Designing Liquid - Gas Rate Window For Aerated Drillingusing Guo Ghalambor Method

Fauzia Fadhila Anwar [1, a] dan Raka Sudira Wardana [1]

[1] *Bachelor Program of Petroleum Engineering, Pertamina University, Jakarta, Indonesia, 12220*
Email : [a] fauziafdhl@gmail.com,

Diterima (25 September 2020), Direvisi (30 Desember 2020)

Abstract. Loss circulation is a common problem in geothermal drilling due to naturally fractured formation and depleted reservoir pressure. This problem might lead to another problem such as a stuck pipe. In some cases, LCM is not effective in curing loss in a naturally fractured formation and cannot be used to cure loss circulation in the production zone. One of the methods that can be used to prevent loss circulation and also preventing reservoir damage in geothermal drilling is underbalanced drilling or aerated drilling. In an underbalanced or aerated drilling operation, the ratio of air injection rate ad liquid rate is critical to ensure the cutting carrying capacity while preventing hole problems. Usually, computer simulations are used to determine the safe gas-liquid rate limit due to the complexity of the multiphase flow in an underbalanced drilling system. Since the simulation software is not always available, a simpler and reliable method is needed to determine the gas-liquid rate limit in aerated drilling. The purpose of this paper is to design the operating window of gas-liquid rate ratio in aerated drilling using a simple yet reliable method such as the Guo-Ghalambor Liquid-Gas Rate Window method. The result of this research is a gas-liquid rate envelope that can be used to promote good cutting transport, preventing formation and borehole damaged while preventing loss circulation in geothermal well.

Keywords: *Aerated drilling, hole cleaning, loss circulation, drilling problems, drilling window*

INTRODUCTION

UP-1 Well is one of the geothermal well in Central Java Indonesia. In a geothermal drilling, common drilling problem that must be faced and anticipated is loss circulation. Lost circulation often occurs in geothermal drilling because geothermal reservoirs are often under pressured reservoir and typically have natural fractures [1]. If this problem is not anticipated, it will cause inadequate cutting transport and the chances of another hole problem such as stuck pipe can increase. Because stuck pipe can be caused by inadequate cutting transport [2].

Using Loss Circulation Material (LCM) is not effective in curing loss in natural fracture formation and not recommended to be used in production zone. Path of production fluid to flow could be blocked and causing formation damage [1]. Therefore, another method is needed to be the solution for loss circulation in production zone.

One of the methods that can be used to prevent loss circulation and also preventing reservoir damage in geothermal drilling is underbalanced drilling. Underbalanced drilling operations can prevent formation damage so the reservoir can be produced effectively [3]. Underbalanced drilling is drilling operation where the fluid column is kept below the formation pressure using air or gas, a light single-phase fluid column, or two-phase fluid column [4]. Aerated liquids or foam drilling is the most common underbalanced drilling [5]. Mixing between liquid phase (mud) and gas phase (air or nitrogen) is the idea of aerated drilling to lower down the mud density [6].

Combination between gas and liquid injection rate is crucial factor because the injection rates determine the wellbore pressure that can cause formation damage and borehole damage [5]. Furthermore, the unfavorable combination between gas and mud flow rate can also cause poor carrying capacity hence maximum penetration rate cannot be achieved [7]. Usually computer simulators for aerated drilling were used to determine the safe gas liquid rate limit due to the complexity of multiphase flow in Underbalanced Drilling system [8]. Since the simulation software is not always available, simpler and reliable method is needed to determine gas-liquid rate limit in aerated drilling. Buyon Guo and Ali Ghalambor develop innovative method in designing gas liquid rate limit [8].

The purpose of this research is to design gas – liquid rate limit for geothermal well in Indonesia using Liquid - Gas Rate Window by Guo-Ghalambor.

