Applied Mechanics and Materials Vol. 819 (2016) pp 376-381
Submitted: 2014-11-10
© (2016) Trans Tech Publications, Switzerland
Revised: 2015-02-01
doi:10.4028/www.scientific.net/AMM.819.376
Accepted: 2015-07-16

Validation of a CFD Non-NewtonianEulerian-EulerianModel for Predicting Wellbore Filter Cake Formation

Ali I. Shehata[1,a],Mohamed Shokry[2,b], Khalid M. Saqr[1,c*], Mohamed Shehadeh[1,d]

[1]College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, P.O. Box 1029, Abu Qir, Alexandria, EGYPT

[2]Nabors Drilling International, JAFZA South Zone 2 Plot No. S20702, P.O. Box 263166, Jebel Ali, Dubai, U.A.E – Corporate HQ: Crown House 2nd Floor, Par-la-ville Road, Hamilton, BERMUDA

[a]aliismail@aast.edu, [b]e.m.shokry@hotmail.com, [c*]k.saqr@aast.edu, [d]ezzfahmy@yahoo.com

Keywords: Filtration, Wellbore drilling, Two phase flow, CFD, Non-Newtonian fluid

Abstract. During oil wellbore drilling processes, filter cake is formed on the sidewalls of the well hole due to filtration of drilling fluid particles. The filter cake is crucial to the drilling process, since it helps to maintain the wellbore hole, protects the drilling bit from jamming and facilitates the subsequent phases of the well development. The most important parameter for filter cake formation is its thickness and its variation due to drilling conditions. In this paper, the drilling fluid particles filtration process was simulated at conditions mimicking deep wellbore drilling. The drilling fluid was simulated as a non-Newtonian two-phase fluid of liquid and particles, utilizing an Eulerian-Eulerian approach. The model successfully predicted a filter cake thickness which agrees well with measurements and previous CFD work.

Introduction

During drilling and completion operations, various drilling fluids are used to assist the drilling process through a number of key functions that determine the success of the wellbore drilling. These fluids mainly consist of liquid and granular solid phases.During the drilling, the granular solid phase is separated from the liquid phase due to the filtration of the fluid through porous rock formation under high pressure [1]. In addition the drilling fluid performs several functions such as transporting drilled formation out of the wellbore, controlling the formation pressure, avoiding loss of fluid to the formation, formation of filter cake etc [2-5]. Due to the pressure differential between the hydrostatic pressure of the mud column and the formation pressure, filtration from drilling fluids occurs [5]. 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 cake of solid particles (i.e. mud) on the wall of the borehole [6]. This filter cake is essential to preserve the borehole and protect it from collapsing.

Prokop [7] has experimentally investigated the effects of mud hydraulics upon the formation and erosion of mud filter cakes under both static and dynamic conditions. The results showed that the major factors controlling filter cake formation in a circulating system is the rate of deposition of solids from the mud, the erosive force that the flowing mud exerts upon the filter cake and the erodability of the filter cake.

Large sums of money are spent by the petroleum industry during drilling operations to control the fluid loss. For chemically treated drilling fluids, both the standard and high pressure high temperature API filter-loss test were found to be inaccurate indicators of trends in dynamic fluid-loss rates under the test conditions used[8]. An analytical approach has been presented by Outman [9] to describe the mechanism of filtration by a theoretical-empirical non-linear equation. The analysis revealed the effects of mud properties like viscosity on the filtration rate. Outman concluded 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 and vice versa.

Earshghi and Azari [10] performed numerical investigation of the filtration process. Their results showed that the filtrate viscosity and cake permeability has a significant effect on the filtrate volumes. Another numerical model has been developed by Fisher [11] for modelling filter cake growth and fluid invasion during drilling. The model was integrated into a time-stepping routine and a cross flow microfiltration model is employed to predict the increase in cake thickness at nodes on the borehole wall at each time step. Earlier research on the filtration [1, 9, 12, 13, 14, 15, and 16] of drilling fluids has suggested that temperature, pressure, hydraulic shear rate, and formation permeability influence the filtration process. However, the influence of individual factors and their interdependencies remains unclear. [16, 17]. A computational fluid dynamics (CFD) program FLUENT has been used by Kabir et al [17] to simulate the filter cake formation at high temperature and pressure conditions. Xu et al [19] proposed the equivalent cake filtration modeling to describe filtration in Newtonian and non Newtonian fluids. Yim and Du Kwon [20] found improvement in average cake resistance values using the concept of filtration permeation. Literature review [3, 5, 12, 18] show that very little research has been presented for filter cake formation during deep drilling, especially using CFD.

