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iMFE 2014

Cuttings Transport Evaluation in Deviated Wells

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Abstract

Cuttings transport efficiency is a measure of the extent to which cuttings are carried to the surface from a drilled hole. It quantifies the success achieved in freeing a well of drilled cuttings. It is also related to the carrying capacity of a drilling mud. Cuttings transport efficiency in vertical and deviated wellbores has been reported to depend on the following factors: hole geometry and inclination, average fluid velocity, fluid flow regime, drill pipe rotation, pipe eccentricity, fluid properties and rheology, cuttings size and shape, cuttings concentration, cuttings transport velocity, rate of penetration and multiphase flow effect. In this study, the effects of mud flow rate, rate of penetration, annular clearance, mud and cuttings densities on annular fluid velocity, transport ratio and mean mud density are investigated for highly deviated wells. Equations are developed and used to generate graphs. These equations and graphs could be applied in the field during directional drilling to determine annular fluid velocity, mud flow rate, transport ratio and mean mud density.

Keywords: Annular clearance, Annular fluid velocity, Cuttings transport efficiency, Mean mud density, Transport ratio

Introduction

Transportation of cuttings and efficiency of hole cleaning has been one of the major concerns of stake holders in the oil and gas industry. This is because a successful drilling program is a key to a productive and profitable oil and gas business. A successful drilling program is as a result of an efficiently cleaned hole. On the other hand, a poor or inefficient hole cleaning implies accumulation of cuttings or formation of cuttings bed in the well. This often leads to decreased rate of penetration, increased cost of drilling, fractured formation, increased plastic viscosity of mud as a result of grinding of cuttings and stuck pipe. Hole cleaning is effected primarily with a drilling fluid. The function of a drilling fluid is chiefly the transportation of cuttings out of a drilled hole. Other major functions of a drilling fluid in a drilling program include: cooling and lubricating the bit and drill string, cleaning of the bottom of the hole, removal of cuttings from mud at the surface, minimizing of formation damage, controlling of formation pressures, hole integrity maintenance, improving of drilling rate, aiding of well logging operations, minimizing torque, drag, pipe sticking as well as corrosion of the drill string, casings and tubings (Bourgoyne, et al., 1986).

Cuttings transport evaluations in vertical and deviated wells have been reported over the last four decades. Studies have shown that cuttings transport efficiency of a drilling program depends on

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the following factors: hole geometry and inclination, average fluid velocity, fluid flow regime (lamina, transitional or turbulent), drill pipe rotation, pipe eccentricity, fluid properties and rheology, cuttings size and shape, cuttings concentration, cutting transport velocity, rate of penetration, multiphase flow effect (Larsen, et al., 1997; Peden, et al., 1990; Adari, et al., 2000). Some correlations and charts have been developed on the parameters that affect carrying capacity of fluid and hole cleaning efficiency (Tomren, et al., 1986; Gavignet & Sobey, 1989; Peden, et al., 1990; Luo, et al., 1994; Larsen, et al., 1997; Kamp & Rivero, 1999; Mirhaj, et al., 2007). Some of these correlations are empirical, based on a number of experiments (Tomren, et al., 1986; Peden, et al., 1990; Luo, et al., 1994; Larsen, et al., 1997; Mirhaj, et al., 2007) while others are mechanistic, through numerical solution and simulation of cuttings transport models (Gavignet & Sobey, 1989; Kamp & Rivero, 1999). Charts are usually developed for field applications. These are necessary in predicting drilling parameters and optimizing a drilling program to avoid the problems highlighted earlier. Luo et al. (1994), for example, developed simple charts for determining hole cleaning requirements in deviated wells. The developed charts relate plastic viscosity with yield points, mud flow rate with rate of penetration for different hole sizes and transport indices, critical flow rate with yield point and washout hole size.

The ease of control and monitoring over the above factors vary in the field. Adari et al. (2000) presented those parameters that are easily controlled and monitored in the field which include: flow rate, fluid rheology, rate of penetration and to a lesser degree drill pipe rotation, hole size and hole inclination. In this work, these parameters are further studied. Equations governing cuttings transportation in deviated wells are developed. Bingham plastic fluid model, which closely approximates most field drilling fluids, is employed. Furthermore, graphs are generated for field application during drilling operation.

