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Issues of Air-Lift Reverse Circulation Drilling Technologies for Geothermal Wells in China

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ABSTRACT

Geothermal energy is starting to boom in China. Hard formations and frequent drilling fluid loss are the most common challenges encountered in geothermal well drilling. While hard formations result in low rate of penetration, fluid loss increases consumption in loss control materials and drilling muds along with severe formation damage and subsequently diminished productivity. Low rate of penetration and poor productivity contribute to the rising drilling costs while depressing public confidence in this new type of renewable energy. Air-lift reverse circulation drilling is recognized by the geothermal industry and is expected to overcome the above-mentioned problems. There are many successes, however some problems still remain. This article analyzes the pressures and establishes the demanding depth of dual-wall drill pipes for different well depth under various conditions; furthermore, borehole stabilization is discussed by analyzing the pressure profiles and other hydraulic parameters in the borehole annulus. Appropriate properties of drilling fluid to be able to use air-lift reverse circulation are proposed for some not very consolidated formation.

1. INTRODUCTION

Since 1970 the reverse circulation air-lift technique has been used on many drilling projects throughout the world. In the beginning, most of these projects have been connected with foundation pile and pier holes (Allen, 1976) and have shown the following advantages:

- High drilling efficiency with strong ability to remove cuttings;
- Long bit life;
- Continuous sampling drilling, saving the auxiliary time and reducing labor intensity;
- Low pressure to avoid or reduce lost circulation;
- The low equivalent circulation density is helpful to mitigate formation damage or improve productivity. It has become one of the main technical methods of hydrogeological drilling and geothermal wells.

Since the 1990s, gas lift reverse circulation drilling technology has been introduced into geothermal deep well drilling in China, and some successes were reported. From 1993 to 1994, Beijing hydrogeology engineering geology group successfully completed the "Tangre-29" geothermal well with a depth of 1,117.79m (Zhang, 1996). In 2001, a geothermal deep well drilling was successfully completed in Fengtai of Beijing with a depth of 2,470.88m (Wang, et al., 2001). In 2007, Guizhou geological prospecting research institute completed the "ZK3" underground hot water well in Guiyang with the completion depth of 2191.23m (Chen, et al., 2009). In 2010, Fuzhou successfully completed the "XG12" geothermal well with a designed well depth of 1200m (Lin, 2010). In 2012, in Shunyi of Beijing the deepest well of 4,200m was completed with air-lift reverse circulation drilling (Yang, 2012). In 2016, the interval of 2,700m and 3,212m of a geothermal well in Xushui of Hebei province and a water well in Shandong were completed using this technique (Lv, et al., 2009 and Wang, 2016).

While most of these projects have been very successful, some minor problems and troubles have been experienced. The main problems have been inadequate drilling fluid circulation rates, dual-wall drill pipe leaking, air-water mixer and water way of bit blockage, Kelly bearing capacity insufficient, small ratio of tail pipe length and dual-wall drilling pipe, insufficient depth of dual-wall drill pipes, the selection of air compressor, etc. So before reverse circulation-air lift calculations can be made, certain criteria must be established such as proposed circulation rates, entrance and exit fluid velocities and minimum and optimum submergence to lift ratios (Zhang, 2014).

The purpose of the article is to analyze the pressure profiles of air-lift reverse drilling to guide selection of the air compressor, the dual-wall drill pipe, and the depth of the dual-wall pipes for different well depth; Furthermore, the article discusses the feasibility of this technique for some not very stable formation, such as unconsolidated sand formation.

2. THE DEMANDING DEPTH OF DUAL-WALL DRILL PIPES BELOW WELLHEAD

2.1 The Rationale of Air-lift Reverse Circulation

As shown in Figure 1, compressed air flows downwards along the annulus of dual-wall drill pipes and via the gas-liquid mixing chamber upwards with the mixer of drilling fluid and cuttings to the mud pit at the surface. The mud pit is conducted to the annulus of the drill pipes and borehole so that the drilling fluid flows downwards through the annulus to the well bottom and is lifted to pass the drill bit and flows back upwards in the center of the rear rod, bearing the cuttings by the pressure differential created by the lower air density. The depth of dual-wall drill pipe below wellhead is critical to realize the reverse circulation, and there are minimal and optimal values for different well depth, for which the analysis of the dynamic pressure of the fluids is required.