The objectives of the present study were to establish a CFD model which is capable of predicting the filtration process with conditions similar to deep wellbore drilling, validate such model, and investigate its sensitivity to boundary conditions. The general purpose CFD solver FLUENT 6.3 was used to achieve such objectives, along with the pre-processing package GAMBIT 2.4.

CFD Model Details

Mathematical model

The CFD model presented herein adopted steady, incompressible, laminar two-phase flow assumptions, with non-Newtonian power law viscosity. The model details can be found in FLUENT theory guide. Therefore, neglecting the intra-phase mass transfer and any external sources, the conservation of mass in the model can be expressed as:

For liquid, $\nabla.(\alpha_l v_l) = 0$ (1)

For solids, $\nabla.(\alpha_s v_s) = 0$ (2)

where α is the volume fraction and subscripts l and s denote liquid and solid phases, respectively. Moreover, $\alpha_l + \alpha_s = 1$ must be satisfied. vl and vs are the velocities of the solid and liquid phases, respectively.

The momentum equation for the liquid phase in a solid-liquid system is expressed as:

$$\nabla.(\alpha_l \rho_l \vec{v_l}\vec{v_s}) = -\alpha_l \nabla P + \nabla.\overline{\tau_1} + \alpha_l \rho_l \vec{g} - \{K_{sl}(\vec{v_l} - \vec{v_s})\} \quad (3)$$

where ρ_l is the liquid density, ∇P is the pressure gradient $\overline{\tau_1}$ is the stress tensor of the liquid phase, which is related to the strain tensor $\overline{\gamma_l} = \nabla\vec{v_l} + (\nabla\vec{v_l})^{tr}$ by $\overline{\tau_1} = \alpha_l \tau \overline{\gamma_l} + \alpha_l \left(\lambda_l - \frac{2}{3}\tau\right)\nabla.\vec{v_l}\bar{I}$, and $\tau = k|\overline{\gamma_l}|^{n-1}$ and $|\overline{\gamma_l}|$ is the magnitude of the strain rate tensor defined as $|\bar{\gamma}| = \sqrt{\frac{1}{2}\sum_i \sum_j \dot{\gamma_{ij}}\dot{\gamma_{ji}}}$ and, k and n are the non-Newtonian consistency index and power-law exponent, respectively.

The momentum equation for the solid phase in a solid-liquid system can be expressed as:

$$\nabla.(\alpha_s \rho_s \vec{v_s}\vec{v_s}) = -\alpha_s \nabla p - \nabla p_s + \nabla.\overline{\tau_s} + \alpha_s \rho_s \vec{g} + \{(K_{ls}(\vec{v_l} - \vec{v_s}))\} \quad (4)$$

and the solids pressure, ρ_s, stress, $\overline{\tau_s}$ and viscosity, μ_s are determined by particle fluctuations and the kinetic energy associated to these fluctuations, granular temperature Θ. The stress-strain relationship for the solid phase s is $\overline{\tau_s} = \alpha_s \mu_s \overline{\gamma_s} + \alpha_s \left(\lambda_s - \frac{2}{3}\mu_s\right)\nabla.\vec{v_s}\bar{I}$. Where solid strain rate tensor $.\overline{\gamma_s} = \nabla\vec{v_s} + (\nabla\vec{v_s})^{tr}$. Interaction forces are considered here to account for the effects of other phases and are reduced to zero for single phase flow.

