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Effects of ROP on Selected Foam Rheological Properties in Vertical Wells

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Abstract

Foam drilling is one of the different techniques of underbalanced drilling which is to intentionally design the proper compressible fluid as drilling mud. The main characteristics of the foam fluids are its wide range of low densities which are generally from 1 to 5 ppg; and its high effective viscosities which are superior to those of both constituents; liquid and gas. Literature reported case stories of foam drilling in most challenging formations with excessive and complete losses due to reservoir depletion, fractured strata, unconsolidated beds etc. For good cuttings removal and desired hole cleaning, the technique of foam drilling relies upon foam high effective viscosity and annular mixture velocity. To guarantee adequate hole cleaning in foam drilling, factors affecting these two parameters must be carefully monitored and controlled during the entire hole sections.

As foam rheological properties are among the most affecting parameters for hole cleaning, their detailed studies are not considered exaggerated. Carrying out foam drilling in producing formations results in annular foam rheological properties much different than those in the string due to the intrusion of formation cuttings and fluids into the annular mud stream. Therefore, detailed analysis of different parameters affecting on the annular foam rheology is crucial for optimum foam drilling. Rate of penetration (ROP) is a determinant parameter for drilling economy, but might also be one of the main causes for the changes of the annular rheology of foam. In this paper, we developed a recent program using VISUAL BASIC for a hydraulic model of foam drilling in vertical wells to investigate the influence of ROP on selected foam rheological properties. For the particular conditions in the Appendix Table of this paper, foam annular velocity, quality, density, power index, Reynolds number and cuttings concentration all increase proportionally with the increase of ROP, whereas, annular surface pressure, effective viscosity, consistency index and friction factor all decrease inversely with the ROP increase.

Introduction

Foam is made of discontinuous gas bubbles entrapped within the continuous liquid film. For this mixture fluid to remain homogeneous and coherent, foaming agents or surfactants are added for better foam stability; and this type of foam is known as stable foam. Stiff foam will contain the same mentioned constituents in addition to some polymers and, sometimes, some solids in order to better deal with special formation-related problems. Most foam fluids contain water as liquid phase, but recently, oil has been reported in the literature as liquid phase for foam drilling in water- sensitive formations. Except harmful and toxic gases such as H_2S, any type of gas can act as gas phase in foam drilling. Therefore, air, nitrogen, carbon dioxide and natural gas have all been well reported and documented in the literature [1].

As foam is made of continuous liquid and discontinuous gas, it might be treated as double-phase inside the string; and as three-phase in the annulus due to the presence of variable-sized drilled cuttings. Thus, the hydraulics of foam as a drilling medium becomes much more complex than the conventional overbalanced drilling one. The complexity of multi-phase algorism pushed some investigators to adopt simplifying assumptions that are scarcely satisfied and met in real drilling conditions. Therefore, literature revealed proposed several hydraulic models for foam drilling in spite of the reported inaccuracy of some of them when tested in areas different than where they were developed. This was the encouraging and guiding factor to extensively lead researches to build reliable models that should not compromise the accuracy of the results in spite of the adoption of some simplifying assumptions. As a first step for achieving so, detailed analysis of foam rheological properties in addition to the impacts of different drilling conditions on the rheology is crucial. In this paper, the impact of ROP on selected foam rheological properties shall be analyzed in details.

Literature Review

Lord built and proposed an equation of state for foam fluids based on the pressure and temperature [2-7]. His equation was, then, extended to include the calculations of foam density as functions of pressure, temperature, density of the basic liquid and the gas mass fractional assuming the real gas behavior. Based on the mechanical energy balance principle, the author also built equations to statically and dynamically calculate foam quality, density and pressure drop at any position along the borehole. His final form of the model was a differential equation which could be numerically solved to predict the injection pressure. His model was found to predict accurately the down hole pressures with proppant-laden foam.

Okpobiri and Ikoku, based on a semi-empirical model, proposed a methodology to calculate the frictional component of the pressure drop as the result of the presence of the drilled solids in the annular returning foam [4,5]. The study of the authors was also exploited to predict the minimum volumetric requirements of the foam drilling operations. The results of their experimental works concluded that friction factor was due to the frictional factor of the basic circulating foam and that of the drilled solids. The authors stated that at constant Reynolds Number, the frictional factor increased as the concentration of the drilled solids also increased. Their assumption was that all foam drilling operations took place at laminar region, and that the foam quality decreased as the pressure increased. They also assumed the quality between 55 and 96%. The authors also recommended the use of the surface back pressure to control and maintain the foam quality within the assumed range. They, finally, concluded that the increase of the cuttings size increased the volumetric requirements of the foam and that the ROP had negligible effect on the foam volumetric requirements.