Development of Equations

Annular mud velocity: The average transport velocity of cuttings, $\bar{v}_c$, in an annular area, A_{an}, of a well is given by (Bourgoyne, et al., 1986):

$$\bar{v}_c = \frac{Q_c}{A_{an}C_f} \tag{1}$$

Where Q_c is the cuttings flow rate, generated at the bit and C_f is the fractional cuttings concentration in the mud. The annular mud velocity, $\bar{v}_{an}$, is determined as a function of mud flow rate, Q_m, as (Bourgoyne, et al., 1986):

$$\bar{v}_{an} = \frac{Q_m}{A_{an}(1 - C_f)} \tag{2}$$

Expressing $\bar{v}_{an}$ in terms of percentage cuttings concentration, C_{fp}, equation (2) becomes:

$$\bar{v}_{an} = \frac{100Q_m}{A_{an}(100 - C_{fp})} \tag{3}$$

Using Bingham plastic fluids in highly deviated wells (55^0 to 90^0), Larsen et al. (1997) (corroborated by Mirhaj et al., 2007) showed from their experiments that:

$$C_{fp} = 0.01778P_r + 0.505 \tag{4}$$

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Where P_r is the penetration rate in ft/hr. The above equations lead to an expression for annular mud velocity in field unit (details in Appendix A) as:

$$\bar{v}_{an} = \frac{40.8528Q_m}{(99.5 - 0.01778P_r)(2D_{pipe}+A_{cl})A_{cl}} \tag{5}$$

Where D_{pipe} is the drillpipe diameter, A_{cl} is the annular clearance defined by Equation (6)

$$A_{cl} = D_{hole} - D_{pipe} \tag{6}$$

D_{hole} is the hole diameter.

Transport ratio: Transport ratio, T_r , is defined as (Bourgoyne, et al., 1986)

$$T_r = \frac{\bar{v}_c}{\bar{v}_{an}} \tag{7}$$

An expression for T_r is obtained (details in Appendix B) as a function of A_{cl} as

$$T_r = \frac{(99.5 - 0.01778P_r)(D_{pipe} + A_{cl})^2}{Q_m\left(26.149 + \frac{742.7}{P_r}\right)} \tag{8}$$

Mean mud density: The mean mud density is derived (details in Appendix C) as

$$\bar{\rho} = \frac{1}{100}[0.505\rho_c + 99.5\rho_m + 0.01778(\rho_c - \rho_m)P_r] \tag{9}$$

Validation of Equations

The parameters of an example well in the North sea (Ranjbar, 2010) presented in Table 1 is used to develop a graph of annular clearance against annular fluid velocity for different mud flow rates with Equation 5 as shown in Figure 1. The trend of the figure shows that a particular mud flow rate gives a lower annular mud velocity when the annular clearance increases. This is due to an increasing volume of effluent to be transported per unit annular area. Comparative results with Larsen et al. (1997) method are presented in Table 2 for different hole inclinations. The annular mud velocity is determined with equation (5) while the transport ratio is calculated with Equation (8). In addition, the mean mud density is deduced with equation (9). It is observed that the predicted results are similar with that of Larsen et al. (1997) method. The difference in the mud flow rate is due to the consideration of cuttings concentration in the new equations which is lacking in the Larsen et al. (1997) method.

The new method is employed by determining the optimum transport ratio for the drilling operation. This is used in equation (8) to determine the mud flow rate with which the annular mud velocity is deduced with equation (5). The graph (Figure 1) enables visual and easy deductions for different hole sizes on the field. It is worth mentioning that the new methodology determines the annular mud velocity without recourse to slip velocity; rather, the transport ratio is sought. Further validation with a well section drilling parameters presented in Table 3, also shows similar results in Table 4 and Figure 2.

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Table 1. Example well parameters (Ranjbar, 2010)

Parameters	Values
Drill pipe diameter (in)	5
Hole diameter (in)	8.5
Rate of Penetration (ft/hr)	33
Mud weight (lbm/gal)	10.83
Plastic viscosity (cp)	7
Yield point (lbf/100 ft^2)	7
Cuttings size (in)	0.3
Cuttings density (lbm/gal)	19
Pipe rotation (RPM)	80

Obviously, Equations (5) and (8) do not contain rheological parameters (plastic viscosity and yield point), hole inclination and mud density, thus, simplifying the computation of annular mud velocity and flow rates, and enabling easy application to various hole sizes as drilling progresses and mud density changes. In addition, a real time determination of hydrostatic pressure is ensured from the mean mud density equation (Equation (9)). The graphical representation aids visual deductions and analysis. However, their applications are limited to deviated wellbores and drilling fluids characterized with Bingham plastic fluid model. The new methodology does not differentiate between critical and subcritical fluid flows. But with a carefully determined transport ratio, critical fluid flow is always ensured.