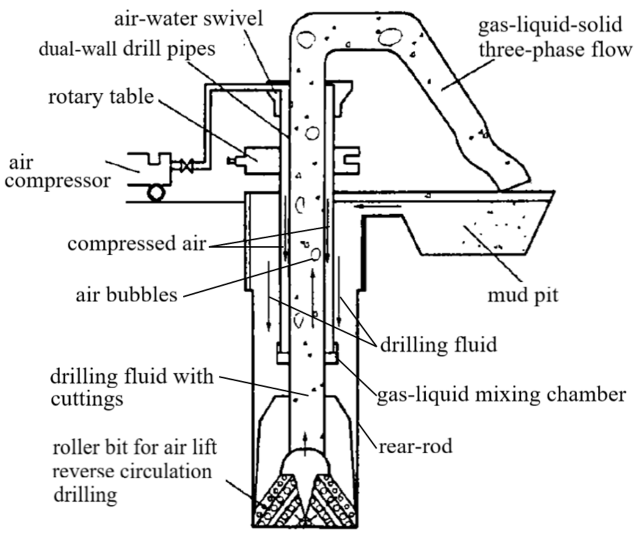

Figure 1: Schematic diagram of air-lift reverse circulation drilling

2.2 The Modeling and Analysis of the Pressure Profiles

Based on the characteristics of geothermal deep wells and air-lift reverse circulation drilling, the following basic assumptions are made:

- The drilling fluid used is incompressible and the density of the drilling fluid does not change with the change of temperature;
- In the gas-liquid-solid three-phase flow, the size and density of solid cuttings are equal; the compressed air is approximately an ideal gas, which conforms to the ideal gas equation; compressed air, drilling fluid and cuttings are uniformly mixed and flow at the same velocity following the basic laws of fluid mechanics;
- The atmospheric pressure and temperature at the surface are the same; the temperature of compressed air, drilling fluid and cuttings at the same depth in the geothermal deep well is the same as that in the well at the same depth;
- The flow resistance loss of compressed air in drilling fluid and the pressure and flow loss of compressed air when it passes through the gas-liquid mixer are not considered;
- The flow of drilling fluid in annular air center channel of dual-wall drill pipes is turbulent;
- The inner diameter of the dual-wall drill pipe and rear rod is the same and taken the value of the inside diameter of inner pipe of the dual-wall drill pipe.

The modeling parameters are shown in Figure 2.

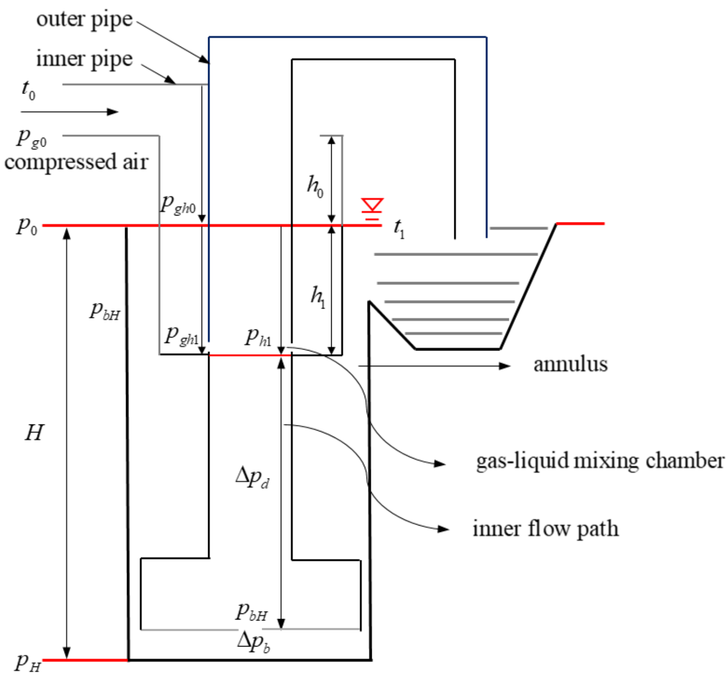

Figure 2: Schematic diagram of air-lift reverse circulation drilling and related physical quantities