Stefan Miska et al. conducted an extensive experimental test to develop a more generalized quality-dependent parameters such as generalized foam flow consistency index and generalized foam flow power index in laminar foam flow for both flow paths (in pipes and annulus) taking into account the effects of the annular cuttings [8,9]. The results of their experimental works revealed that the drilling foam behaved as pseudo plastic fluid with insignificant yield stress. The results of their experimental works concluded also the existence of the non-linear relationship between both of foam flow consistency and foam flow power indices and the foam quality. The results of their proposed model fitted well their experimental data with an average error less than 20% for both pipe and annulus using a range of foam qualities from 70 % to 80 %, but there was less accuracy at foam quality of 90 %.

Nosakhare O. I conducted an extensive experimental investigation to analyze the mechanisms of the drainage of oil-based drilling foam that supposed to be, theoretically, more matching in underbalanced drilling applications in water-sensitive formations [10].

Amit Saxena et al. experimentally conducted studies on foam flow in vertical smooth pipes. The authors studied foam rheology using two different types of foam [11]. They also compared the capability of cuttings removal using different foam qualities within variable pipe sizes. The authors, finally, concluded the dependence of cuttings removal on foam rheology as well as on the conduit sizes.

Results and Discussions

The following results and discussions are based on a simulated and predictive study by running the developed proposed model on input data from the Appendix Table.

Effects of ROP on annular pressure drops (ΔP)

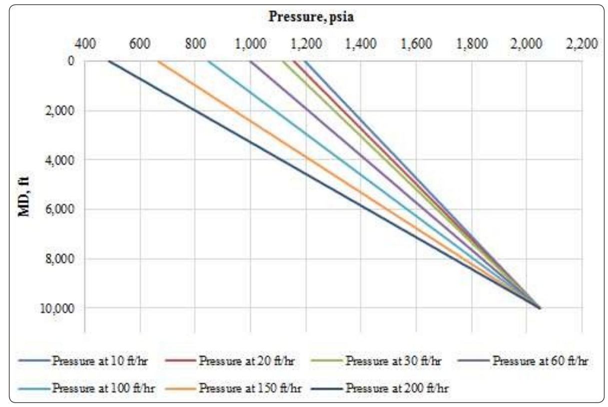

Figure 1: Effects of ROP on annular pressure drops

Fig.1 presents the effects of ROP (Rate of Penetration) on the annular pressure drops. The increase of ROP linearly reduces the annular pressure at the surface. An annular surface pressure of 1,200 psia at an ROP of 10 ft/hr under the conditions given in the Appendix Table will slightly decrease to 1160 psia and to 1120 psia if ROP slightly increases to 20 ft/hr and to 30 ft/hr, respectively. Increasing ROP by significant values will also result in corresponding significant decreases of the annular surface pressure. Therefore, the annular pressure of 1120 psia under the previous conditions will significantly reduce to 1,000, 850, 665 and 490 psia if ROP also and correspondingly increases to 60 ft/hr, 100 ft/hr, 150 ft/hr and 200 ft/hr, respectively.

The reduction of the annular surface pressure with the increase of ROP is due to the fact that, at the increase of ROP, the annulus cleaning will require an additional hydraulic energy and, consequently, an additional power in term of pressures to better remove the cuttings and efficiently clean the wellbore, thus, more circulating pressures will be dedicated and consumed in the annulus, and therefore, the final remaining amount of the pressure at the annular surface will correspondingly decrease.

Effects of ROP on Annular Mixture Velocity (U)

Fig.2 shows the effects of ROP on the annular mixture velocity. As annular mixture comprises the injected liquid and gas at the surfaces, the liberated fluids from the drill cuttings, the influxes from the porous permeable formations and the drilled solids, the increase of ROP increases these annular mixture constituents and, consequently, increases the annular mixture velocity.

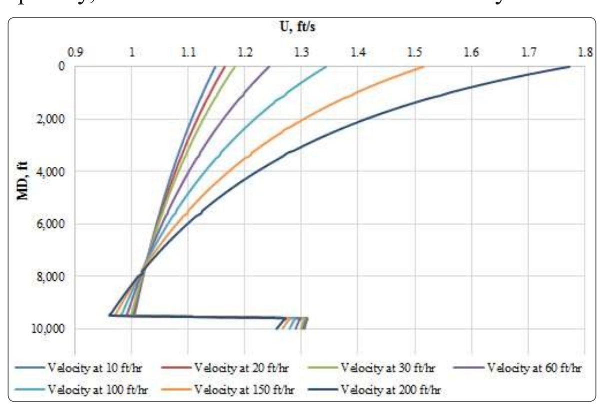

Figure 2: Effects of ROP on annular mixture velocity

An annular surface mixture velocity of 1.15 ft/s at an ROP of 10 ft/hr will increase to 1.16, 1.18, 1.24, 1.34, 1.52 and 1.77 ft/s should the ROP correspondingly increase to 20, 30, 60, 100, 150 and 200 ft/hr, respectively. Fig.2 also shows that annular mixture velocity decreases with the increase of ROP at the bottom and higher depths of the annulus. This is explained by the fact that annular mixture constituents at the bottom are affected by high hydrostatic pressure and gravitational forces downward. These pressures and forces will be acting against the force acting to lift the annular mixture upward. The upward force will equalize the opposing downward forces at a depth point somewhere higher than the bottom. In Fig.2, the equalization depth point is at 7,600 ft. above the equalization point, the lifting force becomes gradually dominant over its opposing downward forces, and the annular mixture velocity starts increasing by the increase of ROP. The increase of the annular mixture velocity over the equalization depth will be enhanced by the reduction of the annular pressure due to the reduction of the hydrostatic head as the annular mixture flows upward.

