Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 14 (23): 3263-3269, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.3263.3269

Modelling of Pressure Drop and Cuttings Concentration in Eccentric Narrow Horizontal Wellbore with Rotating Drillpipe

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Abstract: In drilling operations, estimation of pressure drop and cuttings concentration in the annulus is very complex due to the combination of interacting drilling parameters. Over the years, many investigators have developed empirical correlations to determine these parameters, however, the use of these correlations are limited to their experimental data range and setup and cannot be applicable to all cases. Computational Fluid Dynamics (CFD) method has been widely accepted as the best technique, not only due to its ability to handle complex multiphase flow problems but also its ability to handle unlimited number of physical and operational conditions. The present study examines the effects of annular diameter ratio, flow rate (fluid velocity), drillpipe rotation and fluid type on pressure drop and cuttings concentration in eccentric horizontal wellbore using CFD method. The annular diameter ratio varies from 0.64-0.90 with the drillpipe positioned at eccentricity of 0.623 and rotating about its own axis at 80 and 120 rpm. The drilling fluids were modelled using Newtonian and Power-Law fluids. Results show that at diameter ratio of 0.90, pressure drop is very dramatic yet, the amount of cuttings transported remained almost constant for all fluid velocities. Experimental pressure drop and cuttings concentration data compared favourably with simulation data with mean percentage error of 0.84 and 12%, respectively, confirming the validity of the current model.

Key words: CFD, cuttings concentration, Newtonian fluid, power-law model, pressure drop

INTRODUCTION

Pressure drop and cuttings concentration estimation in annular wellbores are strongly affected by varying drilling parameters such as flow rate, fluid properties (density, viscosity), cutting size and density, hole-pipe eccentricity, drillpipe rotation and annular geometry. There are few attempts made by some investigators over the years to estimate the pressure drop in annulus with cuttings present with and without drillpipe rotation.

Tomren *et al*. (1986) is one of the first to conduct extensive experimental study on cuttings transport at varying angle of inclinations. The authors studied the effects of fluid velocity, fluid rheological properties, pipe-hole eccentricity, drillpipe rotation and flow regimes on cuttings concentration at steady state condition. They concluded that fluid velocity, hole inclination and mud rheological properties were the major factors regarding mud carrying capacity. Becker and Azar (1985) also investigated experimentally the effects of mud weight and annular gap on the performance of hole cleaning in inclined wellbores. The authors observed that drillpipe size variation has minimum effect on particle concentration for same fluid velocity. According to Adari *et al*. (2000), the practical use of these factors in controlling cuttings transport is much dependent on their controllability in the field. It is believed that, cuttings transported in the annulus are not always affected by a single parameter but a combination of parameters to ensure efficient hole cleaning (Sifferman and Becker, 1992). It is confirmed that increase in flow rate results in a decrease in cuttings accumulation in the wellbore (Ahmed *et al*., 2010; Ozbayoglu *et al*., 2010a; Ogunrinde and Dosunmu, 2012). Ozbayoglu and Sorgun (2010) also conducted cuttings transport experiment and developed empirical correlations for estimating pressure drop with the presence of cuttings and drillpipe rotation in horizontal and inclined wellbores. They observed that the influence of drillpipe rotation on pressure drop is more significant if fluid is non-Newtonian. The annular test section has diameter ratio of 0.62. Another cuttings transport experiment was carried out by Sorgun *et al*. (2011) in horizontal and inclined flow loops of diameter ratio of 0.62. The authors observed that the existence of

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cuttings in the system caused an increase in pressure drop due to a decrease in flow area inside the wellbore. Further observation was that, drillpipe rotation decreases the pressure drop significantly if the drillpipe is making orbital motion in eccentric annulus. Some "very-difficult-to-identify" data for estimating total pressure drop and cuttings concentration in horizontal and inclined annuli were determined by Ozbayoglu *et al*. (2010b) from cuttings transport experiment. Results from their study indicate that drillpipe rotation speed does not have significant influence on pressure drop for constant Rate of Penetration (ROP) and flow rate. The annular test section has diameter ratio of 0.64.