Liquid-Gas Rate Window

Liquid – Gas Rate Window [LGRW] is gas-liquid rate combination envelope that will prevent formation damage, borhole damage, cutting transport problem while maintaining underbalanced condition. Liquid – Gas Rate Window [LGRW] will be constructed by four boundaries.

Boyun Guo and Ali Ghalambor developed Liquid – Gas Rate Window [LGRW] from multiphase flow equation that derived from the first law of thermodynamics to predict bottom hole pressure. Several assumptions that are used are bubbly flow exist in flow path of drilling fluid and there is no slipping effect between gas phase, liquid phase, and solid phase (cuttings) [9].

The success of aerated drilling will be affected by liquid injected flowrate and gas injected flowrate. Combination of those parameter creating a bottom-hole pressure. While bottom-hole pressure needs to be maintained to not provoke the other drilling problems. Those Liquid – Gas Rate Window [LGRW] are constructed based on collapse pressure limit, balance pressure limit, cutting carrying capacity limit and wellbore washout limit [10].

Collapse Pressure Limit

This limit will be stand as the right boundary of LGRW. Focus of this limit is to prevent wellbore from collapsing by maintaining the wellbore pressure bigger than collapse pressure. Equation 1 until 10 construct the right boundary of LGRW [5]. This condition is affected by circulation break bottom hole pressure (Phy). A condition where there is no circulation occur on the well (static condition).

$$A = \frac{\pi}{4}\left({d_o}^2 - {d_i}^2\right) \quad (1)$$

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

$$a" = \frac{9.45 \times 10^{-5} {d_b}^2 S_s R_P + 1.667 \times 10^{-2} W_m Q_m + \cdots}{6.7846 \times 10^{-2} T Q_{go}}$$

$$\frac{\ldots + 9.7327\times10^{-2} S_l Q_f + 1.275\times10^{-3} S_g Q_{go}}{6.7846\times10^{-2} T Q_{go}} \quad (3)$$

$$b" = \frac{2.2283\times10^{-3} Q_m + 1.5597\times10^{-3} Q_f}{6.7846\times10^{-2} T Q_{go}} \quad (4)$$

$$c" = \frac{9.77 T Q_{go}}{A} \quad (5)$$

$$d" = \frac{0.33 Q_m + 0.22 Q_f}{A} \quad (6)$$

$$e" = \frac{f}{2 g D_H} \quad (7)$$

Hydrostatic Pressure Vertical Section

$$b"\left(P_{hy} - P_s\right) + \ln\left(\frac{P_{hy}}{P_s}\right) = a"H \quad (8)$$

Hydrostatic Pressure Angle Build Up Section

$$b"\left(\mathrm{P_{hy}} - \mathrm{P_s}\right) + \ln\left(\frac{\mathrm{P_{hy}}}{\mathrm{P_s}}\right) = \mathrm{a"R}\sin(\mathrm{I_m}) \quad (9)$$

Hydrostatic Pressure Slant Section

$$b"\left(P_{hy} - P_s\right) + \ln\left(\frac{P_{hy}}{P_s}\right) = a"S\cos(I_m) \quad (10)$$

To create the boundary line, varieties of mud flowrate and gas flowrate should be used for calculation.

Balance Pressure Limit

Balance pressure limit will act as the left boundary. The bottom-hole pressure is maintained to become lower than the formation pressure so the underbalanced condition can be accomplished. If bottom-hole pressure is higher than the formation pressure, the bottom hole condition will become overbalanced, therefore It can provoke loss circulation. Focus of this boundary is when there is circulation in the wellbore. So frictional pressure will affect this boundary. This boundary is a sum up between hydrostatic pressure (Phy) and frictional pressure due to friction (Pfr). To calculate the frictional pressure, equation 11 until 20 is used [5].

