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A Comprehensive Model of Slimhole Geothermal Well Drilling Design

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ABSTRACT

The application of slimhole geothermal well, where its final diameter is less than 6”, is based on economic factor, especially when exploration activities and reservoir assessment are conducted. Design of slimhole drilling is less expensive because the tangible and the intangible costs are lower. However, the slimhole well design has more engineering challenges comparing to conventional well: the highest pressure loss in annulus, higher directional difficulty index (DDI), the wellbore instability, lower pipe clearance restricts, etc. This paper investigates all of the drilling aspects of slimhole well design using basic concept of drilling engineering.common calculations in the industry. A model of decision making of slimhole well design based on engineering and economic view will be built so that all significant factors that can limit the use of slimhole can be identified and optimized.

1. INTRODUCTION

Geothermal is thermal energy generated and stored in the earth. This thermal energy is contained in the fluid that stored in the reservoir. This thermal energy can be utilized by producing the fluid to the surface. Same as oil and gas production, it is needed a drilling process to produce the fluids. But it is not totally same as oil and gas sector since there is a different formation type to be drilled (Marbun et al. 2014). There are four geothermal systems which are:

(1) Geopressured-geothermal systems that containing water at a temperature above the temperature normal and hydrostatic pressure greater than the normal hydrostatic pressure,
(2) Hot dry rock geothermal system that is in the form of rock with low water content and low permeability but has high temperature between 200^{o}C - 350^{o}C,
(3) Hydrothermal systems that contain water in the pore and fracture inside the rock with large permeability that is enough to produced large volume of fluids, and
(4) Magmatic system that is a system with a temperature between 600^{o}C - 1400^{o}C.

Rocks that are often encountered in geothermal reservoir are granite, quartzite, basalt and volcanic tuff (Finger and Blankenship 2010). There are two classifications of rocks: brittle and ductile. Geothermal formation is a brittle type rock. The rock is called brittle when the rock is lost it strength without significant deformation due to stress acting on the wellbore as shown in figure 1 (a). Whereas, the rock is called ductile, when it subjected to stress, it can deform under significant stress until it reach yield stress point as shown in figure 1 (b). It means that once it reached its yield stress point it would deform permanently.

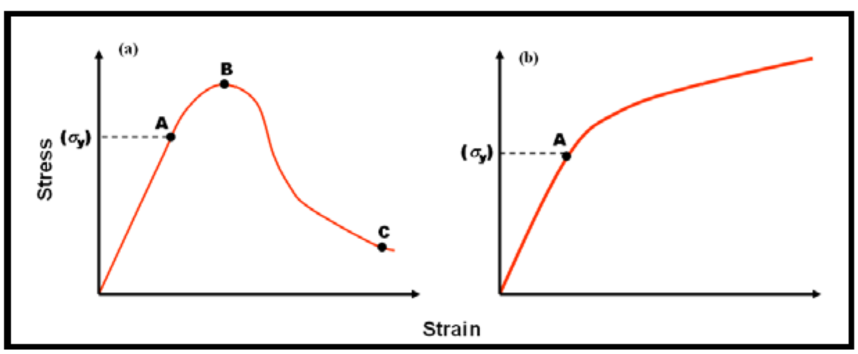

Figure 1 Rock Stress Strain Curve: (a) Brittle and (b) Ductile (Marbun Internal Report 2011)

Geothermal systems typically contain CO_2 and H_2S gas. Both these gases are corrosive gas that can cause problems in drilling operation in terms of technical, health, environment and safety. Problems are often experienced during geothermal drilling is:

1. Lost circulation. It usually occurs in the feed zone that is interval where formation pressure is under hydrostatic pressure and highly fractured.

2. Temperature Constrain. High Temperature in geothermal drilling environment can result to performance reduction of many parts of conventional drilling systems. For examples: logging tools, seals & lubricants, mud & other fluids, and downhole tools & bits.
3. Cement Displacement. By facing a high temperature environment, the tendency of a fluid to be degraded or gelling increases, it will increase the difficulty in the displacement process. As an impact on the uncemented casing parts, the possibility of experiencing casing failure due to the production cycle of the geothermal fluid increases.

