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Aerated drilling cutting transport analysis in geothermal well

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Abstract. Aeratad drilling widely used for geothermal drilling especially when drilled into predicted production zone. Aerated drilling give better performance on preventing lost circulation problem, improving rate of penetration, and avoiding drilling fluid invasion to productive zone. While well is drilled, cutting is produced and should be carried to surface by drilling fluid. Hole problem, especially pipe sticking will occur while the cutting is not lifted properly to surface. The problem will effect on drilling schedule; non-productive time finally result more cost to be spent. Geothermal formation has different characteristic comparing oil and gas formation. Geothermal mainly has igneous rock while oil and gas mostly sedimentary rock. In same depth, formation pressure in geothermal well commonly lower than oil and gas well while formation temperature geothermal well is higher. While aerated drilling is applied in geothermal well, Igneous rock density has higher density than sedimentary rock and aerated drilling fluid is lighter than water based mud hence minimum velocity requirement to transport cutting is larger than in oil/gas well drilling. Temperature and pressure also has impact on drilling fluid (aerated) density. High temperature in geothermal well decrease drilling fluid density hence the effect of pressure and temperature also considered. In this paper, Aerated drilling cutting transport performance on geothermal well will be analysed due to different rock and drilling fluid density. Additionally, temperature and pressure effect on drilling fluid density also presented to merge.

1. Introduction

In geothermal drilling, many challenges will be faced. One of them is the reservoir pressure. Formation pressure found in geothermal drilling is smaller than the hydrostatic pressure of the mud used when drilling. Therefore, when drilling mud is applied, its pressure will exceed the formation pressure. Then drilling will be lost and enter to the formation itself. This is certainly not desirable. Aerated drilling method is not a new method used in drilling applications. However, this method can be used to address some of the problems that occurred in the geothermal field.

In this paper, it will discuss about the use of method of aerated drilling in the geothermal field. The density of the rock in geothermal field that will face is relatively bigger than the rock in the field of oil and gas. The greater the density of the rock that will face, the harder it will drill bit to penetrate the formation. Also, the drill cutting will be increasingly difficult to be transported to the surface.

In the other hand, the use of aerated drilling method requires a limited amount of gas that can be used to lower the density of the mud that pump into the annulus. Therefore, this paper will be modelled on a technical restriction that can be applied to drill using aerated drilling techniques.

2. Geothermal Well Drilling

The Geothermal well drilling process is basically similar to the process of drilling the wells of oil/gas, both in terms of the stages of the process, technology, tools, as well as its drilling expert. There are two major challenges in drilling geothermal wells at once that distinguishes it from drilling in oil and gas wells, especially, in terms of temperature and lost circulation problem.

Lost circulation occurs because the target in a geothermal well are fractures. The fracture is connected to a heat source. When the fracture is appeared through in the drilling process, most likely drilling mud will enter the fracture instead of returning to the surface. This lost circulation condition is technically giving some negative impact on the drilling process and need to be tackled.

In terms of temperature, the target of geothermal wells has a high temperature, because the temperature is what the energy that wants to be extracted. The higher the temperature is, the more economical the project of geothermal well it will be. However, in terms of the drilling process, It will become more challenging because the technology adopted from the drilling of oil and gas industry is actually designed for a relatively lower temperature, and it is often a barrier.

The conditions met in geothermal operation are [5]. Some of these conditions are as follows:

a. Lost Zones: Partial and lost circulation zones range from 7 to as much as 42 requiring cement plugging.
b. Hole Temperature: Bottom hole temperature range from 300^{o}C and 425^{o}C (compared to low or ambient temperature in oil-gas wells) at depth of 7000 to 11000 feet.
c. Lithology: Soil formation are hard silicified volcanic rocks as compared with generally sedimentary rock formation in oil and gas lithology.
d. Mud Density: Mud weight requirements are already on reduced density level such as 8.8 to 10.5 ppg compared with more than 13 ppg for oil and gas.
e. Hole Acidity: Hole condition is highly corrosive with pH range of 3 to 5 pH which can be aggravated by introduction of oxygen from air injection during mud circulation.
f. Blind Drilling: When zones of total lost circulation are encountered on the 8 ½” hole interval, the use of mud is stopped and blind drilling with water is conducted.