$$P_{fr} = P_{fr1} + P_{fr2} + P_{fr3} \quad (11)$$

Frictional Pressure Vertical Section

$$b''(P_{fr1} - P_s) + \ln\left(\frac{P_{fr1}}{P_s}\right) = a''d''^2e''H \quad (12)$$

$$\frac{b''}{2}\left(P_{fr2}^2 - P_s^2\right) + (P_{fr2} - P_s) = 2a''c''d''e''H \quad (13)$$

$$\frac{b''}{3}\left(P_{fr3}^3 - P_s^3\right) + \frac{1}{2}\left(P_{fr2}^2 - P_s^2\right) = a''c''^2e''H \quad (14)$$

Frictional Pressure Angle Build Up Section

$$b''(P_{fr1} - P_s) + \ln\left(\frac{P_{fr1}}{P_s}\right) = a''d''^2e''RI_m \quad (15)$$

$$\frac{b''}{2}\left(P_{fr2}^2 - P_s^2\right) + (P_{fr2} - P_s) = 2a''c''d''e''\ RI_m \quad (16)$$

$$\frac{b''}{3}\left(P_{fr3}^3 - P_s^3\right) + \frac{1}{2}\left(P_{fr2}^2 - P_s^2\right) = a''c''^2e''\ RI_m \quad (17)$$

Frictional Pressure Slant Section

$$b''(P_{fr1} - P_s) + \ln\left(\frac{P_{fr1}}{P_s}\right) = a''d''^2e''S \quad (18)$$

$$\frac{b''}{2}\left(P_{fr2}^2 - P_s^2\right) + (P_{fr2} - P_s) = 2a''c''d''e''\ S \quad (19)$$

$$\frac{b''}{3}\left(P_{fr3}^3 - P_s^3\right) + \frac{1}{2}\left(P_{fr2}^2 - P_s^2\right) = a''c''^2e''\ S \quad (20)$$

Varieties of mud and gas flowrate should be also used to create the boundary line.

Cutting Carrying Capacity Limit

One the challenges in every drilling operation is to transport cutting properly and prevent cutting from settling around the drilling equipment. Cutting carrying capacity limit will take place as the lower boundary in LGRW. Guo-Ghalambor uses kinetic energy as the parameter for cutting carrying capacity. Minimum kinetic energy of fluid that can carry cutting is equal to 3 ft-lb/ft^3 [5]. Minimum kinetic energy can be calculated using equation (21) until equation (31) [5].

$$Q_l = \frac{0.1337Q_m}{60} + \frac{5.615Q_f}{3600} \quad (21)$$

$$Q_g = \frac{6.7846 \times 10^{-2}\ TQ_{go}}{Phy} \quad (22)$$

$$f_l = \frac{Q_l}{Q_l + Q_g} \quad (23)$$

$$\rho_g = \frac{S_g\ Phy}{53.3\ T} \quad (24)$$

$$\rho_f = f_l\rho_l + (1 - f_l)\rho_g \quad (25)$$

$$v_m = v_{sl} + v_{tr} \quad (26)$$

$$v_m = \frac{c''}{Phy} + d'' \quad (27)$$

$$v_{tr} = \frac{\pi d_b^2}{4C_pA}\left(\frac{R_p}{3600}\right) \quad (28)$$

$$v_{sl} = 5.35\sqrt{\frac{D_s\,(\rho_s - \rho_f)}{\rho_f}} \quad (29)$$

$$\gamma_m = \frac{a''\ Phy}{b''\ Phy + 1} \quad (30)$$

$$E_m = \frac{1}{2}\frac{\gamma_m}{g}v_m^2 \quad (31)$$

Wellbore Washout Limit

Guo-Ghalambor uses wellbore wash out limit as the upper limit of LGRW. Washout is a condition where wellbore become larger than the bit diameter. Washout is usually caused by high flowrate in unconsolidated formation. But in geothermal formation, this condition is not commonly found. So, the equipment limit is such as the maximum flowrate for mud motor can be used as the upper limit [11].

METHODOLOGY

The well data in this research were collected from Well UP-01. Well UP-01 is geothermal drilling well that will be drilled using aerated drilling to prevent loss circulation. The maximum inclination of this well is 30 degree. All data that were used for calculation is shown in Table 1.