The momentum exchanges coefficients are indistinguishable ($K_{ls} = K_{\mathrm{sl}}$), $K_{\mathrm{sl}} = \frac{\alpha_s \rho_s f}{T_s^p}$. This function and coefficients are suitable for drilling process modeling where recirculation multiphase fluids contain high solid fraction. Here,T_s^p is the particulate relaxation time and is the model-dependent drag function. The relaxation time is expressed as: $T_s^p = \frac{\rho_s {d_s}^2}{18\mu_l}$where d_s is the solid particle diameter. The Syamlal-O'Brien drag function is used$f = \frac{C_D Re_s \alpha_l}{24\, {v^2}_{r,s}}$.

To describe the conservation of energy in Eulerian multiphase applications, a separate steady-state enthalpy equation can be written for each phase q (liquid or solid) (FLUENT, 2006; Cornelissena, 2007) as follows:

$$\nabla.\left[\alpha_q \rho_q \overrightarrow{u_{\mathrm{q}}} h_{\mathrm{q}}\right] = \overline{\tau_q} : \nabla\overrightarrow{u_{\mathrm{q}}} - \nabla.\overrightarrow{q_{\mathrm{q}}} + \sum_{p-1}^{n} \left[\overrightarrow{Q_{\mathrm{pq}}}\right] \qquad (5)$$

where h_{q} is specific phase enthalpy, $\overrightarrow{q_{\mathrm{q}}}$ is the heat flux, and $\overrightarrow{Q_{\mathrm{pq}}}$ is the intensity of heat exchange between phases.

Computational domain and solver settings

The computational domain was decomposed to 3750 quadrilateral cells (25 x 150) with Dirichlet boundary conditions for the pressure field at the inlet and outlet plans of the domain. Absolute residuals of the iterative solver was used as a criteria convergence and was set to value of 1×10^{-4} for both velocity and pressure. Second order discretization scheme was used, and the SIMPLE algorithm was used to couple the velocity and pressure terms in the governing equations. The simulation was performed for pressure filtration where inlet pressure was kept at 100 kPa. The filtration cell was initially filled with multiphase particulate drilling fluid, and pressure was applied at the top (inlet) with porous media at the bottom (outlet).

Model Validation

In order to ensure that the computational model produces physically correct results, comparison with previous analytical calculations was undertaken. The case sought for validation in the present work is reported in [17]. The applied pressure forced fluid through the porous media and separated solid particles in the form of filter cake on the porous media. During filtration, the filter cake reached equilibrium with the applied pressure at the top. It represents the cake formation at the bottom of a laboratory-scale pressure filtration cell. Figure (1) shows a comparison between the present numerical results and previous analytical calculations of such case. The result of the validation case agrees well with previous published simulations [17]. Figure 2 shows a qualitative comparison between the solid volume fraction contours of the present study and that of Kabir and Gamwo [17]. Very good agreement between both results are observed. A third comparison is given in figure 3, where the filter cake thickness, under similar conditions to such used in the present work, of experimental [18] and analytical works are shown.