Fig.2 also shows that the increase of the annular mixture velocity is not necessarily linear. The rate of velocity increase with ROP over the equalization depth point is not constant. Also, the effects of annular geometries on annular mixture velocity are significant in Fig.2. The initial value of annular mixture velocity across the drill collars (DC) is much higher than that across HWDP. For the annular section across the 6 inches DC, the fact of the increase of the annular mixture velocity could not be satisfied due to the short length of that section. For the annular section across the 5 inches HWDP, the fact of the increase of the annular mixture velocity occurred after the equalization point because of sufficient length. Therefore, the annular mixture velocity, first, decreases with the increase of the ROP before the equalization point, and then, increases with the increase of ROP. It is worthy to note that the annular mixture velocity is not the annular fluid velocity, but the average equivalent velocity of all annular mixture constituents. So, the annular fluid velocity becomes slightly more than the mixture one due to effects of the slip velocity.

Effects of ROP on Annular Foam Quality (Γ)

Fig.3 presents the effects of the ROP on the annular foam quality. The increase of the ROP apparently increases the annular foam quality. An annular foam quality of 0.9625 (96.25 %) at an ROP of 10 ft/hr will slightly increase to 0.9631, 0.9637, 0.9657, 0.9683, 0.9719 and 0.9759 should the ROP also increase to 20, 30, 60, 100, 150 and 200 ft/hr, respectively. The increase of the annular foam quality with the increase of the ROP is due to two reasons; firstly: the increase of the gas amount in the annulus due the liberation of the drilled cuttings and influx gases, and secondly: the reduction of the annular pressure due to the reduction of the hydrostatic head during the upward flow of the annular stream.

It is also worthy to note that the increase of the annular foam quality with the increase of the ROP is not always an absolute fact, but really depends on the formation gas saturation and reservoir gas bubble point. The current conclusion might be restricted to the conditions in the Appendix Table.

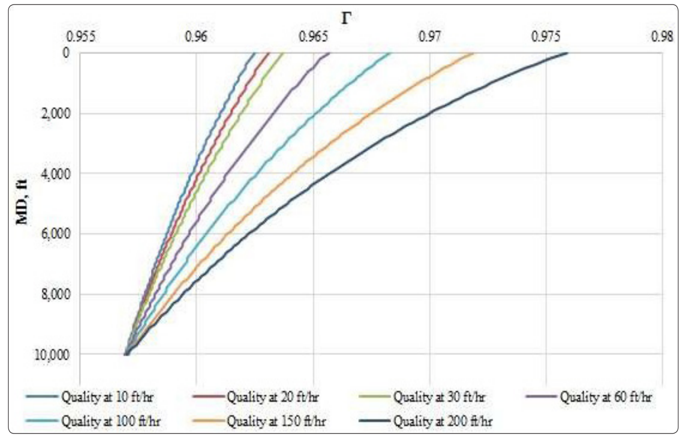

Figure 3: Effects of the ROP on the annular foam quality

Effects of ROP on Annular Foam Density (ρ)

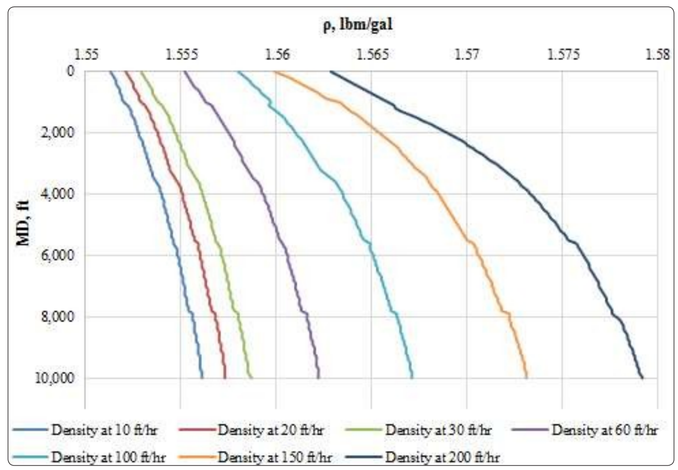

Figure 4: Effects of ROP on the annular foam density

Fig.4 illustrates the effects of the ROP on the annular mixture density. As annular mixture constituents contain only 25 to 40% of the annular pore fluids and 60 to 75 % of the annular drilled solids, regardless of the types of the formation fluids, the dominant constituent for controlling the annular mixture density is the drilled solids. Therefore, the increase of the ROP increases the annular mixture density, especially, at the annular bottom where cuttings concentrations are greater.