The steps in designing LGRW for this research can be seen in figure 1. Well design, formation characteristic, and drilling parameter wre collected to become the input parameter.

After the data is gathered, the collapse pressure limit can be established using equation (1) to equation (7). Those parameters will be used to calculate Phy. The well trajectory will affect the Phy equation. Phy calculation on curved hole trajectory is divided based on its section, whether its vertical section, angle build up section and slant section. For vertical section of the well, equation (8) will be used. For the build up section equation (9) will be used and for the slant section equation (10) will be used. This calculation is executed using several mud flow rate and several gas flowrate to create curve line. Several combinations of gas – liquid rate that intersect with the wellbore stability pressure is taken to construct the collapse pressure limit.

The next step after calculating Phy for collapse pressure limit, is calculating Pfr for balance pressure limit. It is similar to Phy procedure calculation. The well trajectory will also affect the use of equation for calculation Pfr. For vertical section, Pfr calculation will use equation (12) until equation (14). While for build up section, it will use equation (15) until equation (17) and slant section will use equation (18) until equation (20). Several combinations of gas – liquid rate that intersect with the reservoir pressure is taken to construct the balance pressure limit. To define cutting carrying capacity limit, equation (21) until equation (31) will be used. Calculation will be done using various injection rate.

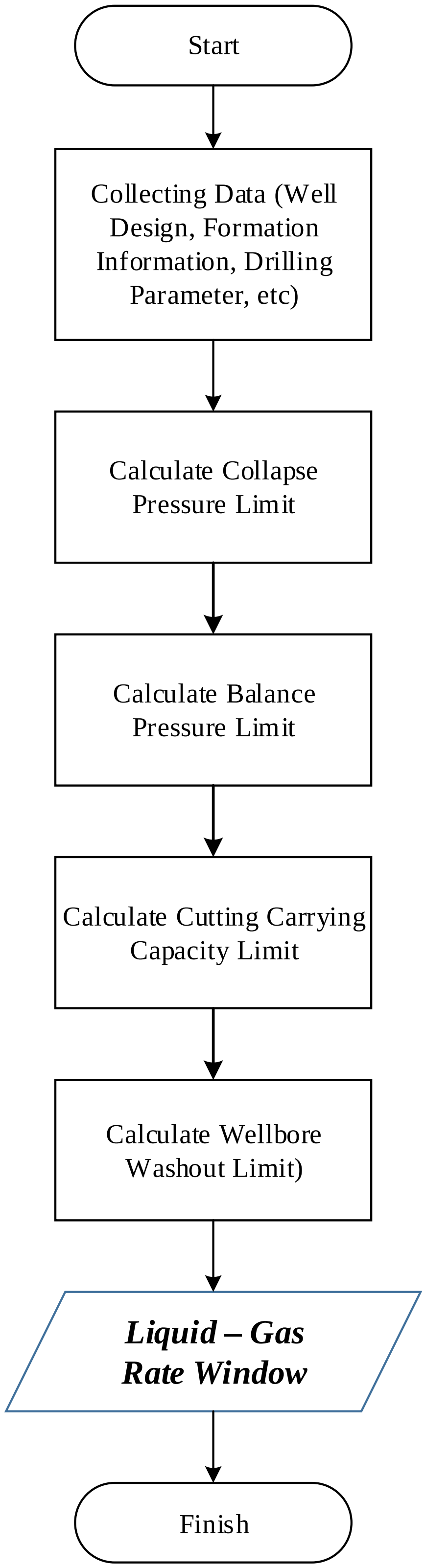

Figure 1: Flowchart for LGRW Design using Guo-Ghalambor Method

Table 1. Data used for Calculation

Design Basis:		
Reservoir Pressure:	4067	psia
Desired Pressure Differential:	700	psi
Collapse Pressure:	3305	psia
Wellbore Geometry:		
Total Measured Depth	10545	ft
Kick Off Point	600	ft
Max. Inclination	30	^{o}
Casing ID:	13-3/8	in
Open Hole Diameter:	12-1/4	in
Vertical Depth:	1968.5	ft
Measured Depth:	10545	ft
Drill Pipe OD	5	in
Material Properties:		
