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Design and Application of Aerated and Foam Drilling Fluid, Case Study in Drilling Operation in Indonesia

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ABSTRACT

Underbalance drilling is a common application in highly fractured and subnormal pressured formation. Technical reasons such as reservoir damage, drilling in depleted zone and hard drilling lead to more economic value in drilling operation. There are several ways to achieve underbalanced well pressure while drilling. One of the most common technique is air, aerated-mud and foam drilling or commonly known as Aerated Drilling.

Drilling with air, aerated-fluid and foam can lead to numerous advantages. In spite of the advantages, it also brings more challenge in design and operation. Cutting transport should be properly calculated to achieve a clean bottom hole condition. Air and gas parameters should be properly designed to prevent wellbore wash out and formation collapse. All of them should be properly design while maintaining underbalance condition.

In some cases, improper aerated drilling parameters potentially lead to drilling problems such as lost circulation and stuck pipe. This condition should have been mitigated with the proper design of Air, Gas and Foam injection rate. Guo and Ghalambor in 2002 describe main criterion in aerated drilling design. Guo's technique can be applied in air, foam and aerated-liquid drilling. In 2009 Lyons adds more complicated technique, including calculation of liquid hold up and unstable foam drilling. Calculations in this paper are based on both criterion and technique. On operational side, several key takeaways are drawn based on operational challenges in multiple combinations of operational conditions.

This paper proposes comprehensive techniques to design and parameter in operation in aerated drilling. Several cases are presented in this paper and being evaluated using proposed technique. All of the data are taken from real underbalance drilling parameters in Drilling Operation in Indonesia

INTRODUCTION

Underbalanced conditions are required while drilling trough fractured and low-pressure formation. Common applications to achieve underbalanced conditions are foam mud, aerated fluid and air/mist drilling. There are two parameters as variable to be controlled in those techniques, air rate and liquid rate.

Inadequate air and liquid flow rate combination can lead to other hole problem. Lack of bottomhole pressure below casing shoe can lead to hole instability issue, inadequate cutting carrying capacity can lead to cutting pack off and high velocity air lead to wellbore washout problem. Those problems should be accounted while maintaining underbalanced conditions.

METHOD

This paper uses Guo et al. (2002) criterions for underbalanced drilling with air, foam and aerated drilling. The detailed criterions are minimum velocity, minimum kinetic energy, bottomhole pressure and foam stability. When drilling with mud motor, flow rate shoud be calculated using two phase flow equations.

Air Drilling

Minimum Velocity criteria:

$$V_t = \sqrt{4gd_c\frac{\rho_c - \rho_f}{3C_d\rho_f}}$$

Minimum Kinetic Energy :

$$V_{min} = V_s\sqrt{\frac{P_s}{P_{bh}}}$$

Bottomhole Pressure :

$$P_b = \sqrt{\left(P_s^2 - \frac{abT_s^2}{G-a}\right)\left(\frac{T}{T_s}\right)^{\frac{2a}{G}} + \frac{abT^2}{G-a}}$$

$$\mathrm{T} = T_s + Gh$$

$$\mathrm{a} = \frac{SQ + 28.8\, ROP\, D_h^2}{53.3Q}$$

$$b = \frac{1.625\, x\, 10^{-6} Q^2}{\left(D_h - D_p\right)^{1.333}\left(D_h^2 - D_p^2\right)^2}$$

Foam Drilling

In foam drilling, the mixture of foam and cuttings cannot be treated as a homogeneous mixture. It makes the minimum kinetic energy criterion for air drilling cannot be applied in foam drilling. The cutting transport requirements for foam drilling are presented below:

$$V_{si} = 1.56 \frac{D_s\left(\rho_s - \rho_{fm}\right)^{0.667}}{\rho_{fm}^{0.333} - \mu_e^{0.333}}$$

Foam Stability

Foam are stable when volumetric gas content is 0.55-0.975. When the gas phase is greater than 0.975, the continuous cellular foam structure that entraps gaseous phase become unstable, and the foam turns into mist. When the gas phase is less than 0.55, the foam structure tends to break down.