Han *et al*. (2010) is among the first to conduct experimental and CFD studies on cuttings transport in vertical and highly deviated slim hole annulus. They concluded that, pressure drop in a solid-liquid mixture flow increases with mixture flow rate, annular inclination and drillpipe rotation speed. The annular test section has diameter ratio of 0.7. Similarly, Mokhtari *et al*. (2012) employed CFD method to model the effects of eccentricity and flow behaviour index on annular pressure drop and velocity profile for varying diameter ratios from 0.30-0.90. The authors, however, did not include cuttings in the annular mainstream. The above studies show that the effects of drilling parameters on pressure drop and cuttings concentration for cuttings-liquid flow in an annulus is limited to annular diameter ratio of 0.70. Although, recent studies show an extension of diameter ratio to 0.90, yet, the studies are without cuttings present in the annulus. The present study examines the effects of annular diameter ratio (ranging from 0.64-0.90), flow rate, drillpipe rotation and fluid type on pressure drop and cuttings concentration for cuttings-liquid flow in eccentric horizontal wellbore.

METHODOLOGY

Governing equations: The multiphase component of the CFD software ANSYS CFX 14.0 (ANSYS Inc., 2011) is used in this study. The Eulerian-Eulerian model, also known as two-fluid model, which regards the dispersed phase as a continuous phase is adopted. In this study, inhomogeneous Eulerian-Eulerian model which treats the two phases as distinct, interpenetrating continua is used to simulate the flow of cuttings-liquid in a horizontal annulus. The particle model is selected to model the interfacial area density and the interphase transfer terms (ANSYS Inc., 2011). The following continuity and momentum equations representing the two-phase flow model are described for the sake of brevity.

Continuity equations: Fluid phase continuity equation assuming isothermal flow condition can be expressed as (Van Wachem and Almstedt, 2003):

$$\frac{\partial}{\partial t}(\rho_f C_f) + \nabla.(\rho_f C_f U_f) = 0 \tag{1}$$

Similarly, for a solid phase:

$$\frac{\partial}{\partial t}(\rho_S C_S) + \nabla.(\rho_S C_S U_S) = 0 \tag{2}$$

Solid and fluid phase volume fraction:

$$C_s + C_f = 1 \tag{3}$$

where, subscript f and s are fluid and solid phase respectively, U is velocity vector and t is time. At steady state condition:

$$\frac{\partial}{\partial t} = 0$$

Momentum equations: These include forces acting on each phase, interphase momentum transfer term that models the interaction between each phase (Van Wachem and Almstedt, 2003).

For fluid phase:

$$\rho_f C_f\left[\frac{\partial U_f}{\partial t} + U_f.\nabla U_f\right] = -C_f \nabla p + C_f \nabla.\overline{\overline{\tau}}_f + C_f \rho_f g - M \tag{4}$$

Similarly, for solid phase:

$$\rho_S C_S\left[\frac{\partial U_S}{\partial t} + U_S.\nabla U_S\right] = -C_S \nabla p + C_S \nabla.\overline{\overline{\tau}}_S - \nabla P_S + C_S \rho_S g + M \tag{5}$$

where, p is pressure, $\overline{\overline{\tau}}$ is viscous stress tensor, P_S is solid pressure and M is interfacial momentum transfer per unit volume and consists of the drag force, buoyancy force and lift force. At steady state condition:

$$\frac{\partial}{\partial t} = 0$$

Turbulence k-ϵ two-phase model: The k-ϵ model is used to estimate the effective viscosity of two-phase flow as:

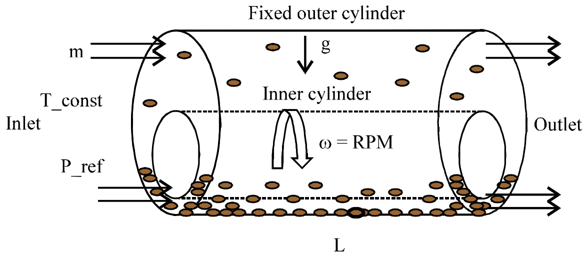

Fig. 1: Physical model for cuttings-liquid flow

$$\mu_{eff} = \mu + \mu^{t\alpha} \quad (6)$$

The k-ϵ model assumes that the turbulence viscosity is linked to the turbulence kinetic energy and dissipation by the relation:

$$\mu_{t\alpha} = C_{\mu}\rho_{\alpha}\frac{k_{\alpha}^{2}}{\varepsilon_{\alpha}} \quad (7)$$

where, μ is dynamic viscosity, C_μ is equal to 0.09, ρα is density of each phase, k_α is turbulent kinetic energy, ε_α is turbulent dissipation energy.

The governing sets of partial differential equations were discretized using finite volume technique. The discretized equations together with initial and boundary conditions are solved iteratively for each control volume of pressure drop and cuttings concentration using ANSYS CFX 14.0 solver (ANSYS Inc., 2011).

Physical model and test matrix: A two-phase cuttings-liquid flow in eccentric horizontal wellbore with drillpipe rotation is presented. The flow is considered as incompressible, steady state and isothermal. Mixture mass flow rate boundary condition was specified at the inlet while atmospheric pressure at the outlet was specified relative to the inlet pressure. A homogeneous volume fraction of each phase was specified at the inlet. No-slip boundary conditions were imposed at both inner and outer wall surfaces. Water was modelled for turbulent flow using k-ε model, while, Power-Law model was modelled for laminar flow. Figure 1 shows the physical model for cuttings-liquid flow.

Four horizontal annular geometries were modelled and discretized using ANSYS workbench CFX 14.0 (Fig. 2). The geometries were meshed into tetrahedral cells resulting in grids approximately 2.5-4.5×10^6 cells depending on the diameter ratio.

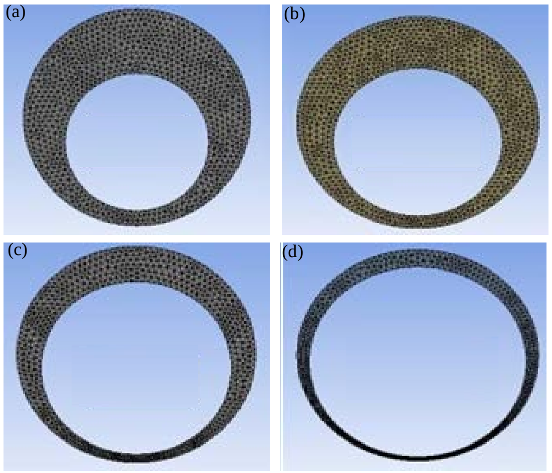

Fig. 2(a-d): Cross section of discretized annular geometry at (a) κ= 0.64, κ = 0.70, (c) κ= 0.80 and (d) κ = 0.90

RESULTS AND DISCUSSION

Validation of simulation model: Experimental 'Base Case' data in Table 1 are used to validate the simulation model in terms of pressure drop and cuttings concentration. Figure 3 and 4 compare experimental and simulation data and their regression analysis, respectively (Osgouei, 2010).

The regression analysis in Fig. 3b and 4b indicate a good comparison between experimental and simulation data for pressure drop and cuttings concentration with mean percentage error of 0.84% and 12% respectively, confirming the validity of the current model setup.

Effect of diameter ratio: The diameter ratio is defined as the ratio of drillpipe diameter to hole diameter. It can be seen from Fig. 5 that increasing the diameter ratio results in an increase in pressure drop and a decrease in cuttings concentration for each fluid velocity, respectively. The highest effect is significant at diameter ratio of 0.90 which recorded the lowest cuttings concentration for all fluid velocities.