Bit and tool performance can be measured from their life. Bit and tool life can be influenced by the drilling parameters and characteristics of the geothermal formation itself. As for geothermal environment, where harder rock is commonly encountered and additional of high temperature formation, proper bit selection becomes critical issue. Improper bit selection will cause many problems including slow rate of penetration (ROP) and bit damage. For more comprehensive analysis, rock strength and hardness level should be recorded with detailed scale while drilling in order to get objective comparison (Marbun et al. 2015).

2. SLIMHOLE WELL DESIGN

Well design is start from project development and data collection. From the data collected, pore pressure and fracture gradient can be predicted to create mud window. Mud window is useful to determine casing setting depth and size of the wellbore. It is followed by the completion planning, mud plan, cement plan, bit programs, casing design, tubing design, drillstring design, rig sizing, drill time projections and cost estimation. Size of the wellbore is an important aspect in designing slimhole well. It affects drilling cost savings in drilling operation.

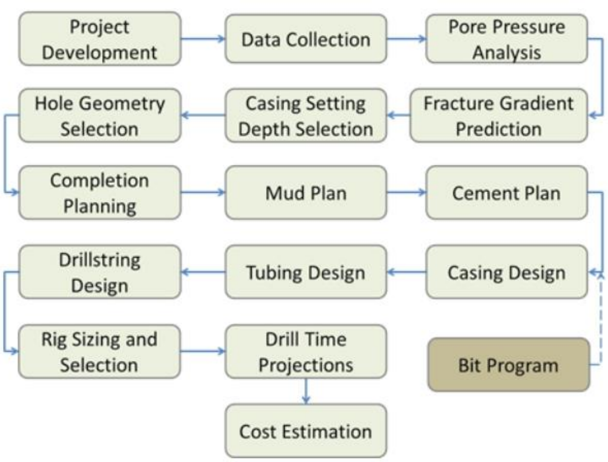

Figure 2 Flow path of drilling design and operation (Adams 1985)

Slimhole is a well that has a diameter smaller than usual. Commonly, casing diameter of a slimhole in the total depth is 2 7/8" with hole diameter at the conductor 10 ¾". The slimhole concept gives significantly effect to the costs reduction of the drilling operation; especially in the geothermal wells where typically has a large diameter hole. Equipment and procedures used in the drilling of the slimhole is more or less the same as in the conventional wells. Slimhole only focus on reducing the size of the hole and the casing on each hole interval.

There are several advantages of slimhole drilling applications related to diameter of the wellbore. Wellbore with small diameter can reduce mud consumption and cutting generated. From BP case study in West Africa, reducing the diameter hole by 50% from conventional drilling can reduce mud consumption, cutting generated and drilling site needed by 75%. Overall drilling costs can reduce between 40% and 50% due to slimhole drilling implementation. Moreover, slimhole drilling can reduce waste disposal (Murray et al. 1993).

There are technical challenges in slimhole drilling operation. Details of the cost that can be cut off come from material, site preparation, mobilization, crew, etc. Technical challenges that have to be noticed are associated with hydraulics, mud characteristics and tools that can be run into the wellbore. Main concern in hydraulic is due to high velocity and high pressure losses in the annulus. Mud density is one of the mud characteristics that very important because equivalent circulating density in slimhole drilling is very high. So it is hard to get desired mud weight. Equipment that can fit into the hole is limited such as bits and logging tools. However, because of the logging tool is not used in geothermal wells so it is not an important issue in geothermal well.

3. SLIMHOLE CHALLENGES

Technical challenges that will be discussed in this paper is consists of pipe clearance, pressure losses, Directional Difficulty Index (DDI), and wellbore instability in slimhole. Pipe clearance will determine the next casing in the slimhole due to diameter bit that can enter into hole based on drift diameter of the current casing. Pressure losses and DDI is used for comparing between slimhole and conventional hole. Wellbore instability is analyzed due to properties of the geothermal formation.