Solid Specific Gravity:	2.55	water = 1
Mud Weight:	8.4	ppg
Formation Fluid Specific Gravity:	1	water = 1
Gas Specific Gravity:	1	air = 1
Pipe Roughness:	0.0018	in
Influx Rate	24	bbl/hr
Environment:		
Ambient Pressure:	14.7	psia
Ambient Temperature:	64	^{o}F
Drilling Parameter:		
Bit Diameter:	12-1/4	in
Penetration Rate:	15	ft/hr
Choke Pressure:	30	psia

RESULT AND DISCUSSION

Circulation Break Bottom hole pressure graphs were established at various mud flow rate and gas injection flow rate (as can be seen in Figure 2). The collapse pressure line was drawn at 3,305 psi and becoming the limitation. If the bottom hole pressure is lower than collapse pressure, then the wellbore will be collapsed. The higher the gas rate used in a constant mud flow rate, the lower the bottom hole pressure. So, it will be safe to use the gas – liquid rate combination that produces bottom hole pressure above the collapse pressure line (orange area on figure 2). This collapse pressure line intersects the circulation break Bottom hole pressure at several points that can be seen in Table 2. Then the intersection point were plotted in a different graph (LGRW graph) and became right boundary.

Flowing bottom hole pressure graphs were established at various mud flow rate and gas injection flow rate (as can be seen in Figure 3). The reservoir pressure line was drawn at 4,067 psi and becoming the limitation. If the bottom hole pressure is higher than reservoir pressure, then loss circulation could be occurred. The higher the liquid rate used in a constant mud flow rate, the higher the bottom hole pressure.

So, it will be safe to use the gas – liquid rate combination that produces bottom hole pressure lower than the reservoir pressure line (blue area on figure 3). This reservoir pressure line intersects the flowing bottom hole pressure at several points that can be seen in Table 3. Then the intersection point were plotted in a different graph (LGRW graph) and became the left boundary.

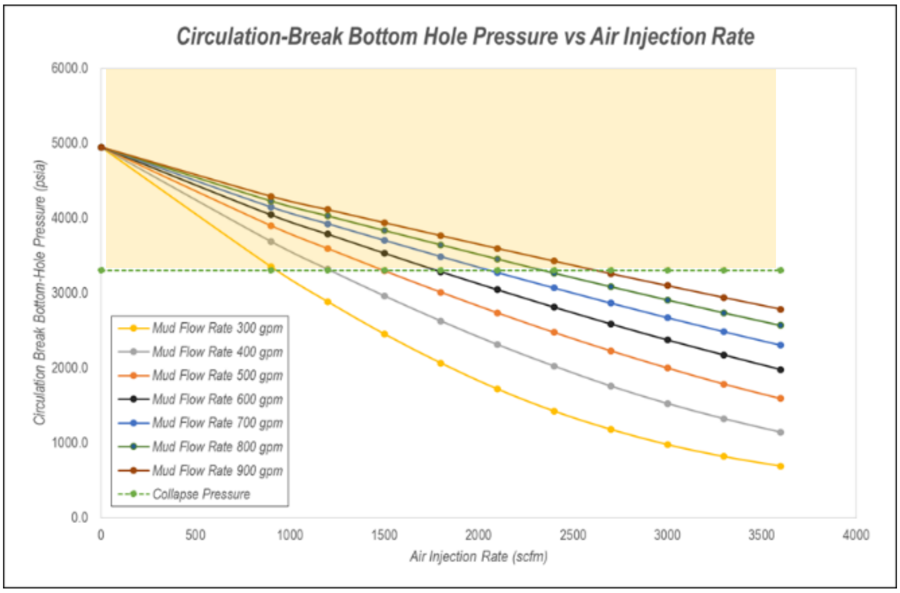

Figure 2: Circulation-break bottom hole pressure (hydrostatic pressure) with various mud flow rate and gas flow rate which intersect collapse pressure.