3. Managed Pressure Drilling (MPD)

MPD is drilling technique that the mud pressure in bottom hole is kept constant using certain technique. It is important to anticipate several problems that can be encountered such as drilling in narrow pressure window and loss circulation zone. Based on International Association of Drilling Contractors (IADC), MPD is an adaptive drilling process used to more precisely control the annular pressure profile throughout the wellbore to obtain several objectives:

1. To ascertain the downhole pressure environment limits
2. To manage the annular hydraulic pressure profile

4. Underbalance Drilling

Underbalance technique is using light drilling fluid where drilling fluid pressure is low than the pore pressure of formation rock. The fluids that commonly used such as air, gas, aerated water, and foam. Underbalance drilling technique can increase penetration rate, minimized differential sticking, improve formation evaluation, reduce formation damage, and prolonged bit life. The disadvantages of underbalance drilling are corrosion problem, high cost and difficult hydraulic calculation.

5. Aerated Drilling

5.1. Volume Requirement

Methods to reduce the hydrostatic pressure of the wellbore is to add gas into the system. Extra gas will result in a pressure drop due on replacing fluid pushed by the gas so that the density of the system will decrease by itself. The most important parameter in making the design of aerated drilling cuttings is to determine the carry capacity on a mixed system of drilling fluid. For a specific gas injection rate and injection rate of the fluid must be able to lift the whole cutting perfectly formed at the bottom of the well to the surface.

Produced cutting in geothermal drilling is relatively large and has a density that is larger than oil and gas field. Therefore, it will take the value of the minimum velocity rate of the fluid mixture and gas to lift the cutting to surface. In the application of aerated drilling is almost certain that the regime of the flow is turbulent. Then, the primary consideration in the designing flow rate is to include turbulent factor in the calculation. The basic step in planning for aerated drilling is shown in figure 1.

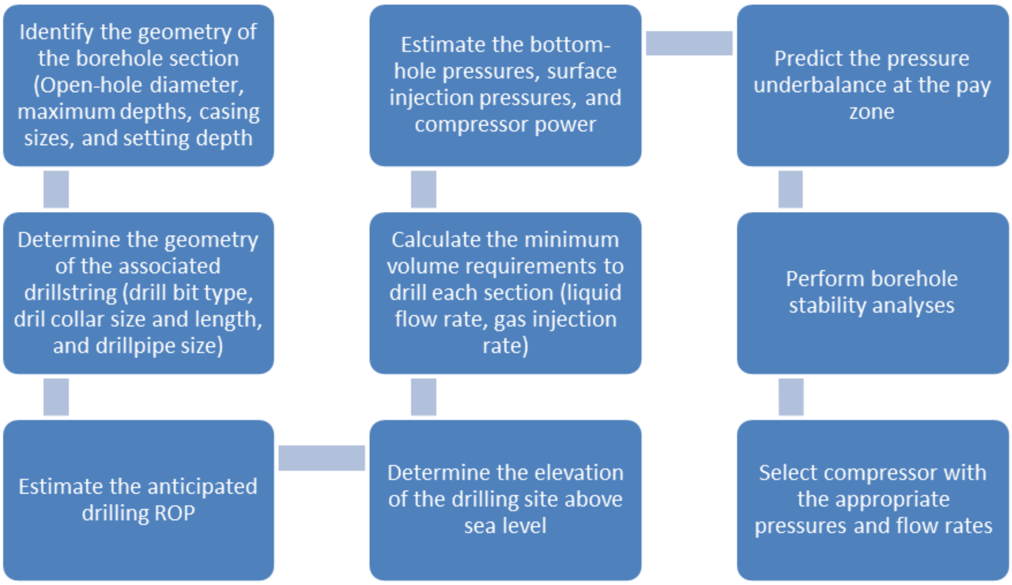

Figure 1. Workflow for calculating volume requirement in aerated drilling techniques [4]

5.2. *Cutting Transport*

5.2.1. Cuttings-Carrying Capacity. The cutting-carrying capacity of the aerated mud is defined as the maximum cutting size that can be lifted by the aerated drilling mud. Rittenger's formula [2] can be used to calculate the slip velocity, as follows:

$$V_{sl} = 7.3x\left(\frac{D_c x\,(\rho_c - \rho_f)}{\rho_f}\right)^{0.5} \quad (1)$$

The required cutting transport velocity, V_{tr} depends on the rate of penetration, R, and the allowable cutting concentration, C_c in the annulus.

$$V_{tr} = \frac{R}{C_c} \quad (2)$$

$$V_{tr} = \frac{\pi \ x \ d_b^2}{4xC_c xA} \quad (3)$$

The volumetric flow rate of liquid Q_l is defined as follows:

$$Q_l = \frac{2.2283}{10^3} \cdot Q_m + \frac{1.5597}{10^3} \cdot Q_i \quad (4)$$