Foam quality also related to cutting lifting capacity. Figure 1 shows the relation between foam quality and relative lifting force. The lifting capacity starts to increase at foam quality of 0.6. The best lifting capacity achieved with foam quality ranges from 0.72 – 0.97. It declines after reach 0.97 as the foam begins to unstable.

Foam quality index is defined as :

$$\Gamma = \frac{V_g}{V_g + V_l}$$

The pressure ratio between bottom hole pressures to surface pressure should be maintained to keep the foam quality as desired.

$$\frac{P_{bh}}{P_s} = \frac{T_{bh}\Gamma_s(1 - \Gamma_{bh})}{T_s\Gamma_{bh}(1 - \Gamma_s)}$$

Foamer

Foam is a low density system that has the advantage of having a high lifting and hole cleaning capacity that can be combined with a very low fluid flow. Foam operation has several advantages and common in underbalance drilling operations.

Main objectives when design foam operations are foam quality and stability. Half-life measures the persistence of the foam under atmospheric pressure. Higher value shows higher quality. Foam quality can be achieved with foamer additive. Figure 2 shows optimum foam quality can be achieved with 1 % foamer concentration. After reach optimum concentration, adding more foamer would not affect much on foam quality.

Special considerations should also be accounted when dealing with foam drilling, those are: motor operation, bottom hole temperature and presence of hydrocarbon.

Aerated Drilling Cutting transport

In aerated mud drilling, cuttings are large and move up the annulus at velocities significantly less than the in situ fluid velocity. Generally, flow of aerated water falls into a turbulent flow and flow in oil falls into a transitional regime between turbulent and laminar. It is safe to consider the flow as turbulent flow region. For turbulent flow (Re>2000) the cuttings terminal settling velocity can be estimated using the following equations

$$v_{sl} = 5.35 \sqrt{\frac{D_s\left(\rho_s - \rho_f\right)}{\rho_f}}$$

$$v_m = v_{sl} + v_{tr}$$

$$v_{tr} = \frac{\pi d_b^2}{4AC_p}\left(\frac{ROP}{3600}\right)$$

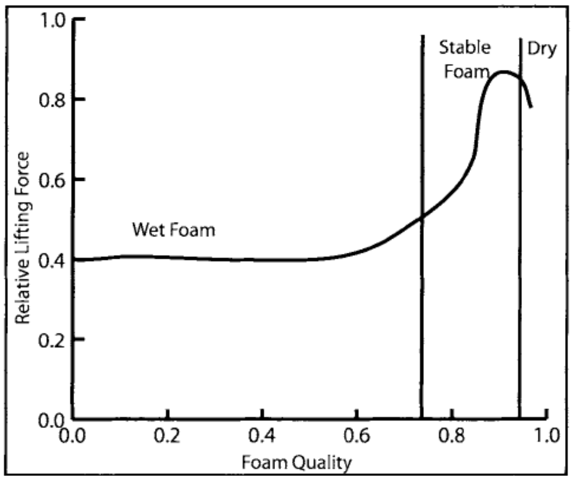

Figure1. Foam lifting capacity curve from Bayer et al. (1972)

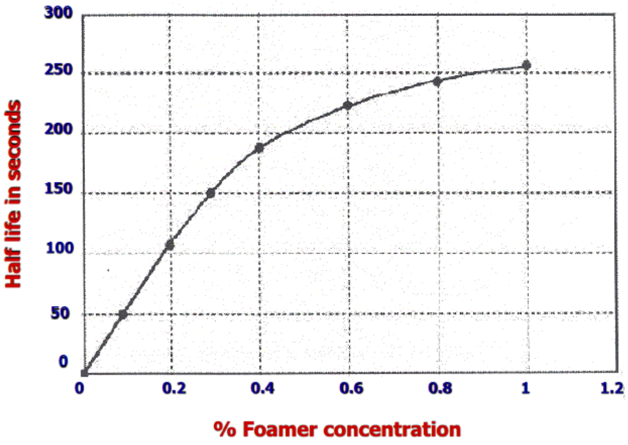

Figure 2. Half life foam curve from Beyer et al. (1972)

Borehole Pressure Criteria

Flowing bottom hole pressure is an important parameter in aerated drilling. Mixture of air and liquids are generating flowing bottom hole pressure while pressure drop occurs in the annulus. Liquids are combinations of drilling mud and any formation fluid presence.