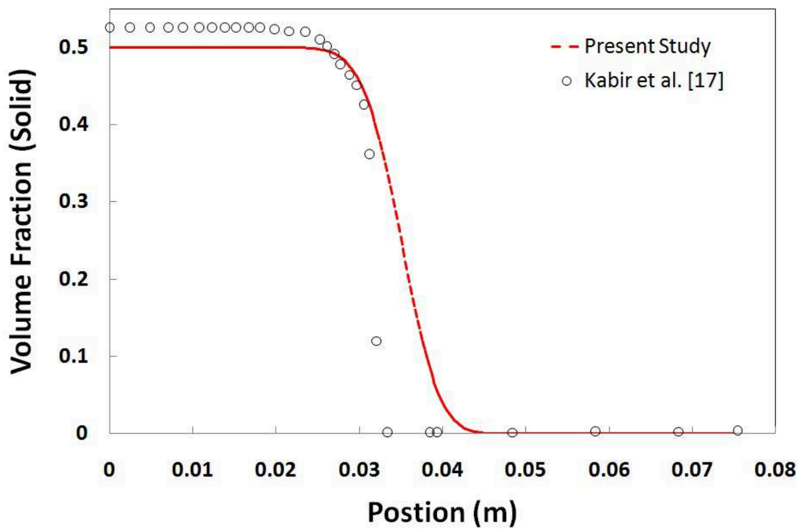

Figure (1): Quantitative solid concentration profile along the vertical axis

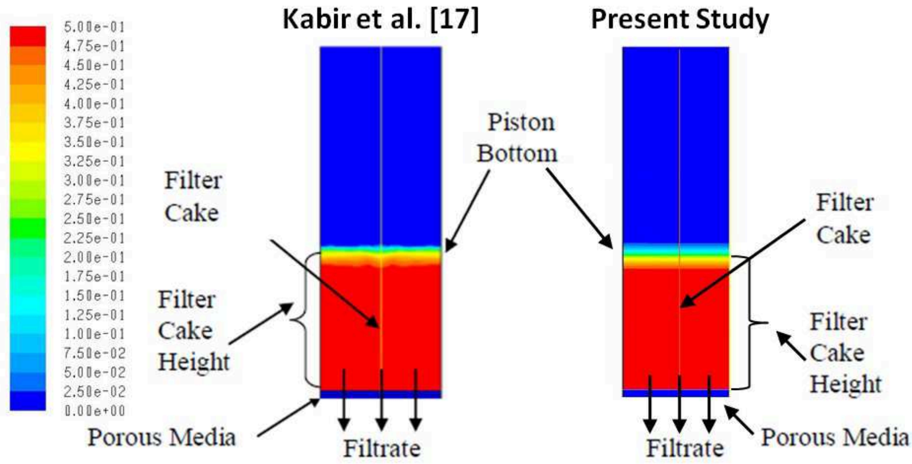

Figure (2): Filter cake formation and profile and solid volume fraction distribution for the present study and kabir el al. [17]

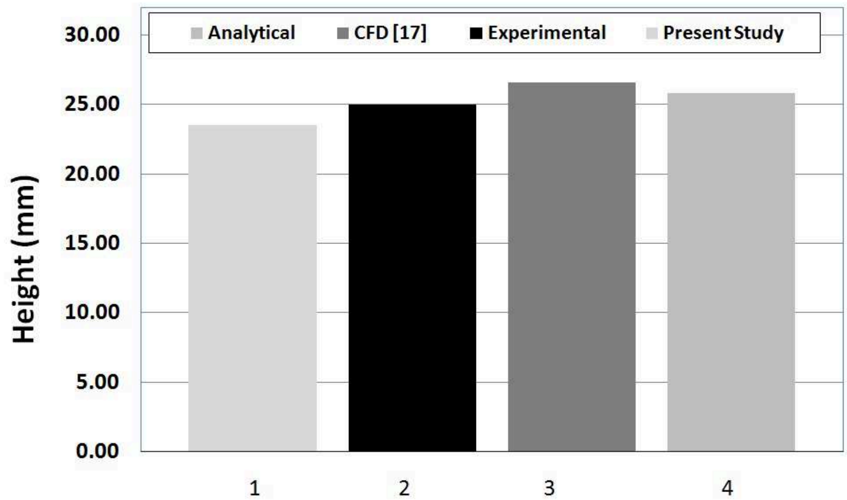

Figure (3): Comparison of filter cake thicknesses

Model Sensetivity to Boundary Conditions

The model sensetivity to a number of boundary conditions has been tested. Figure 4 shows the model sensetivity to the debris particle diameter. The filter cake thickness and gradient showed quite insignificant response to the debris particle diameter, under fixed consitions of pressure and drilling fluid density and particle diameter. Moreover, when the inlet pressure was varied, as in figure 5, the model did not respond significantly as well. The filter cake thickness remaind constant.