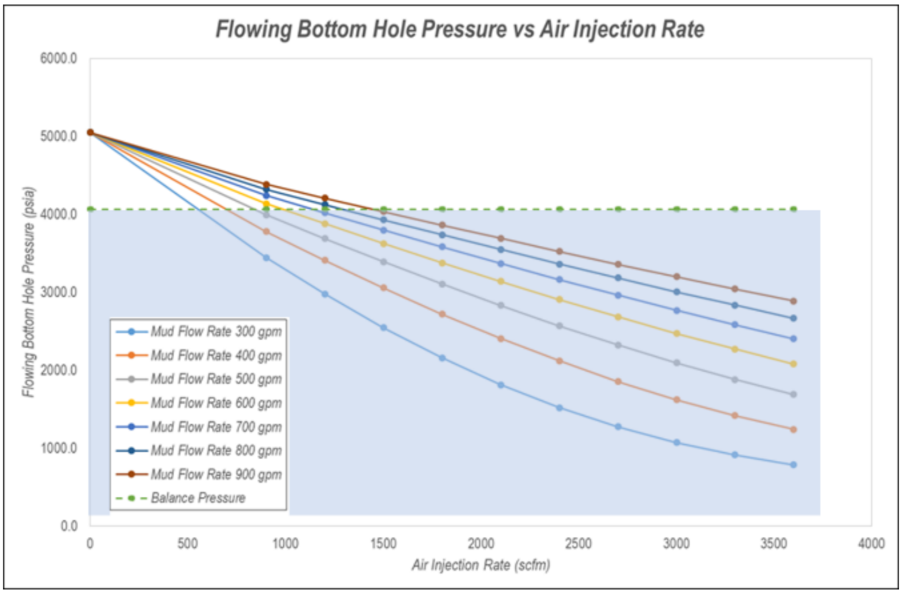

Figure 3: Flowing bottom hole pressure (hydrostatic pressure plus frictional pressure) with various mud flow rate and gas flow rate which intersect formation pressure

Table 2. Combination of Qgo and Qm on intersect points on Figure 2

Qgo (scfm)	Qm (scfm)
920	300
1200	400
1500	500
1800	600
2060	700
2360	800
2610	900

Table 3. Combination of Qgo and Qm on intersect points on Figure 3

Qgo (scfm)	Qm (scfm)
550	300
695	400
820	500
990	600
1140	700
1300	800
1450	900

Table 4. Kinetic energy calculation result of several gas injection rate and liquid injection rate

Qgo (scfm)	Qm (scfm)	Kinetic Energy (ft-lb/ft3)
720	300	2.6
950	400	4.5
1100	500	6.9
1400	600	9.9
1600	700	13.3
1750	800	17.2
2050	900	21.8

For lower boundary, the combination between mud flowrate and gas flowrate that resulting kinetic energy 3 ft-lb/ft^3 plotted in LGRW graph. When the operating flowrate has kinetic energy below 3 ft-lb/ft^3 then the hole cleaning is not sufficient. This can lead into stuck pipe due to cutting settling. Table 4 shows that the minimum kinetic energy is not achieved when the liquid flow rate is 300 gpm.

The upper boundary or the equipment limit indicates the maximum flowrate that can be used for the operations. On this research, 8" mud motor were used. The maximum operation flow rate for the mud motor is 900 gpm. If the flowrate exceeds the maximum limit, then the drilling equipment (mud motor) could run into problem.