Effect of flow rate (fluid velocity): Previous experimental studies (Tomren *et al*., 1986; Sifferman and Becker, 1992) have revealed that fluid velocity is the most dominant factor affecting cuttings transport although their studies were limited to a diameter ratio of 0.56. This is also evident in the present study however, the effect of fluid velocity diminishes significantly as diameter ratio increases. For a

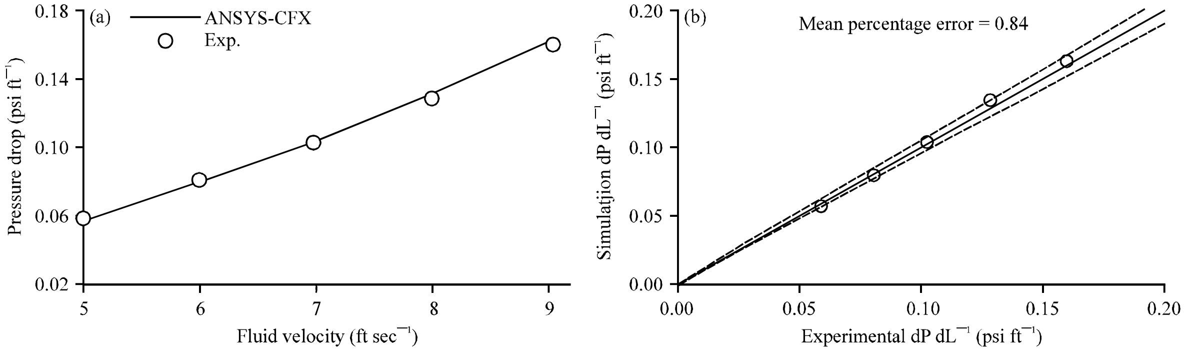

Fig. 3(a-b): Experimental and simulation data for (a) Pressure drop and (b) Regression analysis for cuttings-water flow at 80 rpm and $\kappa = 0.64$

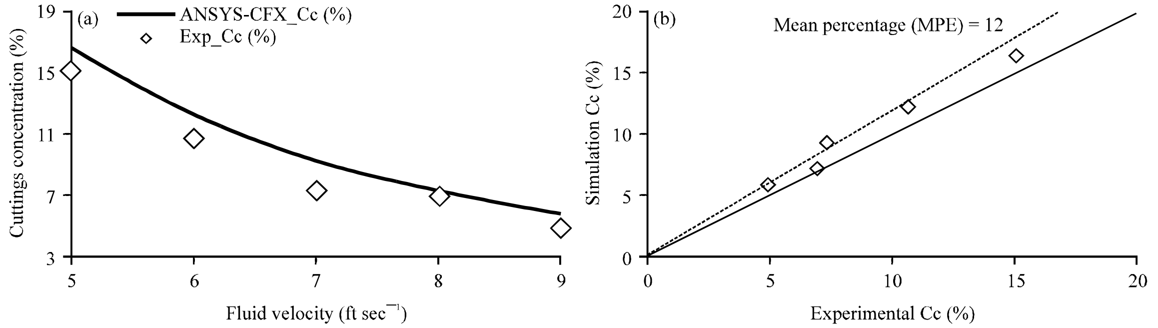

Fig. 4(a-b): Experimental and simulation data for (a) Cuttings concentration and (b) Regression analysis at 80 rpm and $\kappa = 0.64$ using water

Table 1: Simulation data for cuttings-liquid flow

		Case	
	Base case	1	2
Drilling parameters	Water	Water	Mud
Fluid density (ppg)	8.335	8.335	8.4
Cuttings density (ppg)	23.05	23.05	23.05
Cuttings size (inch)	0.079	0.079	0.079
Flow index (n)	1	1	0.51
Viscosity consistency, K (eq.cP)	1	1	289
Fluid velocity (ft sec^{-1})	5-9	5-9	5-9
Rotation speed (rpm)	80	80, 120	80, 120
Hole size (inch)	2.91	2.91	2.91
Diameter ratio (κ = Di/Do)	0.64	0.64, 0.70, 0.80, 0.90	0.64, 0.70, 0.80, 0.90
Eccentricity (ε)	0.623	0.623	0.623
ROP (ft h^{-1})	60	60	60

constant diameter ratio of 0.90, increasing fluid velocity has negligible effect on cuttings transport, although a dramatic pressure drop is recorded. Figure 6 shows the analysis.