The flowing borehole pressure is formulated as follow:

$$\mathrm{dP} = \gamma_m\left(1 + \frac{fv^3}{2gD_h}\right)dh$$

Where

$$\gamma_m = \frac{A+B+C+D}{E[F+1]}$$

$$A = 9.45 \times 10^{-5} d_b^2 S_s R_p$$

$$B = 1.667 \times 10^{-2} W_m Q_m$$

$$C = 9.7327 \times 10^{-2} S_l Q_f$$

$$D = 1.275 \times 10^{-3} S_g Q_{g0} P$$

$$E = 6.7846 \times 10^{-2} T Q_{go}$$

$$F = \frac{2.2283 \times 10^{-3} Q_m + 1.5597 \times 10^{-3} Q_f}{6.7846 \times 10^{-2} T Q_{go}} P$$

$$f = \left[\frac{1}{1.74 - 2log\left(\frac{2_e}{d_H}\right)} \right]^2$$

Liquid-Gas Rate Window

Guo et al., 2002 describe the liquid gas rate window (LGRW) as combinations of liquid flow rate that meets a certain requirements. The gas injection rate should be carefully designed, so the flowing bottom-hole pressure is less than formation pore pressure under drilling condition, and bottom hole pressure is greater than formation collapse pressure. In this paper, the formation collapse pressure is measured at the weakest point of open hole, which is pressure at the casing shoe. Other limits in designing liquid and gas rate include cutting-carrying capacity and wellbore washout or equipment limit.

The right boundary of LGRW is the curve of liquid gas rate combination that yield casing shoe pressure. This pressure should be maintained to be higher than formation collapse pressure. Since both liquid and gas should be constantly pumped into the well during drilling, this boundary counts the limit as circulating pressure. During circulation-break such as during connection, liquid and gas was replaced by high viscosity mud and original mud. Both has higher hydrostatic pressure relative to aerated drilling. Determining formation collapse pressure is complex tasks of geo-mechanics. This paper did not cover this task.

The left boundary of LGWR is determined by the curve of combination of liquid and gas rate that meets the requirements for an underbalanced condition. Both needs to be maintained below formation pressure at the bottom hole. The combination of liquid and gas rate that equal to formation pressure can be determined based on Guo's model. For the same mud rate, higher gas injection rate result in lower bottom hole pressure.

The lower boundary of LGRW can be determined based on carrying capacity of the fluid and gas mixture under bottom hole condition. This can be determined by plot the maximum allowable cutting diameter under certain mud flow rate and air injection rate. Guo et al. determined the upper limit as a combination of liquid and gas rate that achieved wellbore washout pressure. The wellbore washout is not a common in geothermal formation. This paper will use equipment's technical limit as the upper limit of LGRW.

Mud Motor Operation

For operating with mud motor, we need to know equivalent flow rate for air injection under bottom hole conditions. Best estimation on two phase flow inside pipe are described as follow

$$V_{eq} = \frac{\left(\frac{P_s}{P_{bh}}\right)\left(\frac{T_{bh}}{T_s}\right) Q_g + Q_m}{\frac{\pi}{4} D_h^2}$$

As a result of pressure as function of depth, velocity is also change with depth.

RESULT

Foam Drilling

In foam drilling, foam quality is the most important parameter. To achieve stable foam, foam quality should be maintain between 0.65-0.97. Foam quality will change as temperature and pressure change. This simulation based on assumption that desired foam quality at the bottom of the hole is 0.65 and foam quality at the surface 0.97. Another parameter that related to foam quality is gas-liquid ratio (GLR). GLR should be maintain at calculated ranges to achieve desired foam quality at certain pressure and temperature. Figure 3shows required GLR vs actual GLR.