Conclusion

A new methodology is developed which presents equations for determining average annular mud velocity, mud flow rate and transport ratio, taken into consideration cuttings concentration. These are necessary for optimal cuttings transportation and drilling operation. These equations are developed for highly deviated wellbore and for fluids represented with Bingham plastic fluid model. The equations are validated with two well drilling parameters which produced similar results with Larsen et al. (1997) method. The equations are used to develop graphs for easy field applications.

Acknowledgement

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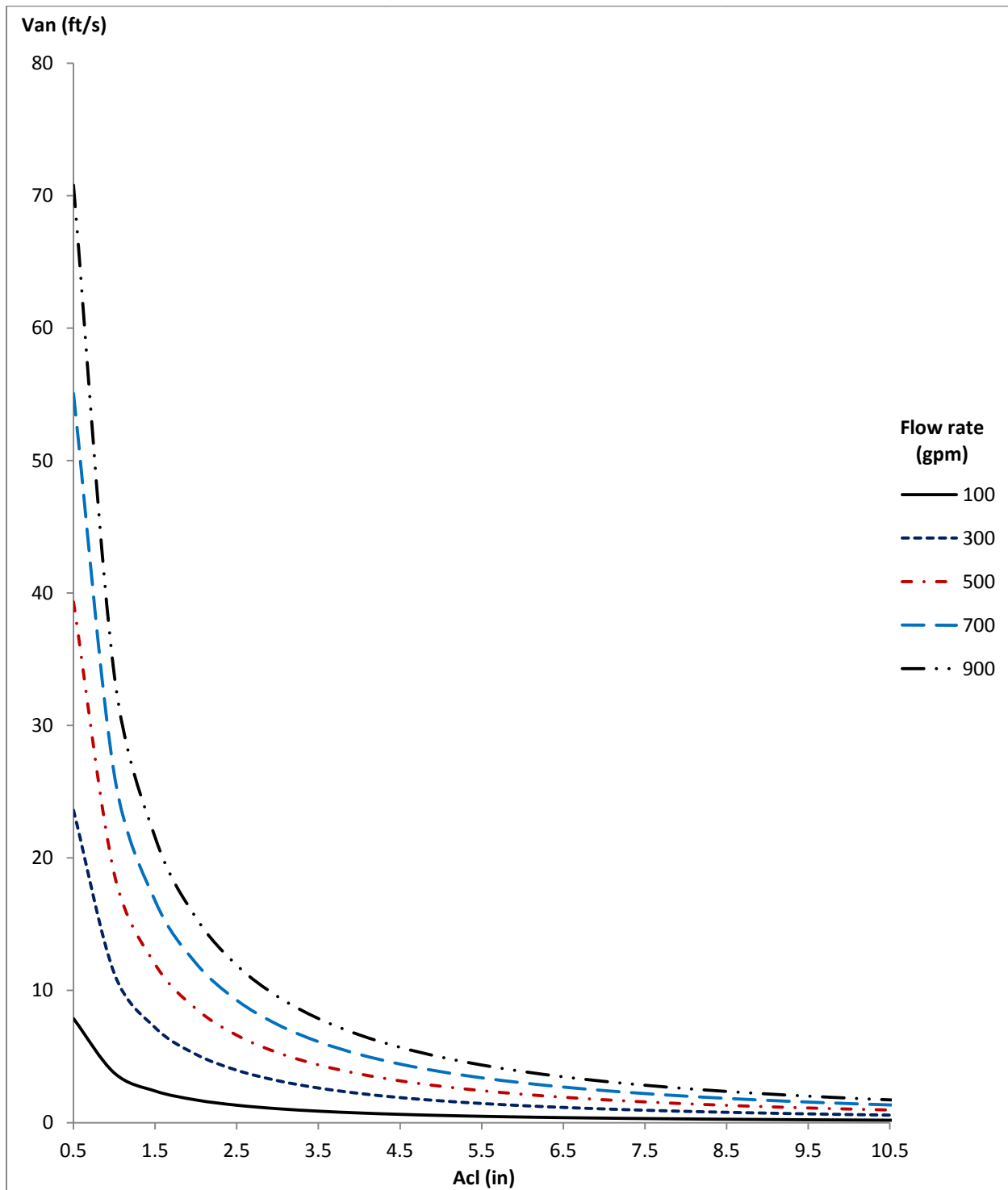
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Figure 1. Graph of annular velocity against annular clearance for different flow rates

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Table 2. Comparative results of the methods

Parameters	Larsen et al. (1997) method	New equations	Larsen et al. (1997) method	New equations
Hole inclination (^{o})	65	-	90	-
Annular clearance (in)	3.50	3.50	5.00	5.00
Annular velocity (ft/s)	4.24	4.28	3.99	4.00
Mud flow rate (gal/min)	490.26	489.60	733.29	726.05
Transport ratio	0.30	0.30	0.28	0.28
Mean mud density (lb/gal)	-	10.92	-	10.92