2.2.1 The Pressures of Compressed Air Flowing Downwards in the Annulus of Dual-Wall Drill Pipes

The compressed air from compressor flows downwards through the annulus of dual-wall drill pipes. The differential pressure *dp* occurs over an incremental distance of *dh*. According to this differential pressure can be approximated as follows (Daugherty, et al., 1985, Lyons, 2009).

$$dp = \gamma_g \left[1 - \frac{f_g V_g^2}{2g\left(d_h - d_p\right)} \right] dh \tag{1}$$

where γ_g, f_g, V_g, g, d_h, d_p are specific weight of compressed air (N/m^3), Fanning friction coefficient (dimensionless), flow rate of compressed air (m/s), gravity acceleration (9.81m/s^2), inside diameter of outer dual-wall drill pipe (m), and outside diameter of inner dual-wall drill pipe (m), respectively.

f_g is determined by von Karman empirical correlation:

$$f_g = \left[2\lg\left(\frac{d_h - d_p}{e_p} \right) + 1.14 \right]^{-2} \tag{2}$$

where e_p is absolute roughness of the drill pipe (the absolute roughness of the surface of steel pipe), 0.0002m.

Then the compressed air pressures between the dual pipes at positions of ground surface (p_{gh0} , Pa) and the gas-liquid mixer (p_{gh1} , Pa) can be calculated using Equations (3) and (4).

$$p_{gh0} = \left[\left(p_{g0}^2 + b_a T_0^2 \right) e^{\frac{2a_a h_0}{T_0}} - b_a T_0^2 \right]^{0.5} \tag{3}$$

$$p_{gh1} = \left[\left(p_{gh0}^2 + b_a T_{av}^2 \right) e^{\frac{2a_a h_1}{T_{av}}} - b_a T_{av}^2 \right]^{0.5} \tag{4}$$

where,

$$a_a = \frac{S_g}{R_e}, b_a = -\frac{f_g}{2g\left(d_h - d_p\right)} \left(\frac{R_e}{S_g} \right)^2 \cdot \left[\frac{\dot{w}_{g0}}{\frac{\pi}{4}\left(d_h^2 - d_p^2\right)} \right]^2, \quad f_g = \left[2\lg\left(\frac{d_h - d_p}{e_p} \right) + 1.14 \right]^{-2},$$

$$\dot{w}_{g0} = \frac{p_{g0} S_g Q_{g0}}{R_e T_0}, T_{av} = \frac{T_1 + T_{h1}}{2}, T_{h1} = T_1 + \Delta t \cdot h_1$$

where p_{g0}, T_0, h_0, T_{av}, S_g, R_e, $\dot{w}_{g0}$, Q_{g0}, T_1, T_{h1}, Δt, h_1 are compressor output pressure (Pa), thermodynamic temperature at surface ground (K), lift height (m), average temperature between the wellhead and the gas-liquid mixer (K), relative density of air (1.0), engineering gas constant (29.31 N·m/(N·K)), weight flow rate of compressed air output by the air compressor (N/s), air supply volume of air compressor (m^3/s), thermodynamic temperature at wellhead (K), thermodynamic temperature at gas-liquid mixer (K), geothermal gradient (℃/m), depth of dual-wall drill pipes below the wellhead (m), respectively.