As shown in figure 3. actual GLR are lower than required GLR. This means, foam are not in stable condition and has actual foam quality less than 0.65. Unstable foam quality will result in improper hole cleaning. One of the reason of foam drilling is to ensure hole cleaning in underbraced condition. The liquid phase of foam in well C-1 is water. Without proper additives, water does not perform good quality hole cleaning.

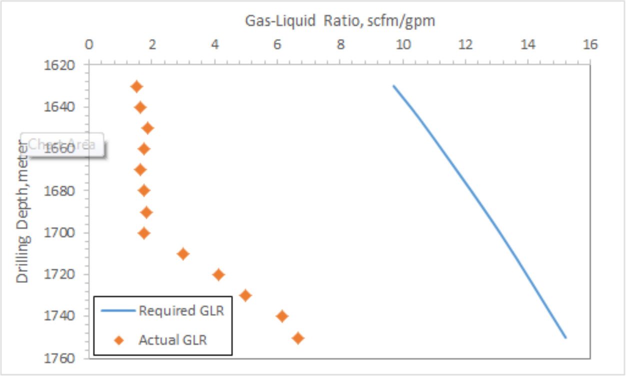

Figure 3. Required gas-liquid ratio vs actual gas-liquid ratio

Guo et al, 2002 describe that under surface conditions GLR should be maintain below 4.32 scfm/gpm. When required GLR for bottomhole condition is higher than 4.32 scfm/gpm, surface backpressure should be applied to the choke. Figure 4 shows required surface back pressure to maintain surface foam quality index above 0.97

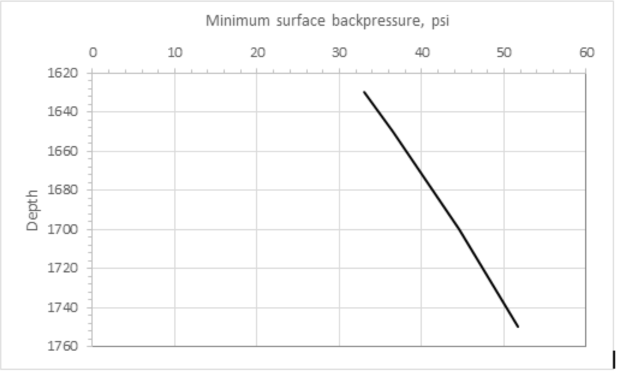

Figure 4. Minimum surface back pressure

The gas final result of gas-liquid volume requirements for well C-1 at depth of 1750 mMD, with several assumptions:

Γs : 0.97

Γbh : 0.65

v_f : 2.2 fps

Simulation results:

Q_{go} : 2567 scfm

Q_l : 161 gpm

GLR : 16 scfm/gpm

P_{bh} : 1223 psi

Based on simulations, actual gas and liquid injection rate in well C-1 is not adequate to form stable foam. This simulation is based on Guo's model for foam drilling

Aerated Drilling

Figure 5 shows combination of air injection and mud rate that balance formation pressure (dashed line). Above the red line, bottomhole pressure will exceed formation pressure. Below the red line, bottomhole pressure will less than formation pressure. The latter is required condition in underbalanced drilling. The combinations then plotted in LGWR chart as left boundary.

Figure 6 shows combination of air injection and mud rate that balance formation collapse pressure at point below casing shoe. Above the red line, pressure at casing shoe will exceed required formation breakout pressure. Below the red line, borehole pressures at casing shoe will less than required formation collapse pressure. Pressure at casing shoe should be maintain above formation collapse pressure. The combinations then plotted in LGWR chart as right boundary.