Effect of drillpipe rotation: The effect of increasing drillpipe rotation is quite significant on cuttings transport especially at a diameter ratio of 0.64. However, as the diameter ratio increases, increasing drillpipe rotation has negligible effect on cuttings transport as shown in Fig. 7. Pressure drop trend also experienced no significant change as drillpipe rotation increases from 80-120 rpm.

Effect of fluid type: The effect of Newtonian (water) and non-Newtonian Power-Law fluid (mud) on pressure drop and cuttings concentration are analysed

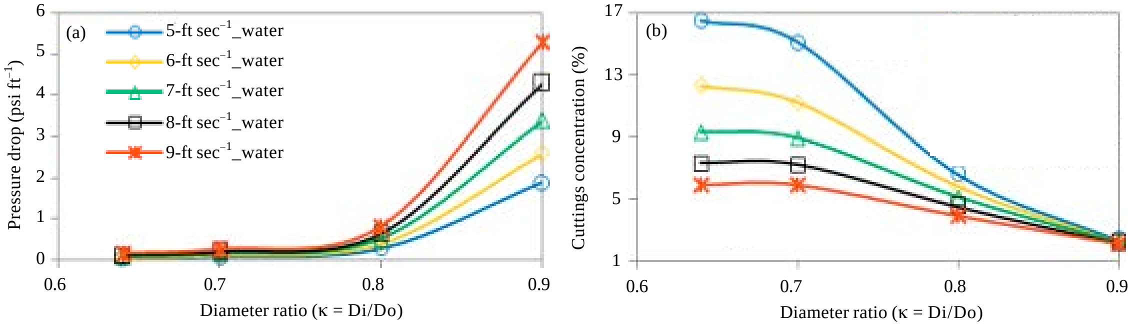

Fig. 5(a-b): Effect of diameter ratio on (a) Pressure drop and (b) Cuttings concentration at 80 rpm using water

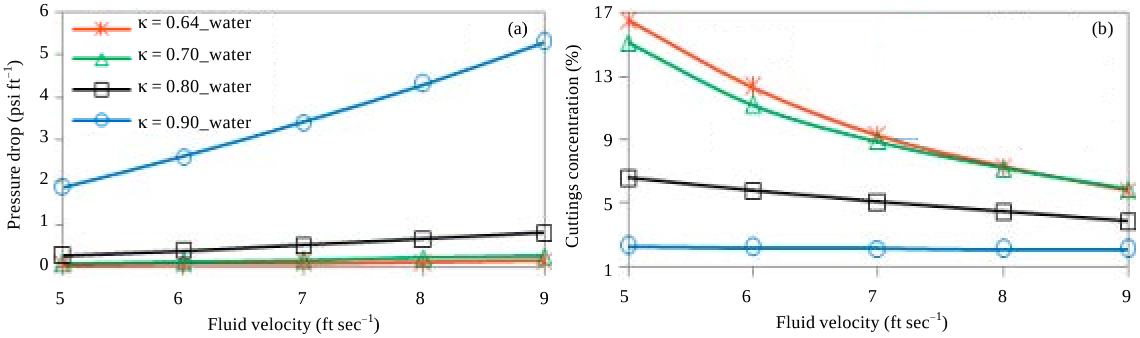

Fig. 6(a-b): Effect of fluid velocity on (a) Pressure drop and (b) Cuttings concentration at 80 rpm using water