3.1. Pipe Clearance

Pipe clearance is the difference between inside diameters of the casing with the equipment that will be passed through the casing. On slim hole drilling conditions, Pipe Clearance has to be considered as an important parameter to support the drilling process, especially because of the size of the casing is smaller than conventional drilling. More specifically, it will affect the determination of the size of the casing and the hole size or drilling bit size in the next section, or any subsurface equipment that will be passed through to perform well logging survey or completion.

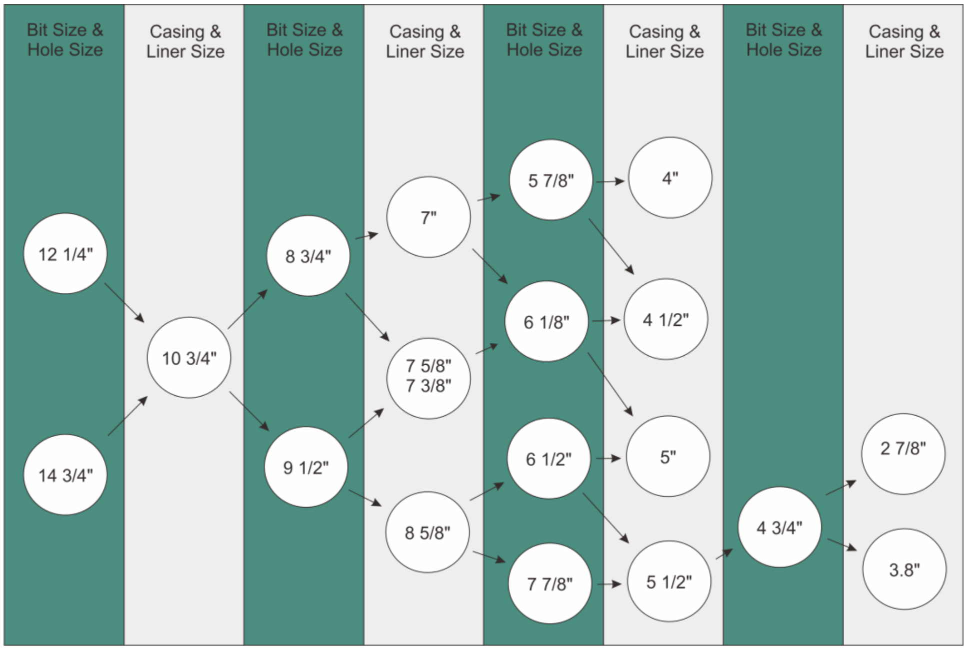

Figure 3 Wellbore Geometry for Slimhole (modified from Heriot Watt University 2005)

Pipe clearance difference will be directly proportional to the degree of difficulty in drilling operations, especially in the tripping operation. With a frequent drilling equipment movement (drill string, drilling bit, well logging or even completion equipment) inside the casing with a small clearance, the greater its friction possibility. Furthermore, this repeated operation can damage the inside part of the casing, or damaging subsurface equipment, such as logging equipment. But if the process of tripping is too careful, it will cause longer tripping time, resulting in NPT.

The above picture shows the size of the casing string size commonly used in slimhole drilling, taken from several field cases. In this paper, wellbore schematic that will be used to calculate pressure losses shown below :

