-1}}{(\Delta x)^2} \quad (17)$$

Hence,

$$\frac{C_{i+1}-2C_i+C_{i-1}}{\Delta x^2}=\frac{\mu}{\rho kBv}q_{m,n} \quad (18)$$

$$C_{i+1}-2C_i+C_{i-1}=\frac{\mu}{\rho kBv}q_{m,n}\Delta x^2 \quad (19)$$

$$C_{i+1}-2C_i+C_{i-1}=4.8\times 10^{-3}q_{m,n}\Delta x^2 \quad (20)$$

Using $C_0 = 100$ at the lower image node of gridblock 1 (which is completely invaded) and $C_6 = C_5$(since $\partial C/\partial x=0$) at the upper image node of gridblock 5, the following systems of equations can be generated at $q(_{m,n}) = 200$ ft3/day. Water Based Mud data for the simulation is presented in Table 1.

Table 1: Data for Model Solution (WBM)

S/No	Variables	Values
1.	Density	12.5lb/gal
2.	Viscosity	30cp
3.	Permeability	0.5Darcy

$$\begin{bmatrix} -2 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} = \begin{bmatrix} -96.16 \\ 3.84 \\ 3.84 \\ 3.84 \\ 3.84 \end{bmatrix} \tag{21}$$

As the invasion progress, the mud flow decreases as a result of plugging from initial invasion; thus resolving the model using mud flowrate of 150 ft^3/day and updating the value of Co to C1 from results of Equation (21) results to Equation (22).

$$\begin{bmatrix} -2 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} = \begin{bmatrix} -77.92 \\ 2.88 \\ 2.88 \\ 2.88 \\ 2.88 \end{bmatrix} \tag{22}$$

Similarly, at flow rates 100 ft^3/day, 50 ft^3/day and 0 ft^3/day (when invasion stops), the following systems of equations can be generated.

$$\begin{bmatrix} -2 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} = \begin{bmatrix} -67.36 \\ 1.92 \\ 1.92 \\ 1.92 \\ 1.92 \end{bmatrix} \tag{23}$$

$$\begin{bmatrix} -2 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} = \begin{bmatrix} -58.72 \\ 0.96 \\ 0.96 \\ 0.96 \\ 0.96 \end{bmatrix} \tag{24}$$

$$\begin{bmatrix} -2 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} = \begin{bmatrix} -55.08 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{25}$$

IV. RESULTS AND DISCUSSION

The sets of Equations (21-25) were resolved using MATLAB and the estimated mud concentration at each gridblock is presented in Table 2. The input mud flow rate was varied from 200 to 0 ft^3/day in order to accommodate the relative reduction in volume of the mud into the porous media caused by macro plugging from the previous mud particles retained in the porous media during the invasion process. A zero mud flow rate was used to simulate the end of in-situ fluid displacement by the invading mud filtrates.

Table 2: Mud Concentration and at different grid

MUD FLOW RATE	MUD CONCENTRATION AT DIFFERENT GRIDBLOCKS				
	C_1	**C_2**	**C_3**	**C_4**	**C_5**
200	80.800	65.4400	53.9200	46.2400	42.4000
150	69.280	57.7600	49.1200	43.3600	40.4800
100	59.680	52.0000	46.2400	42.4000	40.4800
50	55.080	51.2400	48.3600	46.4400	45.4800
0	55.0800	55.0800	55.0800	55.0800	55.0000

The results in Table 2 reveal that from the time and space of invasion process initialisation, the mud concentration diffuses into the porous medium. This is indicated by the variation of mud concentration from C_1 equals 80.80 to a value of C_5 equals 42.00. The variation is rapid due to the petrophysical properties used for the model solution which shows that the formation is highly porous and permeable. An initial Co = 100% was used to implement the solution to Equation (21) while the subsequent Equations (22-25) were implemented with Co = C1 of the preceding matrix.

The results shows that during the mudcake build up process, mud concentration diffuses into the porous medium but as time progresses, the mud concentration starts to build up from an inside gridblock and builds up back to a mud concentration value that is equal to that of the first grid block. This can be seen from the solution of matrix four and matrix five of Equations (24) and (25) respectively. This effect of mudcake build up also explains the reason why the mud flowrate reduces from its initial value to a value of 0ft^3/day. At this no flow condition in the wellbore, the porous and permeable formation may have been completely damaged in the near wellbore region to the point where mud particles and filtrate can no longer penetrate the system .its consequence is the termination of the filtration process due to excessive mud particle accumulation (high mud concentration) in the near wellbore area of the invasion environment. A more detailed analysis of mud concentration build up as a function of mud flow rate for each gridblock is shown in Figures (3-8).