An annular surface mixture density of 1.552 ppg at an ROP of 10 ft/hr will increase to 1.553, 1.5535, 1.555, 1.558, 1.56 and 1.563 ppg if the ROP increases to 20, 30, 60, 100, 150 and 200 ft/hr, respectively. The annular mixture density decreases more apparently at lower depths near the surface because of the reduction of annular pressure due to the decrease of hydrostatic head.

Effects of ROP on Annular Foam Effective Viscosity (μeff)

Fig.5 presents the effects of the ROP on the annular foam effective viscosity. The increase of the ROP reduces the annular foam effective viscosity. An annular surface foam effective viscosity of 0.0117 lb/ft-s (17.4 cp) at an ROP of 10 ft/hr can be reduced to 0.0115, 0.0114, 0.0109, 0.0101, 0.0092 and 0.0085 lb/ft-s (12.6 cp) should the ROP increase to 20, 30, 60, 100, 150 and 200 ft/hr, respectively. The reason for the decrease of the annular foam effective viscosity with the increase of the ROP can be explained by the fact that, in addition to annular influx, at the increase of the ROP, the annulus is more loaded due to the accumulation of more cuttings. This requires more hydraulic energy and power in term of annular pressure to transport the cuttings and clean the hole. This requirement will consume more annular pressure, and thus, the annular pressure significantly reduces at the foam upward flow, and reduces the annular effective viscosity.

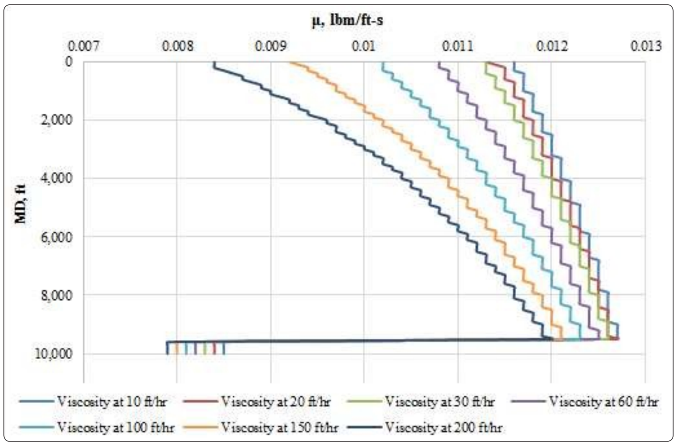

Figure 5: Effects of ROP on the annular foam effective viscosity

Effects of ROP on Annular Foam Flow Power Index (n)

Fig.6 shows the effects of the ROP on the foam flow power index n in the annulus. Normally, the foam flow power index increases with the annular foam upward flow due to the reduction of the pressure. The increase of the ROP increases the annular foam flow power index. A surface value for n of 0.313 for an ROP of 10 ft/hr can be increased to 0.314, 0.315, 0.32, 0.328, 0.337 and 0.347 should the ROP also increase to 20, 30, 60, 100, 150 and 200 ft/hr, respectively.

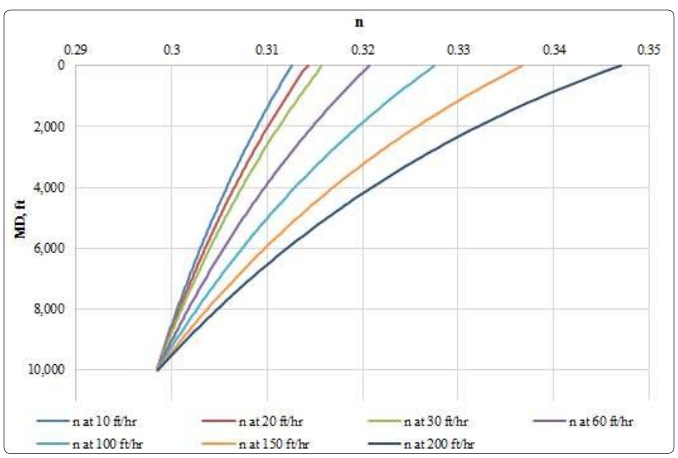

Figure 6: Effects of ROP on the annular foam flow power index

The reason for the increase of n with the increase of the ROP might be explained by the fact that, as long as n approaches the unity, the flow also moves from the Non-Newtonian fluid and approaches the Newtonian one. So, for the conditions given in the Appendix Table, the increase of the ROP increases the annular mixture constituents including the formation liquid (water and oil) which might tend to increase the value of n to slightly transfer the annular medium from purely Non-Newtonian into Newtonian.