2.2.2 The Pressure of the Gas-Liquid-Solid in the Inner Tube of Dual-Wall Drill Pipes

The pressure of the gas-liquid-solid in the inner tube of dual-wall drill pipes is deduced as follows:

$$\int_{p_0}^{p_{h1}} \frac{dp}{\varphi_{h1}(p)} = \int_0^{h_1} dh \tag{5}$$

and, $$\varphi_{h1}(p) = \frac{\dot{w}_m}{\frac{p_{gh1} Q_{gh1}}{p} + Q_L} \cdot \left[1 + \frac{f_m}{2gd} \left(\frac{\frac{p_{gh1} Q_{gh1}}{p} + Q_L}{\frac{\pi}{4} d^2} \right)^2 \right], \quad Q_{gh1} = \frac{p_{g0} Q_{g0} T_{av}}{p_{gh1} T_1},$$

$$\dot{w}_m = \dot{w}_{g0} + \dot{w}_L + \frac{\pi}{4} D_b^2 \gamma_w \times 2.7 \times ROP,\quad \dot{w}_L = \gamma_L Q_L,\quad f_m = \left\{ -1.8\lg\left[\left(\frac{\left(\frac{e_p}{d}\right)}{3.7} \right)^{1.11} + \frac{6.9}{N_R^m} \right] \right\}^{-2},$$

$$N_R^m = \bar{V}_m d \cdot \frac{\dot{w}_{g0} + \dot{w}_L}{\dot{w}_{g0}\bar{v}_{mg} + \dot{w}_L \bar{v}_{mL}},\quad \bar{v}_{mg} = \frac{R_e T_{av} g\left(\mu_{mg0} + \mu_{mgh}\right)}{2pS_g},\quad \bar{v}_{mL} = \frac{\left(\mu_{mL0} + \mu_{mLh}\right) g}{2\gamma_L}$$

where p_{h1}, p_0, $\dot{w}_m$, Q_{gh1}, p, d, Q_L, $\dot{w}_L$, γ_L, D_b, γ_w, ROP, f_m, N_R^m, $\bar{V}_m$, $\bar{v}_{mg}$, $\bar{v}_{mL}$, μ_{mgh}, μ_{mg0}, μ_{mL0}, μ_{mLh} are bottom pressure of the gas-liquid-solid mixture (Pa), atmosphere pressure of wellhead (Pa), weight flow rate of the mixture (N/s), volume flow rate of compressed air at an air-liquid mixer (m^3/s), pressure of mixture in the inner tube (Pa), inside diameter of the inner tube (m), volume flow rate (m^3/s) and weight flow rate (N/s) and specific weight (N/m^3) of drilling fluid, drill bit diameter (m), water specific weight (9810 N/m^3), rate of penetration (m/s), Fanning frictional factor of mixture (dimensionless), Reynolds number (dimensionless), average velocity of mixture (m/s), average kinematic viscosity of air and drilling fluid in the inner tube (m^2/s), air dynamic viscosity at wellhead and at *h* depth (Pa·s) , drilling fluid dynamic viscosity at wellhead and at *h* depth (Pa·s).

2.2.3 The Bottomhole Pressure in the Annulus of Well Wall and the Outer Side of Drill Pipe

The drilling fluid flows downwards in the annulus of well wall and the outer side of drill pipe. The bottom pressure (p_H , Pa) is determined by the following equation:

$$p_H = \int_0^H \gamma_L \left\{ 1 - \frac{f_L}{2g\left(D_h - D_p\right)} \left[\frac{Q_L}{\frac{\pi}{4}\left(D_h^2 - D_p^2\right)} \right]^2 \right\} dh + p_0$$

$$f_L = \left\{ -1.8\lg\left[\left(\frac{\left(\frac{e_{av}}{D_h - D_p}\right)}{3.7} \right)^{1.11} + \frac{6.9}{N_R^L} \right] \right\}^{-2} \tag{6}$$

$$e_{av} = \frac{e_{oh} D_h^2 + e_p D_p^2}{D_h^2 + D_p^2},\quad N_R^L = \frac{2\gamma_L Q_L\left(D_h - D_p\right)}{\frac{\pi}{4}\left(D_h^2 - D_p^2\right)\left(\mu_L^0 + \mu_{LH}\right) g}$$

where H, f_L, D_h, D_p, Q_L, e_{av}, e_{oh}, N_R^L, μ_L^0, μ_{LH} are well depth (m), Fanning frictional factor of drilling fluid in annulus (dimensionless), well diameter (m), outer diameter of drill pipe (m), volume flow rate of drilling fluid (m^3/s), absolute roughness of drill pipe (0.003m) and well wall (0.0002m), Reynolds number (dimensionless) , dynamic viscosities of drilling fluid at the wellhead and bottom (Pa·s).