Table 3. A well section drilling parameters

Parameters	Values
Drill pipe diameter (in)	5
Hole diameter (in)	13.5
Rate of Penetration (ft/hr)	54
Mud weight (lbm/gal)	11
Plastic viscosity (cp)	14
Yield point (lbf/100 ft^2)	15
Cuttings size (in)	0.3

Table 4. Comparative Results of the methods

Parameters	Larsen et al. (1997) method	New equations	Larsen et al. (1997) method	New equations
Hole inclination (^{o})	55	-	75	-
Annular clearance (in)	8.50	8.50	3.50	3.50
Annular velocity (ft/s)	5.47	5.39	4.92	4.89
Mud flow rate (gal/min)	2104.50	2045.80	569.53	557.57
Transport ratio	0.22	0.22	0.32	0.32

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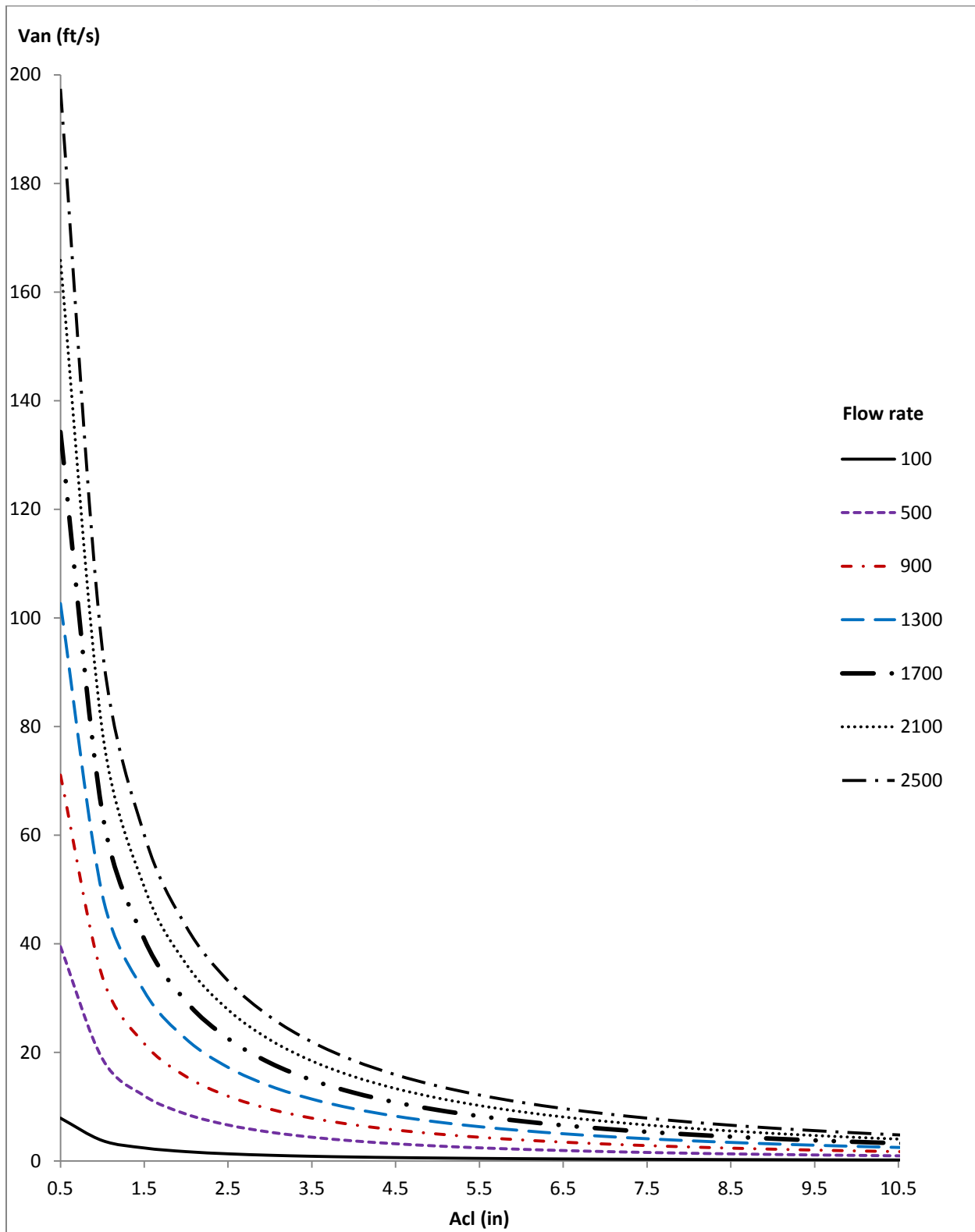
Figure 2. Graph of annular velocity against annular clearance for different flow rates