Effects of ROP on Annular Foam Flow Consistency Index (k)

Fig.7 presents the effects of the ROP on the annular foam flow consistency index k. normally, k decreases with the annular foam upward flow toward the surface due to the reduction of annular pressure. A k surface value of 0.09 lbf-s^n/ft^2 at an ROP of 10 ft/hr can be decreased to 0.089, 0.088, 0.084, 0.078, 0.07 and 0.061 lbf-s^n/ft^2 should the ROP also increase to 20, 30, 60, 100, 150 and 200 ft/hr, respectively. The fact that k decreases with the increase of the ROP might be explained by the fact that k is somehow analogous to the resistance to the fluid pumpability and mobility. Thus, as the ROP increases, more annular generated influxes dilute the foam mixture and reduce the resistance to the pumpability and mobility. Also more annular cuttings will be generated and the annulus will be heavily loaded and consequently, more hydraulic energy and power, in term of the annular pressure, are necessarily consumed for the hole cleaning, therefore, the less remaining annular pressures will act on the annular upward flowing foam mixture and, consequently, less resistance to the pumpability is faced by the foam mixture.

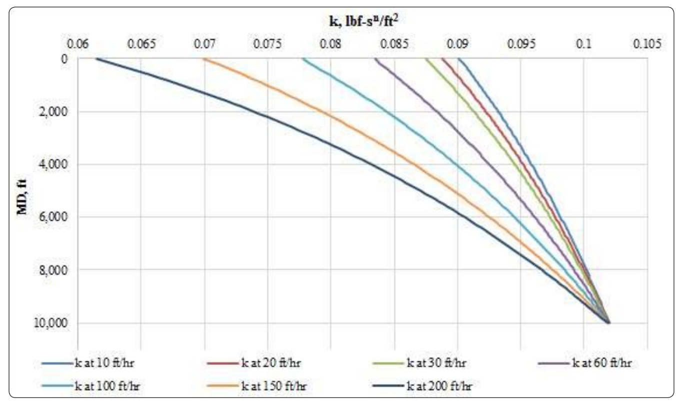

Figure 7: Effects of ROP on the Annular Foam Flow Consistency Index

Effects of ROP on Annular Foam Reynolds Number (NRe)

Fig.8 shows the effects of the ROP on the annular mixture Reynolds number (NRe). Generally, NRe increases with the increase of the ROP. As the annular mixture velocity is directly proportional to NRe, the increase of the annular mixture velocity due to the increase of the ROP increases NRe. A value of NRe of 1130 (laminar flow) on the surface for an ROP of 10 ft/hr can be increased to 1180, 1240, 1440, 1790, 2430 and 3530 (turbulent flow) should the ROP also increase to 20, 30, 60, 100, 150 and 200 ft/hr, respectively.

Fig.8 shows also illustrates that the increase of NRe due to the increase of the ROP is not so significant at the wellbore bottom and higher depths, but becomes gradually significant along the annular mixture upward flow due to the reduction of the pressure and the depth. Also, Fig.8 shows the total dependence of NRe, among others, on the annular geometries. Values for NRe are smaller at deeper annular sections with smaller annular clearances across DC because of higher pressures; and they are higher at higher sections with wider clearances due to the pressure reduction.

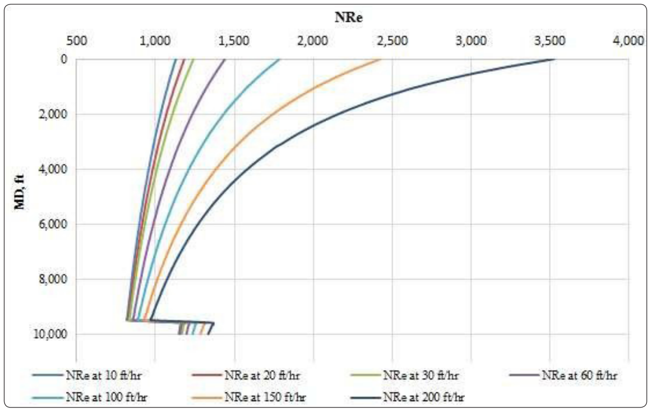

Figure 8: Effects of ROP on the Annular Foam Reynolds Number

Effects of ROP on Annular Foam Friction Factor (FF)

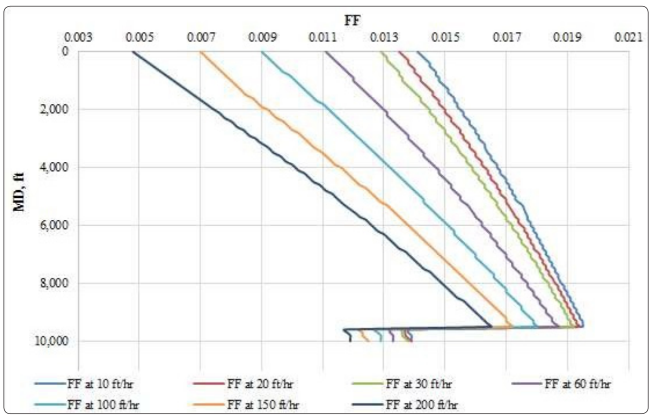

Figure 9: Effects of ROP on the annular foam friction factor

Fig.9 presents the effects of the ROP on annular foam friction factor FF. Generally, FF decreases with the increase of the ROP due to the increase of the annular mixture velocity and Reynolds number. The increase of the ROP increases the annular mixture velocity which is, in its turn, inversely proportional to FF. A value of FF of 0.0141 on the surface for an ROP of 10 ft/hr can be reduced to 0.0135, 0.0129, 0.011, 0.009, 0.007 and 0.0048 if the ROP increases to 20, 30, 60, 100, 150 and 200 ft/hr, respectively.