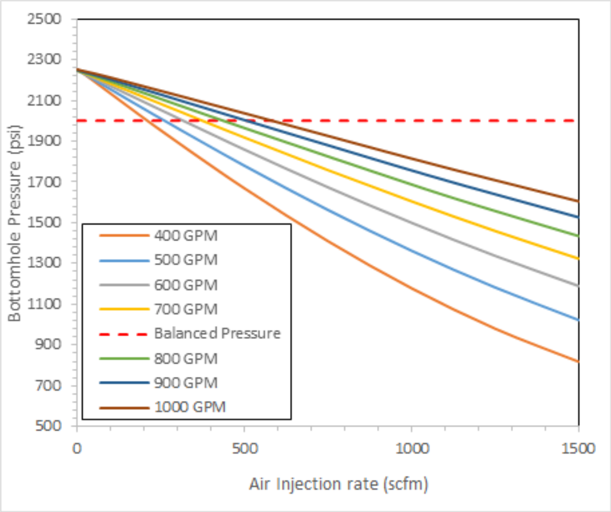

Figure 5. Flow rate combination that will yield balanced bottom hole pressure.

Figure 7 shows maximum cutting diameter for different combinations of air rate and mud flow rate. The red dashed line is desired maximum cutting diameter (Dc: 1 inch). That value achieved at mud flow rate equals to 600 GPM. This mud flow rate is the bottom limit of LGRW.

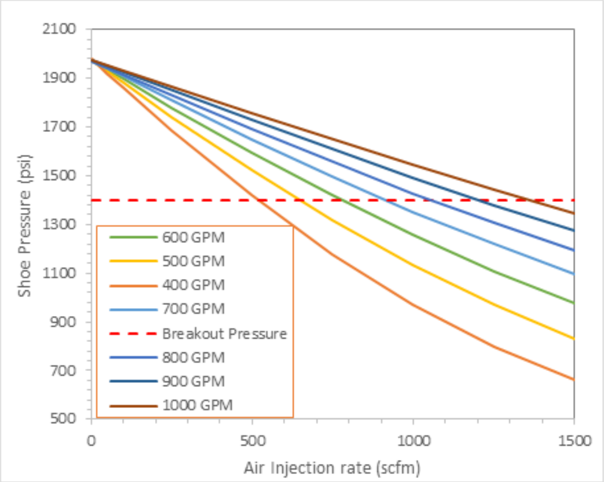

Figure 6. Flow rate combination that will yield to collapse pressure at casing shoe.

Guo et al,2002 described the upper limit of LGRW as wash out pressure. Since wash out pressure is not determined, this upper limit is determined by the maximum flow rate delivered by mud pump. This limit is equal to mechanical limit of mud pump. There are two National 9P-100 with maximum combined flow rate 1000 gpm.

Figure 8 shows final result of LGRW of Well X. This chart based on previous calculation and determination based on Guo's technique. This LGWR is based on assumption of formation pressure equals 2000 psi, formation collapse pressure 1400 psi and desired cutting diameter 1 inch. Actual combination of air and mud flow rate is inside the window. This means actual flow rate is adequate to overcome formation collapse pressure, to achieve underbalance conditions, adequate to lift 1 inch cuttings, and below maximum capacity of mud pump.

CONCLUSION

Combination of mud and air flow rate is an important parameter for aerated drilling. Operating envelopes needs to be designed prior to operation. In the case shown above, air and liquid flow rate combination in Well X is located inside the LGRW. Thus it is adequate based on Guo's criteria.

For foam drilling, GLR and surface back pressure are important parameters in operation. In the case shown above, GLR in well C-1 is below minimum requirements to form stable foam under bottom hole condition. Surface backpressures are needed to form stable foam in the surface condition.