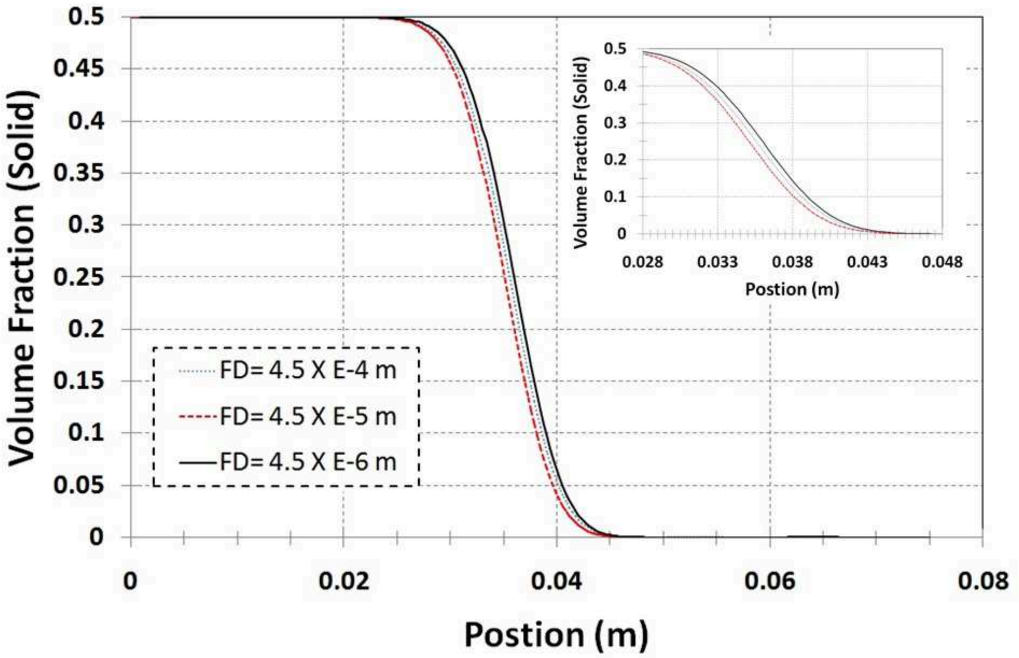

Figure (4): Quantitative solid concentration profile along the vertical axis at P=100 kpa
For different fracture diameters

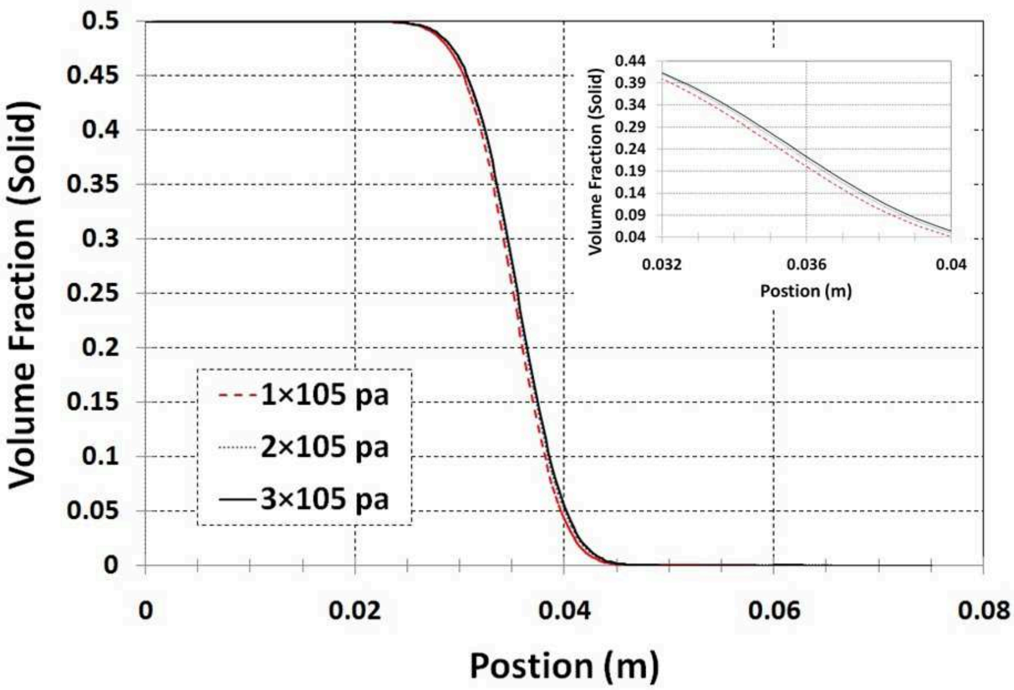

Figure (4): Quantitative solid concentration profile along the vertical axis at FD=4.5×10^{5}m for different inlet pressure

Conclusion

A CFD model for the filter cake formation process in wellbore drilling was constructed using ANSYS Fluent. The model employed an Eulerian-Eulerian multiphse formulation and a non-Newtonian power law viscosity model. The model results were validated against previous CFD work, experimental measurements and analytical predictions of filter cake thickness. The model results showed very good agreement with previous works, which showed the model validity and reliability for mimicking wellbore filter cake formation processes. The future works should consider simulating realistic cases with more complex flow configurations and different drilling fluid properties.