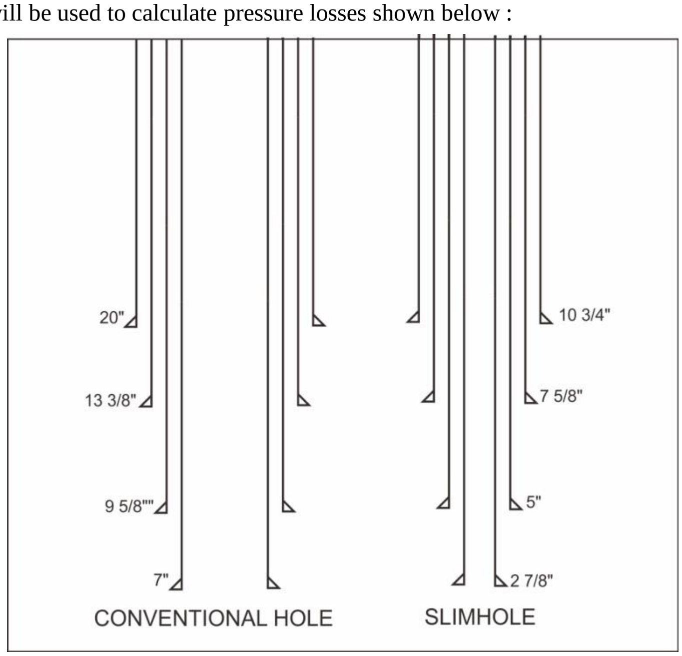

Figure 4 Comparation of Conventional Hole and Slimhole

3.2. Annular Pressure Losses

Pressure losses in the drill string consist of two major parts which are drill collar and drill pipe. This pressure loss is caused by frictional pressure acting in the opposite direction of drilling fluid flow in drill string. Also while drilling fluid is being circulated in the well, the bottom hole pressure (BHP) is greater than the hydrostatic pressure of the mud. The additional pressure is caused by friction losses experienced when the drilling fluid is pumped up the annulus. Determining of pressure loss in drill pipe and drill collar can be used these equation.

However, the actual bottom hole pressure in circulating condition is calculated by adding the annular pressure loss (APL) to the hydrostatic pressure of the mud. Calculation of annular pressure loss can be done using these equations depend on two types of fluid flow. Types of fluid flow are laminar and turbulent. Equation for laminar flow and turbulent flow respectively is:

$$APL = \frac{\mu \cdot v}{1000 \cdot (Dh - Dp)^2} \quad (1)$$

$$APL = \frac{\rho^{0.75} \cdot v^{1.75} \cdot \mu^{0.25}}{1396 \cdot (Dh - Dp)^{1.25}} \quad (2)$$

where

ρ = fluid density, ppg

υ = fluid velocity, ft/s

μ = fluid viscosity, cp

Dh = hole diameter, in

Dp = pipe diameter, in

3.3. Directional Difficulty Index

Directional Difficulty Index, (DDI), provides a first pass evaluation of the relative difficulty to be encountered in drilling a directional well. This index was developed through use of a straightforward questionnaire distributed so as to reach consensus on identifying key performance measures (Oag and Williams 2000).

All the survey files in the company database contain the same basic information: Measured Depth, Inclination & Azimuth. As another post-well engineering analysis done by Drilling Engineers, further values are calculated: TVD, N, E, VSD, AHD, DLS and Tortuosity. AHD can be calculated from resolving the Pythagorean principle which is used from the North and East values as calculated at each survey station. The term ‘tortuosity’ has been derived as a cumulative value to reflect the total curvature imposed on a wellbore and it is this term which was perceived as the more important (Oag and Williams 2000).

$$DDI = log_{10}\left[\frac{MD\ x\ AHD\ x\ Tortuosity}{TVD}\right] \quad (3)$$

In general as the DDI increases then the key performance indicators show lower performance and conversely as DDI decreases the key performance indicators show marked improvements over the average (Oag and Williams 2000). In its application, slim hole directional drilling tend to be more difficult than with conventional drilling, DDI can be the solution to used at several stages:

1. The planning process. To determine which is the most optimum trajectory to achieve the same reserve target.
2. To determine the technology that will be used in the well drilling program.
3. In the preparation of contracts and remuneration to the service providers, where the complexity of the wells will have an effect.
4. The learning process from the wells with the same difficulty level.

3.4. Wellbore Instability in Slimhole

Wellbore instability is caused by mechanical rock failure. Mechanical rock failure occur when the stresses acting on the rock exceed the compressive or the tensile strength of the rock (Lake and Mitchell 2006). Compressive failure is caused by shear stresses as a result of low mud weight, while tensile failure is caused by normal stresses as a result of excessive mud weight. As drilling in geothermal mostly using a low mud weight, compressive failure is likely to occur.