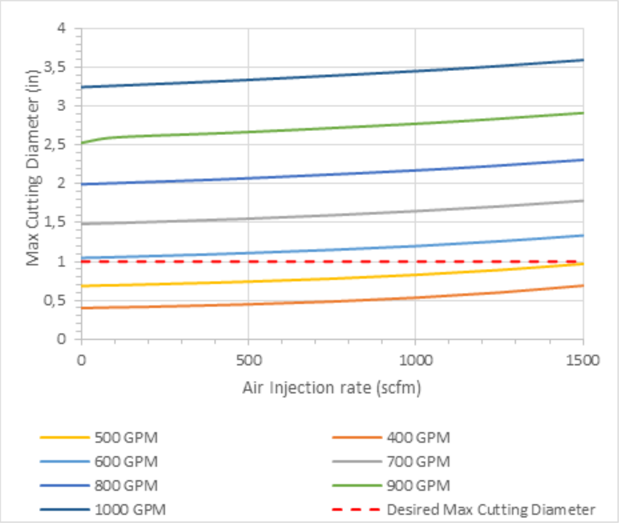

Figure 7. Maximum cutting diameter for combinations of air rate and mudflow

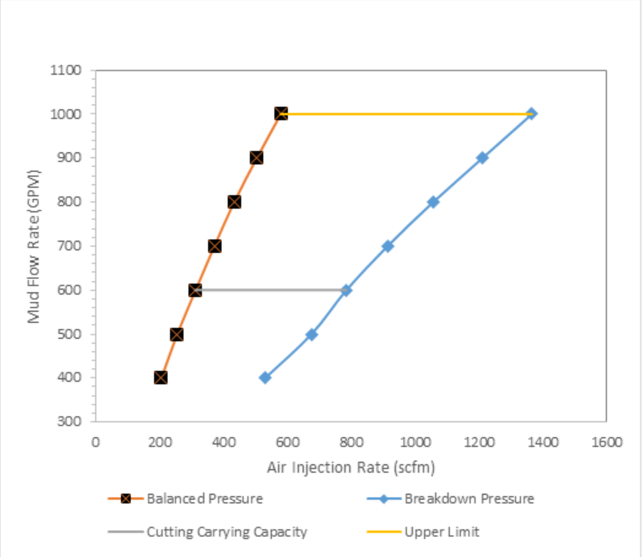

Figure 8. Final result of Liquid – Gas Rate Window

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NOMENCLATURE

g	Gravitational Acceleration (32,17 ft/sec^2)
d_c	Particle diameter, ft
C_d	Drag coeficient

ρ_c	Density of cutting, lbm/ft^3
ρ_f	Density of fluid, lbm/ft^3
P_s	Surface air pressure, psia
T_s	Surface Temperature, °F
G	Annular Temperature Gradient,°F/100 ft
T	Downhole temperature, °F
h	Hole depth,ft
S	Gas Specific Gravity
Q	Gas flow rate, scf/m
ROP	Penetration rate, ft/m
D_h	Hole diameter, ft
D_p	Drill pipe diameter, ft
V_{si}	Slip velocity, ft/s
D_s	Cutting equivalent diameter, ft
ρ_s	Solid density, lb/ft^3
ρ_s	foam density,lb/ft^3
μ_e	effective velocity, lb/ ft s
V_g	gas volume, ft^3
V_l	liquid volume, ft^3
v_{sl}	slip velocity, ft/s (double, previously V_{si})
v_m	mixture velocity, ft/s
v_f	foam velocity, ft/s
v_{tr}	transport velocity, ft/s
d_b	bit diameter, ft
C_p	particle concentration, %
dP	borehole pressure, psi
γm	specific weight of mixture, lb/ft3
f	Moody's friction factor, dimensionless
v	fluid velocity, fps
dh	depth incremental, ft
g	gravity constant, 32.2
d_H	hydraulic diameter, in
db	bit diameter, in
Ss	specific gravity of cuttings relative to water
Wm	mud weight, ppg

Q_m	mud flow, gpm
Sl	specific gravity of mud relative to water
Qf	formation fluid influx rate, bbl/hr
Sg	specific gravity of gas relative to air
Q_g	gas flow rate, sfcm
Ql	liquid/water flow rate
T	average temperature, R
e	material roughness, in
P_{bh}	Bottomhole pressure, psi
P_s	Surface back pressure,psi
T_{bh}	Bottomhole temperature, °F
T_s	Surface temperature, °F
Γbh	Bottomhole foam quality
Γs	Surface foam quality
V_s	Mixture Velocity at surface, ft/s
V_{min}	Minimum Velocity to achieve Min KE, ft/s
V_{eq}	Equivalent Flow Rate, gpm
GLR	Gas Liquid Ratio
LGRW	Liquid Gas Rate Window