Acknowledgment
The authors acknwoledge the financial support provided by the Arab Academy for Science, Technology and Maritime Transport to attend the IMAT 2014 conference. The second author acknowledges the support provided by Nabors Drilling International.

References
[1] Vaussard A, Martin M, Konirsch O (1986). "An experimental study of drilling fluids dynamic filtration." SPE, 15412P.
[2] Tor Henry Omland (2009). "Particle settling in non-Newtonian Drilling Fluids." University of Stavanger. PhD Thesis, NORWAY.
[3] Maurer Engg. Inc. (1997). "Wellbore thermal simulation model: heory and User's Manual." MAURER ENGINEERING INC.
[4] Spooner KM, Bilbo D, McNeil B (2004). "The application of high temperature polymer drilling fluid on Smackover operations in Mississippi." AADE-2004 Drilling Fluids Conference. Houston, Texas.
[5] Ali S (2006). "Reversible drilling-fluid emulsions for improved well performance." Oilfield Review.
[6] Isehunwa S. O. and Falade G. K (2012). "An approximate theory of static filtration of drilling muds in vertical wells." ARPN Journal of Engineering and Applied Sciences , Vol. 7, No. 1, January 2012
[7] Prokop C.L. (1952). "Radial filtration of Drilling Mud". Trans, AIME. Vol. 195, Issue 5.
[8] Roland F. Krueger (1963). "Evaluation of Drilling-Fluid Filter-Loss Additives under Dynamic Conditions." Journal of Petroleum Technology, Vol. 15, Issue 1.
[9] Outman H. D. (1963). Mechanics of Static and Dynamic Filtration in the Borehole. Trans AIME. 228: 236.
[10] Ershaghi I. and Azari A. (1980). "Modeling of filter cake build-up under dynamic -static condition". 50th Annual California Regional Meeting of the Society of Petroleum Engineers, Los Angeles, USA, April 9-10.
[11] Fisher KA, Wakeman RJ, Chiu TW, Meuric OFJ (2000). "Numerical modeling of cake formation and fluid loss from non-Newtonian mud’s during drilling using eccentric/concentric drill strings with/without rotation." Trans I. Chem. Eng., 78(Part A): 707-714.
[12] Klotz JA and Ferguson CK, (1954). "Filtration from mud during drilling." Trans AIME, 201: 29-42.
[13] Peden JM, Avalos MR, Arthur KG (1982). "The analysis of the dynamic filtration and permeability impairment characteristics of inhibited water based muds." SPE Formation Damage Control Symp. Lafayette.
[14] Delhommer HJ, Walker CO (1987). "Method for controlling lost circulation of drilling fluids with hydrocarbon absorbent polymer” US Patent Number, 4: 633-950.
[15] Fordham EJ, Ladva HKJ, Hall C, Baret JF, Sherwood JD (1988). "Dynamic filtration of bentonite muds under different flow conditions". 63rd Annual SPE Conference. Houston, Texas
[16] Sherwood JD, Meeton GH, Farrow CA, Alderman NJ (1991). "Concentration profile within non-uniform mud cakes." J. Chem. Soc. Far. Trans, 84(4): 611(b).
[17] Mohd. A. Kabir and Isaac K. Gamwo (2011). "Filter cake formation on the vertical well at high temperature and high pressure: Computational fluid dynamics modeling and simulations." Journal of Petroleum and Gas Engineering Vol. 2(7), pp. 146-164, November
[18] Saha H (2009). "Pratical application of filtration theorey to the minerals industry." The University of Melbourne, Australia, PhD Thesis