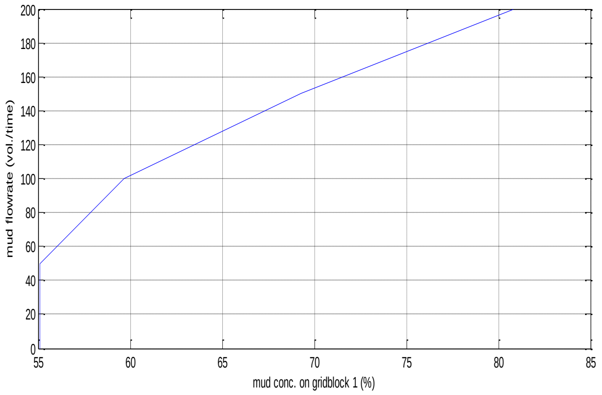

Figure 3: Mud Flow Rate (ft^3/day) versus Mud Concentration (%) for Gridblock1

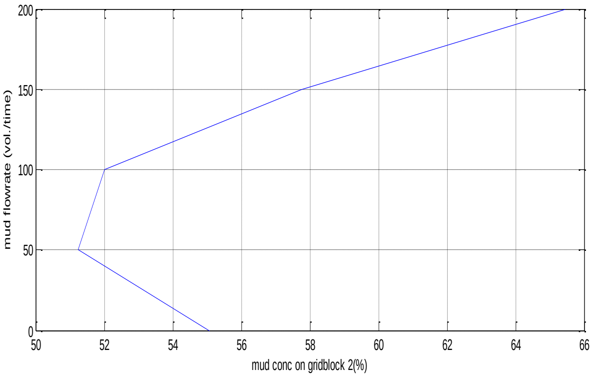

Figure 4: Mud Flow Rate (ft3/day) versus Mud Concentration (%) for Gridblock2

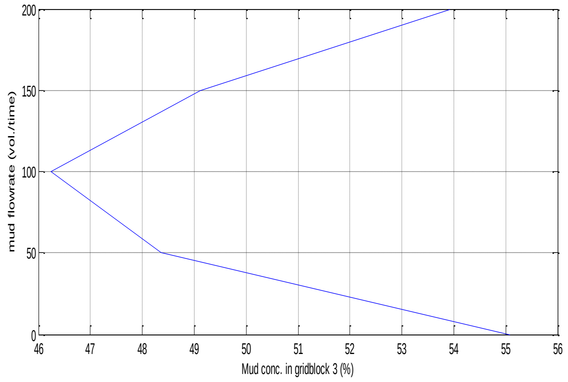

Figure 5: Mud Flow Rate (ft3/day) versus Mud Concentration (%) for Gridblock3

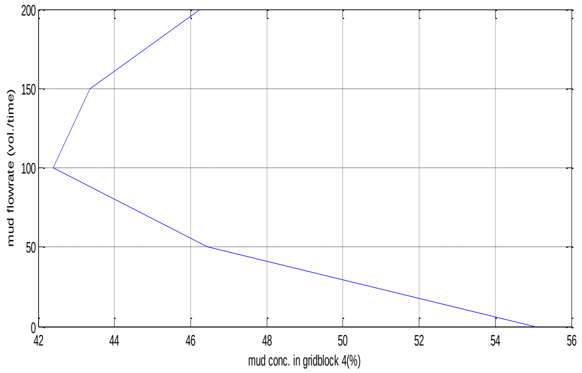

Figure 6: Mud Flow Rate (ft3/day) versus Mud Concentration (%) for Gridblock4

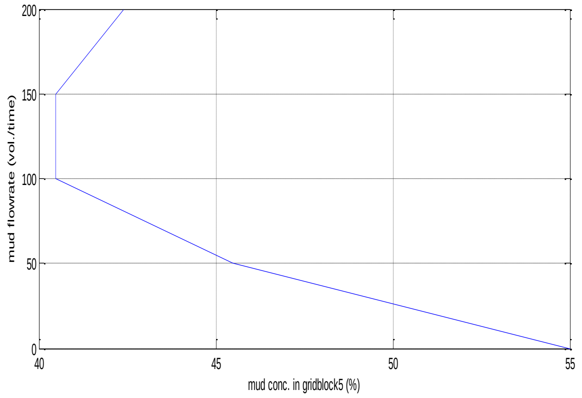

Figure 7: Mud Flow Rate (ft3/day) versus Mud Concentration (%) for Gridblock5

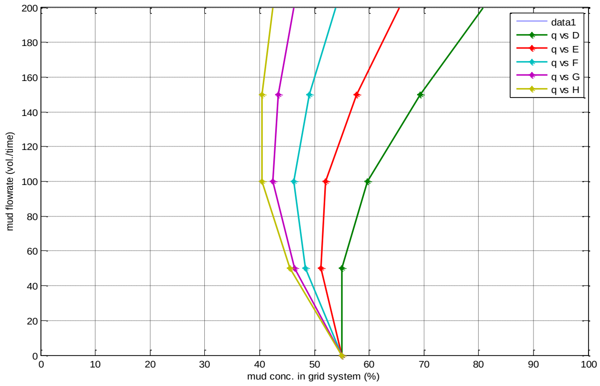

Figure 8: Comparative plot of Mud Flow Rate (ft3/day) versus Mud Concentration (%) for each Gridblock (D= Gridblock1, E= Gridblock2, F= Gridblock3, G= Gridblock4 and H = Gridblok5)

V. CONCLUSION

In this study, the diffusion of mud filtrates into the formation has been investigated using pressure transient analogy of mud concentration gradient as given in Equation (16). The change in volume of the mud that invaded the permeable formation with time was represented with the mud flowrate into the permeable formation. Variations in the mud flowrate was use to account for the mud concentration distribution in each gridblock. It was observed that as the process continues, the mud concentration starts building up causing a pore damage and impediment to further flow of the filtrate into the permeable formation. The filter cake formation can be accounted for from the build up of mud concentration at late time of the invasion process. The diffusion of the mud concentration accounts for the invasion process and this process terminates when the mud concentration buildup is high enough for further flow impediment. The observed relationship between the mud flowrate and the mud concentration plots of each gridblock reveals that the process of mud invasion is not necessarily a piston-like displacement in which a sharp boundary exists between the mud invaded zone, the transition zone and the un-invaded zone. However, the values of the concentration gradient can be used to set a criterion and establish a rule of thumb to distinguish the three zones during mud invasion for easier interpretation of well log data.

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