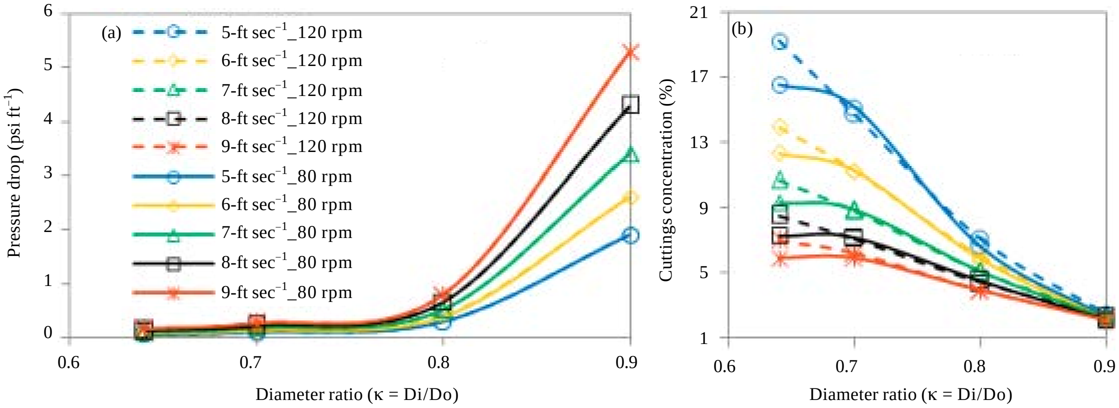

Fig. 7(a-b): Effect of drillpipe rotation on (a) Pressure drop and (b) Cuttings concentration using water

in Fig. 8. Drilling mud recorded high pressure drops compared to water especially at a constant diameter ratio of 0.90 and low fluid velocity of 5 ft sec^{-1}. Similarly, the mud transported much cuttings compared to water especially at low constant diameter ratios and fluid velocities. The cuttings transport performance of both fluids is quite similar at high diameter ratio and fluid velocity.

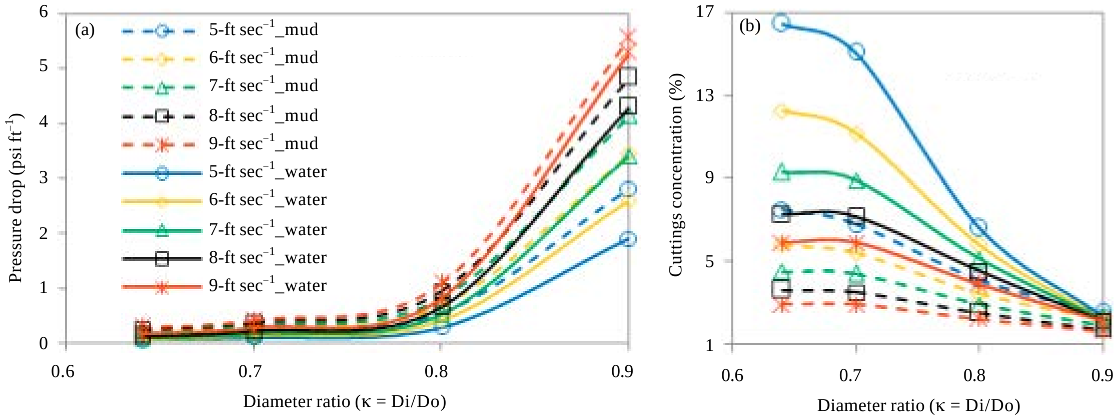

Fig. 8(a-b): Effect of fluid type on (a) Pressure drop and (b) Cuttings concentration at 80 rpm

CONCLUSIONS

The following can be inferred from the present study:

- Current model setup is validated with experimental pressure drop and cuttings concentration data with a mean percentage error of 0.84 and 12%, respectively
- Increase in diameter ratio increases pressure drop but decreases cuttings concentration for each constant fluid velocity
- Although, there is significant effect of fluid velocity on cuttings transport, yet, this effect diminishes drastically as diameter ratio increases. Also, increasing fluid velocity increases pressure drop especially at high diameter ratio of 0.80-0.90
- Increasing drillpipe rotation speed from 80-120 rpm only has significant effect on cuttings transport at diameter ratio of 0.64 for all fluid velocities. Pressure drop also recorded negligible change
- Drilling mud recorded high pressure drops compared to water especially at a constant diameter ratio of 0.90 and low fluid velocity of 5 ft sec^{-1} which also resulted in higher cuttings transport

ACKNOWLEDGMENT

The authors would like to appreciate the effort of the Universiti Teknologi PETRONAS (UTP) for providing the needed funding for this study. The first author also thanks UTP for the continual academic support with graduate assistantship.

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