Liquid – Gas Rate Window

After constructing the right, left, upper and lower boundaries, then all the boundaries were combined to create Liquid – Gas Rate Window [LGRW] (figure 4). If the combination of gas-liquid rate is outside the LGRW, then several drilling problems could occur. If the combination of gas - liquid rate is on the left side of the balance pressure limit (blue line on the figure 4) then the BHP will bigger than reservoir pressure.

When the combination of gas- liquid rate is on the right side of the collapse pressure limit (red line on the figure 4) then the wellbore will collapse. If the combination of gas - liquid rate is under the lower boundary (green line on figure 4), poor cutting transport could occurred. As can be seen in figure 4 the minimum liquid flow rate is 325 and the maximum liquid flow rate is 900 with the combination of minimum gas flow rate is 580 and the maximum gas flow rate is 2610.

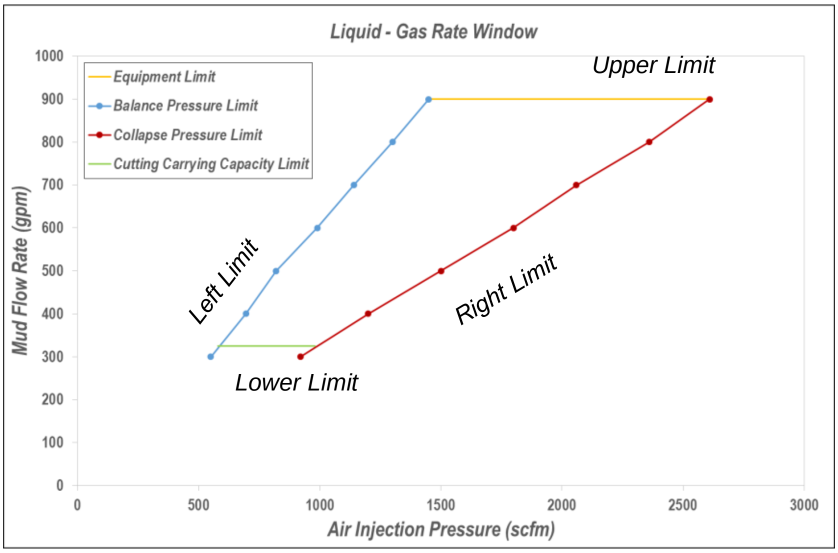

Figure 4: Liquid – Gas Rate Windowfor UP-1 Well

CONCLUSION

Liquid – Gas Rate Window [LGRW] for aerated drilling in UP-1 Well has been established using Guo-Ghalambor Liquid-Gas Rate Window method. This LGRW will be used as the guidelines for the gas-liquid flow rate combination for the aerated drilling parameter.

Based on the LGRW the minimum liquid flow rate (lower limit) is 325 gpm. This limit will ensure adequate flow for cutting transport. The maximum liquid flow rate (upper limit) is 900 gpm. This limit will ensure the mud motor works properly. To ensure the hole condition is underbalance, the combination rate of liquid-gas rate should be on the right side of balance pressure limit (left limit). And to prevent the borehole from collapsing, the combination rate of liquid-gas rate should be on the left side of collapse pressure limit (right limit).

By following this LGRW as the guidelines for aerated drilling operation in UP-1 Well, the underbalanced condition can be maintained to prevent loss circulation while preventing formation damage, wellbore collapse and cutting transport problem.

REFERENCES

[1] A. Lavrov, Lost Circulation Mechanisms and Solutions, Oxford: Elsevier, 2016.

[2] S. Nas and J. S. S. Toralde, "Geothermal Aerated Fluids Drilling Operation in Asia Pacific," in *World Geothermal Congress 2010*, Bali, 2010.

[3] W. C. Lyons, B. Guo, R. L. Graham and G. D. Hawley, Air and Gas Drilling Manual Third Edition, New York, etc: Gulf Professional Publishing, 2009.