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Nomenclature

T_r	Transport Ratio
$\bar{v}_c$	Cuttings Transport Velocity, ft/s,
$\bar{v}_{an}$	Annular Mud Velocity, ft/s,
YP	Yield Point, lbf/100 ft^2
PV	Plastic Viscosity, cp
Q_c	Cuttings Flow Rate, ft^3/s
Q_m	Mud Flow Rate, gal/min
A_{an}	Annular Area, ft^2
C_f	Annular Cuttings Concentration by Volume
C_{fp}	Annular Cuttings Concentration by Volume, percentage (%)
P_r	Rate of Penetration, ft/hr,
A_{hole}	Hole Cross Sectional Area, ft^2
A_{pipe}	Drill Pipe Cross Sectional Area, ft^2
D_{pipe}	Drill Pipe Diameter, in
D_{hole}	Hole Diameter, in
A_{cl}	Annular Clearance, in
$\bar{\rho}$	Mean Mud Density, lbm/gal
ρ_m	Mud Density, lbm/gal
ρ_c	Cuttings Density, lbm/gal
RPM	Revolution per minute

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Appendix A

Substituting equation (4) into equation (3) and simplifying, results to:

$$\bar{v}_{an} = \frac{100Q_m}{A_{an}(99.5 - 0.01778P_r)} \tag{10}$$

The annular area can be expressed as

$$A_{an} = A_{hole} - A_{hole} \tag{11}$$

$$A_{an} = A_{hole}\left[1 - \left(\frac{D_{pipe}}{D_{hole}}\right)^2\right] \tag{12}$$

Substituting equation (12) into (10) gives

$$\bar{v}_{an} = \frac{400Q_m}{\pi\left(D^2{}_{hole} - D^2{}_{pipe}\right)(99.5 - 0.01778P_r)} \tag{13}$$

and

$$\bar{v}_{an} = \frac{127.324Q_m}{\left(D^2{}_{hole} - D^2{}_{pipe}\right)\left(99.5 - 0.01778R_p\right)} \tag{14}$$

Converting to field units

$$\bar{v}_{an} = \frac{40.8528Q_m}{\left(D^2{}_{hole} - D^2{}_{pipe}\right)(99.5 - 0.01778P_r)} \tag{15}$$

Substituting equation (6) in equation (15) yields equation (5)

$$\bar{v}_{an} = \frac{40.8528Q_m}{(99.5 - 0.01778P_r)\left(2D_{pipe} + A_{cl}\right)A_{cl}}$$

Appendix B

Equations (1), (2), (4) and (7) give:

$$C_{fp} = 100C_f = \frac{100Q_c}{Q_c + T_rQ_m} = 0.01778P_r + 0.505 \tag{16}$$

Cuttings flow rate (ft^3/s) can be expressed in terms of rate of penetration (ft/hr) as:

$$Q_c = \frac{P_rA_{hole}}{3600} \tag{17}$$

Solving equations (16) and (17) yields

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$$T_r = \frac{P_r}{36\bar{v}_{an}\left[1 - \left(\frac{D_{pipe}}{D_{hole}}\right)^2\right](0.01778P_r + 0.505\ )} \tag{18}$$

Substituting for $\bar{v}_{an}$ and D_{hole} and simplifying, give equation (8)

$$T_r = \frac{(99.5 - 0.01778R_p)(\ D_{pipe} + A_{cl})^2}{Q_m\left(26.149 + \frac{742.7}{R_p}\right)}$$

Appendix C

Effective annular mud density is given by (Bourgoyne, et al., 1986)

$$\bar{\rho} = \rho_m(1 - C_f) + \rho_c C_f \tag{19}$$

Converting C_f to percentage and substituting equation (4) in equation (19) leads to equation (9)

$$\bar{\rho} = \frac{1}{100}[0.505\rho_c + 99.5\rho_m + 0.01778(\rho_c - \rho_m)P_r]$$

SI Metric Conversion Factors

cp	x 10^0	E – 03 = Pa.s
ft	x 3.048	E – 01 = m
ft^2	x 9.290304	E – 02 = m^2
ft^3	x 2.831685	E- 02 = m^3
gal	x 3.785412	E -03 = m^3
in.	x 2.54	E+02 = m
lbf	x 4.448222	E+00 = N
lbm	x 4.535924	E-01 = kg