Fig.9 shows also that the rate of decrease in FF is higher at the surface and at shallower depths other than at the bottom and higher depths. The difference between the two friction factors at 10 and 200 ft/hr on the surface is 0.0086 whereas the difference between them at the annular bottom across HWDP is only 0.003. The effects of the annular geometries on FF are also shown in Fig.9.

Effects of ROP on Annular Cuttings Concentration (Cc)

Fig.10 illustrates the effects of the ROP on the annular cuttings concentration Cc. Cc increases with the increase of the ROP and this necessitates close monitoring and constant control on the annular foam rheology for, not only hole cleaning, but also hole stability as excessive amounts of the annular cuttings without adequate and optimum hole cleaning might result in excessive back pressure on the formation and, hence, might lead to the excessive overbalanced conditions instead of the required desired underbalanced ones.

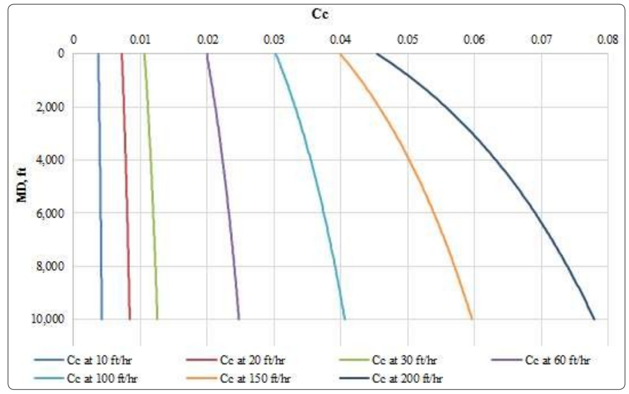

Figure 10: Effects of ROP on the annular cuttings concentration

At a low ROP of 10 ft/hr, the cuttings concentration is more or less constant around 0.004 (0.4 %) along the entire annular section. Slight increase of ROP to (20-30) ft/hr slightly increases Cc with the annular mixture upward flow: from 0.008 (0.8 %) to 0.007 (0.7 %) for the 20 ft/hr and from 0.013 (1.3 %) to 0.011 (1.1 %) for the 30 ft/hr. Increasing the ROP above these values significantly reduces Cc from its upper values at the bottom to its lower ones at the surface: from 2.5 to 2 % for 60 ft/hr, from 4.1 to 3 % for 100 ft/hr, from 6 to 4 % for 150 ft/hr and from 8 to 4.5 % for 200 ft/hr.

Conclusions

1. Based on the specific conditions given in the Appendix Table, it can be concluded that the increase of the ROP decreases the surface annular pressure (casing or choke pressure), foam flow consistency index k, foam effective viscosity and friction factor, whereas the annular mixture velocity, annular mixture density, foam quality, foam flow power index, Reynolds number and cuttings concentration all increase.
2. For general statement; annular foam quality, effective viscosity, power index n and consistency index k vary with respect to the ROP depending on the formation fluid types and saturations.
3. The developed model predicted well the down hole pressures when the model was run on two foam-drilled wells in the Middle East with average errors of 2.56 and 10.85% for the first and second wells, respectively. The model accuracy was also found to be slightly less than that of Valco-Economides' one, and also less that Sporker's one (Figs.11&12 and Tables 1&2).

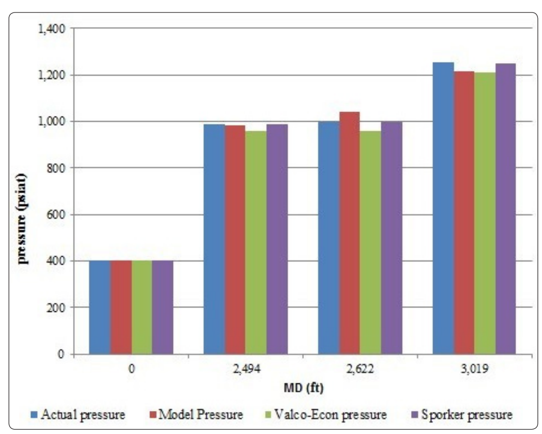

Figure 11: Comparison of the bottomhole pressure among the actual field data, developed model, Valco- Econ' model and Sporker's model for the developed model evaluation with the first well