[4] B. Rehm, A. Haghshenas, A. Paknejad, A. Al-Yami, J. Hughes and J. Schubert, Underbalanced Drilling: Limits and Extremes, Houston, TX: Gulf Publishing Company, 2012.

[5] B. Guo and G. Liu, Applied Drilling Circulation Systems : Hydraulics, Calculations, and Models, New York, etc: Gulf Professional Publishing, 2011.

[6] E. Kuadjovi, M. Djuidje, I. Kongawa, J. Timana and V. Mitoukou, "Aerated Drilling Fluids Used for Geothermal Wells," in *Proceedings of the International Field Exploration and Development Conference 2018*, Springer, 2018, pp. 1920-1933.

[7] B. Guo, G. Hareland and J. Rajtar, "Computer Simulation Predicts Unfavorable Mud Rate and Optimum Air Injection Rate for Aerated Mud Drilling," in *SPE Eastern Regional Conference & Exhibition*, Pittsburgh, 1996.

[8] B. Guo and G. Ghalambor, "An Innovation in Designing Underbalanced Drilling Flow Rates: A Gas-Liquid Rate Window (GLRW) Approach," in *IADC/SPE Asia Pacific Drilling Technology*, Jakarta, 2002.

[9] B. Guo, K. Sun, A. Ghalambor and C. Xiu, "A Closed-Form Hydraulics Equation for Aerated-Mud Drilling in Inclined Wells," in *SPE Latin American and Caribbean Petroleum Engineer Conference*, Trinidad, 2004.

[10] B. Guo and A. Ghalambor, Gas Requirements for Underbalanced Drilling : Deviated Holes, Tulsa, Oklahoma: PennWell Corporation, 2002.

[11] W. Nugroho, M. Sumantri and D. Wibisono, "Design and Application of Aerated and Foam Drilling Fluid, Case Study in Drilling Operation in Indonesia," in *Society of Petroleum Engineer*, Jakarta, 2017.

NOMENCLATURE

A = Annulus area (in^2)
C_p = Cutting concentration in annulus (%)
D_H = Annulus diameter (ft)
D_s = Cuttings Diameter (ft)
d_b = Bit Diameter (in)
d_i = Annulus inner diameter (in)
d_o = Annulus outer diameter (in)
E_m = Kinetic Energy (lbf-ft/ft^3)
e_i = Roughness of inner annulus (in)
e_o = Roughness of outer annulus (in)
$\bar{e}$ = Average roughness (in)
f = Moody's friction factor
f_l = Liquid volume fraction
g = gravitational acceleration (32.2 ft/s^2)
H = Depth (ft)
I_m = Maximum inclination (radians)
P_{fr1} = Frictional pressure 1 (lb/ft^2)
P_{fr2} = Frictional pressure 2 (lb/ft^2)
P_{fr3} = Frictional pressure 3 (lb/ft^2)
P_{fr} = Pressure loss due to friction (lb/ft^2)
P_{hy} = Hydrostatic pressure (lb/ft^2)

P_s = Choke pressure (lb/ft^2)
Q_f = Volumetric Infux flowrate (bbl/hr)
Q_{go} = Volumetric gas flowrate [60 ˚F, 14.7 psia] (scfm)
Q_m = Volumetric mud flowrate (gpm)
R = Radius of Curvature (ft)
Rp = Rate of Penetration (ft/hr)
S = Length of slant section (ft)
S_g = Gas specific gravity (air = 1)
S_l = Influx specific gravity (water = 1)
S_s = Cuttings specific gravity (water = 1)
T = Temperature (Rankine)
v_m = fluid mixtute velocity (fps)
v_{tr} = transport velocity (fps)
v_{sl} = terminal settling velocity (fps)
W_m = Mud Weight (ppg)
ρ_s = Cuttings density (lbm/ft^3)
ρ_g = Gas density (lbm/ft^3)
ρ_f = Influx density (lbm/ft^3)
γ_m = Specific weight of fluid mixture (lbf/ft^3)