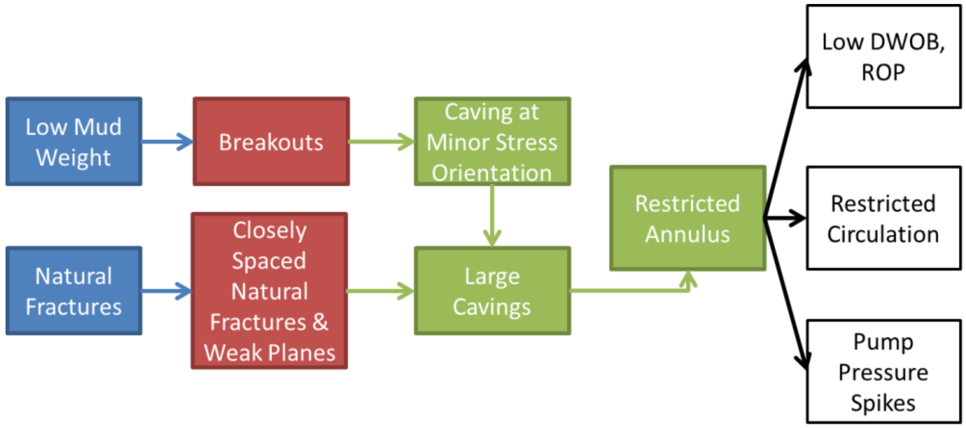

Figure 5 Diagnosis of Well Instability due to Low Mud Weight and Natural Fractures (Marbun Internal Report 2011)

Borehole breakouts are stress-induced enlargements of the wellbore cross-section. When a wellbore is drilled, the material removed from the subsurface is no longer supporting the surrounding rock. As a result, the stresses become concentrated in the surrounding rock (i.e. the wellbore wall). Borehole breakout occurs when the stresses around the borehole exceed that required to cause compressive failure of the borehole wall. The stress concentration around a vertical borehole is greatest in the direction of the minimum horizontal stress (Sh) which can lead to caving at minor stress orientation.

Characteristics of natural fracture from geothermal formations, can be one of contributing factor in the wellbore stability. It occurs when encounter the closely spaced natural fracture & weak plane, which will cause large caving problem. When combined with the caving at minor stress orientation case, this can lead to further problems, which is restricted annulus. Low drilling weight on bit (DWOB) & rate of penetration (ROP), restricted circulation, and pump pressure spikes are indications that can be observed from surface indicator.

4. CASE STUDY

There are several data that used to compare annular pressure losses (APL) between conventional and slimhole drilling based on well geometry in figure 4. The data show us several input parameter that used to generate APL vs. pump rate graph to deeply analyze the effect of pipe clearance to pressure loss in slimhole drilling. Pump rate, viscosity, density of drilling fluid, hole diameter and pipe diameter is critical parameter to calculate annular pressure loss versus several scenarios of pump rates used in drilling operation.

It is acceptable to assume that the density of drilling fluid and its viscosity used in this calculation are same between two comparison well model (conventional hole and slimhole) because the analysis is focusing on pipe clearance effect to annular pressure loss behavior, so the other parameter except hole diameter and pipe diameter is kept constant.

Table 1 Conventional Hole Well Geometry and Pump Rate Data

Conventional Hole				
Hole Size (in)	26	17.5	12.25	8.5
Casing Size (in)	20	13.375	9.625	7
Pump Rate (gpm)	910	613	429	298

Table 2 Slimhole Well Geometry and Pump Rate Data

Slimhole				
Hole Size (in)	14.75	9.5	6.5	4.75
Casing Size (in)	10.75	7.625	5	3.8
Pump Rate (gpm)	516	333	228	166

5. RESULT & DISCUSSION

In slimhole drilling, a smaller hole size provides a smaller annular clearance; for instance a 2 7/8" & 3.8" hole would be drilled with 4 ¾" BHA, while a 4", 4 ½", 5", 5 ½" hole would be drilled with 5 7/8", 6 1/8", 6 ½", & 7 7/8" BHA. For narrow clearance of slimhole drilling, annular velocity generated is high enough compare to conventional drilling. However turbulence flow model in annular pressure loss calculation as shown in equation 2 would be consider rather than laminar flow model as shown in equation 1.