2.2.4 Pressure Loss through Drill Bit and the Pressure above Drill Bit

Pressure loss through drill bit (Δp_b , Pa) is calculated according to SY/T 5234-2004 and the pressure above drill bit (p_{bH} , Pa) is the difference between the bottom pressure in the annulus and drill bit pressure loss.

$$\Delta p_b = \frac{0.9\gamma_L Q_L^2}{g\left(\sum_{i=1}^{k} D_{ki}^2\right)^2} \tag{7}$$

$$p_{bH} = p_H - \Delta p_b \tag{8}$$

where k , D_{ki} are number of nozzles and the ith nozzle diameter(m), respectively.

2.2.5 Pressure in the Rear Rod

The fluids in the rear rod are a mixture of drilling fluid and cuttings, and the pressure equals the difference of the pressures above the drill bit and at the gas-liquid mixer.

$$p_{bH} - p_{h1} = \gamma_{Ls}\left(H - h_1\right) \tag{9}$$

where γ_{Ls} is the specific weight of the mixture of drilling fluid and cuttings, N/m^3.

2.2.6 The Depth of Dual-Wall Drill Pipe below the Ground Surface

The depth of dual-wall drill pipe below the ground surface can be obtained by substituting Equation (8) into Equation (9):

$$p_H - \Delta p_b - p_{h1} = \gamma_{Ls}\left(H - h_1\right) \quad (10)$$

2.3 The Demanding Depth of the Dual Wall Drill Pipe under Conditions for Different Well Depth

Using Φ127/76 dual-wall drill pipes and the parameters in Table 1, the required depth of the dual-wall drill pipes at various air compressor pressures for different drill depth is calculated and plotted in Figure 3. When using 4 MPa air compressor pressure, the required depth of the dual-wall drill pipes versus the well depth for Φ114/73 and Φ127/76 is charted in Figure 4.

Table 1: The values of the parameters for calculation and analysis

Flow rate of air, Q_{g0} (m^3/min)	3	Diameter of drill bit, D_b (mm)	311
Lift height, h_0 (m)	12.5	Rate of penetration, *ROP*(m/h)	2
Temperature at wellhead, t_1 (°C)	50	Atmosphere pressure at wellhead, p_0 (kPa)	101.3
Temperature gradient, Δt (°C/m)	0.03	Number of nozzles, k	1
Specific weight of drilling fluid, γ_L (N/m3)	9810	Nozzle diameter, D_{k1} (mm)	30
Volumetric flow rate of drilling fluid, Q_L (m^3/min)	0.6	Specific weight of drilling fluid/cuttings mixture, γ_{Ls} (N/m^3)	8970
Average velocity of gas-liquid-solid mixture flowing in the inner tube of dual wall drill pipes, $\overline{V_m}$ (m/s)	3	Temperature at surface ground, t_0 (°C)	25

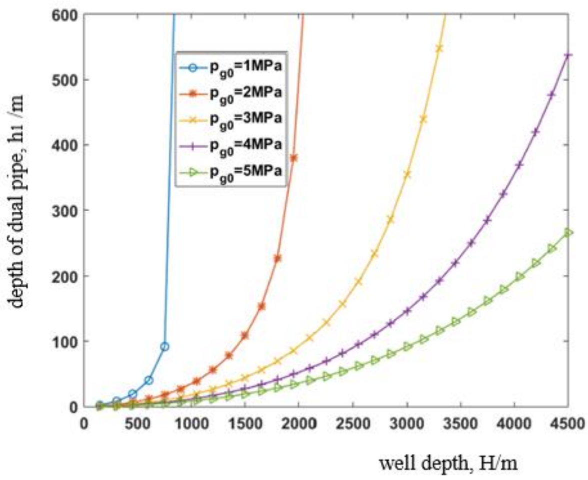

Figure 3: The needed depth of dual pipe for different well depth under various compressor pressures