Table 1: Comparison of the bottom hole pressures among the field data, the developed model, Valco-Economides' model and Sporker's model at 1,600 scf/min gas rate and 40 gal/min liquid rate for the model evaluation and validation with the first well

Depth (ft)	Pinj (psia)	Pactual (psia)	Pmodel (psia)	PValco-Eco (psia)	PSporker (psia)	Error Valco- Econ (%)	Error Valco- Econ (%)	ErrorSporker (%)
2,494	750	989.5	983.7	956.6	986.6	0.59	3.32	0.29
2,622	780	998.5	1,040.1	958.4	995.8	4.17	4.02	0.27
3,019	880	1,252.3	1,215.6	1207.9	1,249	2.92	3.55	0.26

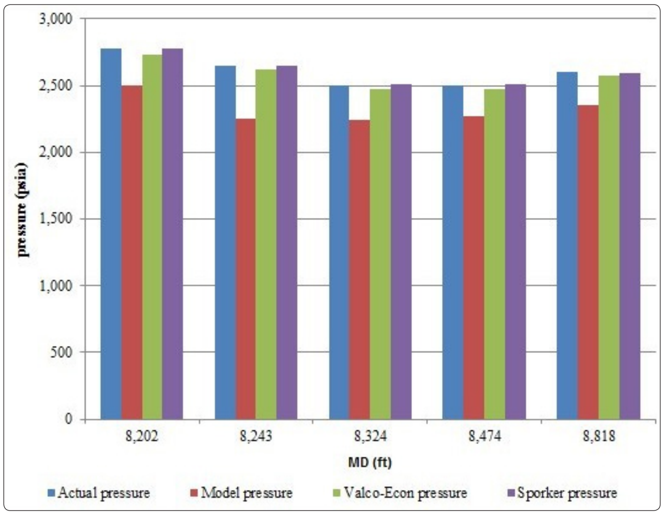

Figure 12: Comparison of the bottomhole pressure among the actual field data, developed model, Valco- Econ' model and Sporker's model for the model evaluation with the second well

Table 2: Comparison of the bottomhole pressures among the field data, the developed model, Valco-Economides' model and Sporker's model at 650 scf/min gas rate and 1,000 psia injection pressure for the model evaluation and validation with the second well

Depth (ft)	QL (gal/ min)	Pactual (psia)	Pmodel (psia)	PValco-Econl (psia)	PSporker (psia)	Errormodel (%)	ErrorValco-Econ (%)	ErrorSporker (%)
8,202	19	2,775	2,497.1	2,732.5	2,773	10.01	1.53	0.10
8,243	14	2,650	2,249	2,622.5	2,646	15.13	1.04	0.15
8,324	14	2,500	2,245	2,473.5	2,505	10.2	1.06	0.20
8,474	14	2,500	2,267.6	2,472.5	2,507	9.3	1.10	0.28
8,818	14	2,600	2,349.8	2,572.5	2,593	9.62	1.06	0.27

Nomenclature

A = Cross sectional area, ft^2
Cc = Cutting concentration, fraction
C_D = Drag coefficient, dimensionless
FF = Fanning friction factor, dimensionless
g = Gravitational acceleration, ft/s^2
gc = Unit conversion factor (32.174 lb_m-ft/$lb_{f\text{-}s}{}^2$)
H_{pen} = Penetrated thickness in reservoir, ft
Htot = Total reservoir thickness, ft
k = flow consistency index, $lb_{f\text{-}s}{}^n/ft^2$
m = mass flow rate, lb_m/s
Mwt = molecular weight of the fluid, (lb_m/lb_{mol})
n = flow power index, dimensionless
P = pressure, lb_f/ft^2
PI = Productivity index, bbl/day-psia
Q = volumetric flow rate, ft^3/s
NRe = Reynolds number, dimensionless
S = wetted perimeter, ft
U = Velocity, ft/s
V = volume, ft^3
ΔZ = Grid cell length, ft
Γ = foam quality, fraction
ρ = density, lbm/ft^3
θ = well inclination from the vertical, degrees
ϕ = average formation porosity, fraction or percentage
μ = effective viscosity, lb_m/ft-s, cp
τ = shear stress, lb/ft^2.