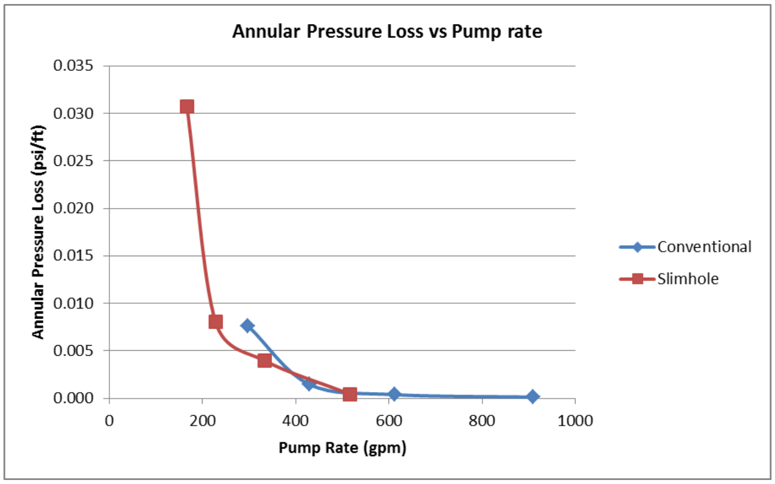

Figure 6 Annular Pressure Loss vs Pump Rate

Based on calculation show in figure 6, the graph explains us that annular pressure loss in slimhole drilling is high than conventional drilling for every different pump rate. The data used to compare pressure losses between conventional hole and slimhole drilling provided in table 1 and table 2. The highes annular pressure loss is obtained in slimhole drilling 0.0307 psi/ft, whereas in conventional drilling, the high annular pressure loss is 0.00762 psi/ft

Table 3 Slimhole Pressure Loss Calculation

Slimhole				
Hole Size (in)	14.75	9.5	6.5	4.75
Casing Size (in)	10.75	7.625	5	3.8
Hole Size - Casing Size (in)	4	1.875	1.5	0.95
Areal of Annular Clearance (in^2)	320.57	100.92	54.21	25.53
Pump Rate (gpm)	516	333	228	166
Velocity (ft/s)	0.52	1.06	1.35	2.09
Reynold Number	3436	4987	4165	4912
Annular Pressure Loss (psi/ft)	0.000441	0.00398	0.00804	0.0307

Table 4 Conventional Hole Pressure Loss Calculation

Conventional Hole				
Hole Size (in)	26	17.5	12.25	8.5
Casing Size (in)	20	13.375	9.625	7
Hole Size - Casing Size (in)	6	4.125	2.625	1.5
Areal of Annular Clearance (in^2)	867.43	400.27	180.47	73.07
Pump Rate (gpm)	910	613	429	298
Velocity (ft/s)	0.34	0.49	0.76	1.31
Reynold Number	4165	4062	4539	5657
Annular Pressure Loss (psi/ft)	0.000126	0.000388	0.00148	0.00762

In the slim hole directional drilling, the implementation will be more difficult when compared with conventional hole directed drilling. Some of the causes are the ability of the surface equipment in its capacity and its power system tends to be smaller, also limits of the subsurface equipment that can be used. One of the steps in trajectory planning will be using Directional Drilling Index (DDI). The use of this DDI will evaluate the design of directional drilling in the drilling of slimhole.

5. CONCLUSION

The following conclusion can be derived based on the study:

1. Pipe clearance must be accounted in planning slimhole design so that proper planning could be achieved. Pipe clearance can be used to determine casing configuration in slimhole.
2. Annular pressure loss is a critical consideration of slimhole drilling. A reduction of hole size will influence the calculation of pressure losses significantly. Annular pressure loss in slimhole drilling is higher than conventional due to narrow annulus.
3. Directional Difficulty Index, (DDI), provides a first pass evaluation of the relative difficulty to be encountered in drilling a directional well. In its application DDI can be the solution for Planning Drilling Program, Contract Preparation & Remuneration, and Learning Process.
4. Wellbore instability due to low mud weight and natural fractures can cause lower WOB, lower ROP, restricted circulation and pump pressure spikes that lead to much trouble in slimhole drilling operation.

6. NOMENCLATURE

AHD Along hole displacement

APL Annular Pressure Losses

DDI Directional Difficulty Index

MD Measured Depth

TVD True Vertical Depth

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