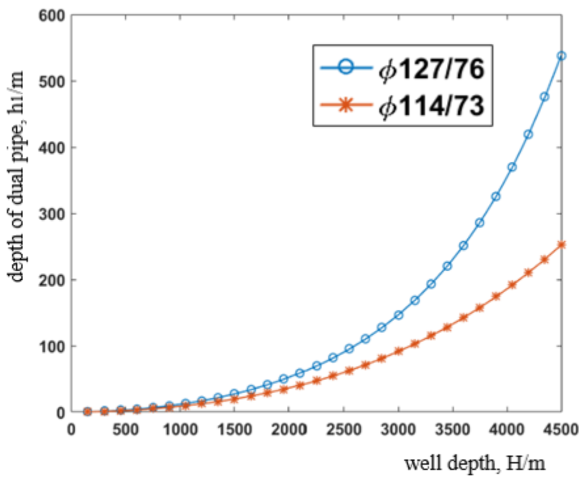

Figure 4: The needed depth of dual pipe for different well depth under various dual pipe sizes

Figure 3 shows that the required depth of the dual wall drill pipes can be decreased when the air compressor can provide higher pressure. When air compressor pressure is 1MPa or 2MPa, the maximum well depth may be less than 600m and 2000m respectively. The figure indicates that deeper depth of dual wall drill pipes is demanded for larger dual wall drill pipes.

3. BOREHOLE STABILIZATION OF DRILLING FLUID IN THE ANNULUS

The difference of drilling fluid of reverse and direct circulation in the annulus to stabilize borehole lies in the direction of frictional losses. The dynamic pressure in the borehole for direct circulation equals to the hydrostatic pressure adding frictional force, while the frictional force is reduced for reverse circulation. Therefore, the frictional loss is a critical factor, which is affected by the well/drill pipe geometry and drilling fluid properties. Referring to the Procedures for Gas Lift Reverse Circulation Drilling and Technical Regulations for Geothermal Drilling, the annulus pressures of different properties of drilling fluids for a 2000m well are calculated and discussed in the following sections.

3.1 The Frictional Loss Changes with Well Diameter, Size of Dual Wall Drill Pipe and the Velocity of Drilling Fluids in the Inner Pipe

It is known that water is often used as drilling fluid for air-lift reverse circulation drilling and 2-3m/s velocity of drilling fluid in the inner pipe is recommended. Based on water density and viscosity at 25℃ and the sizes of dual-wall drill pipes, the hydraulic parameters, such as velocity of drilling fluid, Reynolds number (*Re*), bottom pressure and frictional loss in annulus of borehole are calculated and tabulated in Table 2.

Table 2: The annulus pressure for reverse and direct circulation with water as drilling fluid (ρ=1.0g/cm³, μ=1.0mPa·s)