Appendix A: Basic Developed Equations [1]

$$\frac{dP}{dZ} = -\rho_f \frac{g}{g_c}\cos(\theta) - \frac{S\,\tau_w}{A_{ann}} \quad (1)$$

$$Q_i = A_{hole}.\ ROP.\ \phi.\ Sat_i, \qquad i = \text{water, oil and gas} \quad (2)$$

$$Q_{cuttings} = A_{hole}.ROP\ (1-\phi) \qquad \& \qquad Q_{ann} = A_{hole}.ROP \quad (3)$$

$$Q_{f(ann)} = Q_{g(ann)} + Q_{L(ann)} \quad (4)$$

$$Cc_{(approx)} = \frac{Q_{cuttings}}{Q_{ann+}\ Q_{f(ann)}} \quad (5)$$

$$\rho_{ann(ass)} = \rho_f \text{ x } (1-Cc_{(approx)}) + \rho_{cuttings} \text{ x } Cc_{(approx)} \quad (6)$$

$$Q_{influx(i)} = Q_{max(i)} \text{ x } \left(\frac{H_{pen}}{H_{tot}}\right) \text{ x } \left[1 - 0.2\left(\frac{P_{wf}}{P_{res}}\right) - 0.8\left(\frac{P_{wf}}{P_{res}}\right)^2\right] \quad (7)$$

$$Q_{influx(i)} = PI_i \text{ x } \left(\frac{H_{pen}}{H_{tot}}\right) \text{ x } (P_s - P_{wf}) \quad (8)$$

$$m_i = [Q_{(i)} + Q_{influx(i)}] \text{ x } \rho_{(i)}, \qquad m_{solids} = Q_{cuttings} \text{ x } \rho_{solids} \quad (9)$$

$$Mwt_{(ann)} = Mwt_{(inj)} \text{ x } \frac{Q_{g(inj)}}{Q_{g(inj)}+Q_{(g)}+Q_{influx(g)}} + Mwt_{(influx)} \text{ x } \frac{Q_{(g)}+Q_{influx(g)}}{Q_{g(inj)}+Q_{(g)}+Q_{influx(g)}} \quad (10)$$

$$Q_{tot\ (ann)} = (Q_{cuttings} + Q_{L(inj)} + Q_{g(inj)} + Q_{(g)} + Q_{influx(g)} + Q_{(o)} + Q_{influx(o)} + Q_{(w)} + Q_{influx(w)}) \quad (11)$$

$$Cc = \frac{Q_{cuttings}}{Q_{tot(ann)}} \quad (12)$$

$$\Gamma_{ann} = \frac{Q_{g(inj)} + Q_{(g)} + Q_{influx(g)}}{(Q_{tot(ann)} - Q_{cuttings})} \quad (13)$$

$$m_g = (Q_{(g)} + Q_{influx(g)}) \text{ x } \rho_{g(ann)} \quad (14)$$

$$m_{cuttings} = m_{solids} + \sum m_i \quad (15)$$

$$\rho_{cuttings} = \frac{m_{cuttings}}{Q_{ann}} \quad (16)$$

$$\rho_{mixture} = \frac{\rho_{cuttings}.m_{cuttings} + \rho_{f(ann)}.m_f}{m_{cuttings} + m_f} \quad (17)$$

$$U_{term}^{[8]} = \sqrt{\frac{4\,g_c\,D_{solids}}{3C_D}\left(\frac{\rho_{solids}-\rho_{f(ann)}}{\rho_{f(ann)}}\right)} \quad (18)$$

$$U_h^{[8]} = U_{term}\,(1 - Cc)^h \quad (19)$$

$$U_{ann}^{[6]} = U_{ann(gross)} - \frac{U_h \, \rho_{solids} \, C_C}{\rho_{mixture}}, \qquad U_{ann(gross)} = \frac{Q_{tot(ann)}}{A_{ann}} \tag{20}$$

$$Re_{ann}^{[6]} = \frac{12^{1-n} \, \rho_{f(ann)} \, U_{ann}^{2-n} \, (D_{hole} - OD_{pipe})^n}{K\left(\frac{(2n+1)}{3n}\right)^n} \tag{21}$$

$$\tau = 0.5 \, \rho_{mixture} \, f_f \, U_{ann}^2 \tag{22}$$

Appendix B (Appendix Table), Input data for the foam drilling program [1]

Surface Conditions	Surface Pressure, psia	14.7
	Surface Temperature, °F	60
Injection Conditions	Injection Pressure, psia	1,500
	Injection Temperature, °F	65
	Injection Liquid Rate, gal/min	5
	Injection Gas Rate, scf/min	2,000
Well Data:	Total Depth, ft	10,000
	Last Casing Size, inches	9.25x8.68
	Last Casing Depth, ft	7,000
	Temperature Gradient, °F/ft	0.015
	ROP, ft/hr	Variable
Formation Data:	Porosity, %	25
	Rock Density, lbm/gal	20
	Formation Water Density, lbm/gal	8.5
	Formation Oil Density, lbm/gal	6
	Formation Gas Molecular	
	Weight, lbm/lbmole	22
	Formation Water Saturation, %	40
	Formation Oil Saturation, %	30
	Formation Gas Saturation, %	30
Drill String Geometry:	Drill Pipe ID, inches	4.27
	Drill Pipe OD, inches	5
	Drill Pipe Length, ft	9,000
	HWDP ID, inches	3
	HWDP OD, inches	5
	HWDP Length, ft	500
	Drill Collar ID, inches	2.25
	Drill Collar OD, inches	6
Drill bit	Nozzle Diameters, inches	3x13/32
Foam	Water + Nitrogen	

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