Well Diameter (m)	Velocity of drilling fluid in the inner tube (m/s)	Size of dual wall drill pipes	Velocity of drilling fluid in the annulus of borehole (m/s)	*Re* in the annulus of borehole	Bottom pressure (reverse circulation) (MPa)	Bottom pressure (direct circulation) (MPa)	Frictional loss (MPa)
0.152	2	*Φ89/59*	*0.46*	*28888*	*19.550*	*19.850*	*0.150*
		Φ114/73	1.05	40068	17.961	21.439	1.739
		Φ127/76	1.66	41405	11.479	27.921	8.221
	3	Φ89/59	0.69	43332	19.367	20.033	0.333
		Φ114/73	1.58	60102	15.804	23.597	3.897
		Φ127/76	2.48	62108	1.249	38.151	18.451
0.216	2	*Φ89/59*	*0.18*	*22826*	*19.692*	*19.708*	*0.008*
		Φ114/73	0.32	32297	19.664	19.737	0.036
		Φ127/76	0.38	33679	19.636	19.764	0.064
		Φ140/89	0.59	44500	19.505	19.895	0.195
		Φ168/108	1.27	60750	17.875	21.525	1.825
		Φ178/127	2.15	81873	12.182	27.212	7.515
	3	Φ89/59	0.27	34239	19.681	19.719	0.019
		Φ114/73	0.47	48445	19.619	19.781	0.081
		Φ127/76	0.57	50519	19.557	19.843	0.143
		Φ140/89	0.88	66750	19.265	20.135	0.435
		Φ168/108	1.90	91125	15.606	23.794	4.094
		Φ178/127	3.23	122810	2.817	36.583	16.883
0.311	2	*Φ89/59*	*0.08*	*17405*	*19.699*	*19.701*	*0.001*
		Φ114/73	0.13	25078	19.698	19.703	0.002
		Φ127/76	0.14	26255	19.697	19.704	0.004
		Φ140/89	0.21	35126	19.692	19.708	0.008
		Φ168/108	0.34	48701	19.673	19.727	0.027
		Φ178/127	0.50	65967	19.636	19.764	0.064
		Φ219/168	1.16	106506	19.100	20.300	0.600
	3	Φ89/59	0.12	26108	19.698	19.702	0.002
		Φ114/73	0.19	37616	19.695	19.705	0.005
		Φ127/76	0.22	39382	19.692	19.708	0.008
		Φ140/89	0.31	52690	19.683	19.717	0.017
		Φ168/108	0.51	73052	19.640	19.760	0.060
		Φ178/127	0.74	98951	19.558	19.842	0.142
		Φ219/168	1.74	159758	18.354	21.046	1.3456

Therefore, it can be seen that frictional loss increases with increasing velocity of drilling fluid and decreases with well diameter. For the same velocity, the frictional loss increases with the increases of the size of dual-wall drill pipes. The frictional loss can be very small when parameters are well matched, which means that the bottom pressure for reverse and direct circulation differs by not very much, e.g. the frictional losses can be only 0.150, 0.008 and 0.001MPa under some conditions indicated in italic in Table 2. Thus for some not very weak formation, the air-lift reverse circulation drilling can stabilize the borehole as long as the direct circulation drilling with water works well.

3.2 The Effects of the Density and the Viscosity of Drilling Fluids on the Bottom Pressure

For weak formation, both density and viscosity of drilling fluid should be increased to stabilize the borehole (Yan, 2012). The pressures are calculated for different density and viscosity under following parameters, i.e. 2,000m well depth, 0.152m well diameter, Φ89/59 dual wall drill pipes and 2m/s velocity in the inner tube and 0.46m/s velocity of drilling fluid in the borehole annulus. The results are shown in Table 3. The bottom pressure increases with drilling fluid density, and decreases with viscosity for reverse circulation. Besides, the fluid in the annulus is laminar, which helps to stabilize borehole.

Table 3: The effects of the density and the viscosity of drilling fluids on the frictional losses

Re in the annulus of borehole	Bottom pressure (reverse circulation) (MPa)	Frictional loss (MPa)	Density of drilling fluids (g/cm3)	Viscosity (mPa·s)
28888	19.550	0.146	1.00	1.00
2022	20.467	0.213		15.00
1517	20.451	0.229	1.05	20.00
1213	20.436	0.244		25.00
2118	21.440	0.220		15.00
1589	21.424	0.237	1.10	20.00
1271	21.408	0.252		25.00
2215	22.412	0.228		15.00
1661	22.396	0.244	1.15	20.00
1329	22.380	0.260		25.00

CONCLUSION

A: Air-lift reverse circulation drilling has many advantages for geothermal well drilling, not only with better drilling efficiency but also higher productivity.

B: It is very necessary to design proper parameters for better performance while selecting air compressor and dual-wall drill pipes.

C: Appropriate properties of drilling fluids may ensure that this technique can be used in some not very consolidated formation with some alterations, e.g. adjusting and managing the density, viscosity, YP/PV, filtration properties by which sufficient bottom pressure, on one hand, can be obtained. On the other hand, good rheology and filtration properties can improve the cuttings carrying and mitigation of erosion.

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