The volumetric flow rate of gas Q_g is defined as follows:

$$Q_g = 6.7846 \ x \ 10^{-2} \cdot T \cdot \frac{Q_{air\ inj}}{P} \quad (5)$$

The average velocity can be obtained using the following equation,

$$V_f = \frac{c''}{P} + d'' \quad (6)$$

Where,

$$c'' = \frac{9.77TQ_{air\ inj}}{A} \quad (7)$$

$$d'' = \frac{0.33Q_m + 0.22Q_i}{A} \quad (8)$$

Maximum allowable cuttings settling velocity can be determined using the following equation,

$$V_{sl} = V_f - V_t \quad (9)$$

The density of gas can be also estimated using the ideal gas law,

$$\rho_g = S_g \cdot \frac{P}{53.3 \cdot T} \quad (10)$$

The volume fraction of liquid at certain point for every depth of interest is defined by,

$$f_l = \frac{Q_l}{Q_l + Q_g} \quad (11)$$

5.2.2. Cuttings Transport Efficiency. Test Cuttings transport efficiency is a function of the drilling mud and depends on several factors:

a. The density of the drilling mud

The addition of drilling mud will increase the buoyance force. Every particle of cutting is acting to opposite direction against gravity forces. However, the lifting capacity will be effective to drive out the mud and lift the cutting to the surface.

b. Torque effect
Rotation of drillpipe will affect on sludge removal capacity in laminar or turbulent flow regime. Effects of torque (power play) will cause the particles tend to spin in terms of turning drops up due to variations in velocity of the mud.

c. Viscosity and gel strength
Some mud which have low viscosity and gel strength will give great impact to the particles in the same annular velocity and circulation time. Based on the experiments conducted by Bruce and William, the mud with low viscosity and gel strength only has a small capacity to transport particles to the surface.

d. Distribution of velocity in the annulus
Large cutting lifting capacity can be achieved with turbulent flow than the laminar flow which has a low viscosity. This is because the effects of turbulence sludge tend to minimize settled cutting in the annulus near the pipe or the wall of the wellbore.

e. Dimensional of cutting
Bit design will determine the size and shape of the cutting. Physical magnitude of cutting will greatly affect the capacity of cutting transport. The thickness of cuttings having a large diameter tend to be difficult removed from the wellbore, because the cuttings are going back down to the bottom of a well

6. Case Study

Aerated drilling modeling is based on synthetic data and combined with field data. The well data was released by [1]. The well X-1 was drilled vertically in 2002. At the time, field Y was an untapped resource and an exploration well was needed for more understanding and knowledge of the deep geothermal system. The well location was chosen based on results from a number of surface exploration surveys, which indicated that the reservoir temperature was above 280°C at depth. In the drilling report, increased fluid circulation loss was detectable down to 1600-1700 m depth, which indicates a feed zone below that, [1].

The study was focused to the section 9 5/8 in. The rate of penetration is in the range of 20 to 30 ft/hr for every depth of interest. The summary data that is used can be seen in table 1. The OD and ID of drill collar were 2 13/16 in and 4 ½ in, respectively. Modeling process in aerated drilling will be using a variation of gas injection rate ranged between 250 to 600 scf/min.

Table 1. Well X-1 Data, [1]

Depth	Pressure (bar)	Pressure (psia)	T (C°)	T (Rankine)
0	0	14.7	25	536.67
250	31	449.5	198	848.07
500	52	754	200	851.67
750	71	1029.5	185	824.67
1000	87	1261.5	210	869.67
1250	100	1450	205	860.67
1500	130	1885	170	797.67
1750	146	2117	220	887.67

From Well X-1, nine warm-up profiles and three injection profiles were available figure 2. Only six

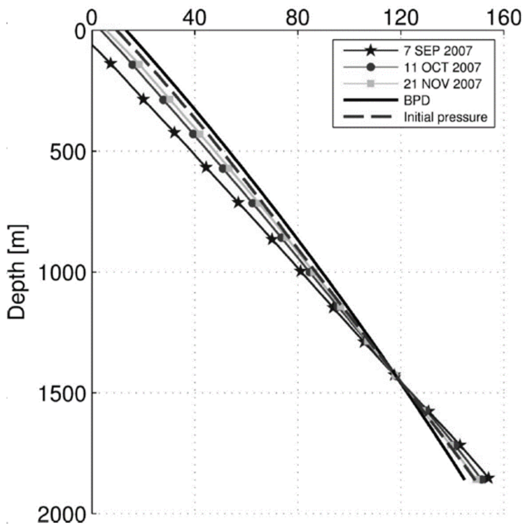

Figure 2. Pressure Profiles and Initial pressure estimation for Well X-1 [1]

warm-up profiles can be used for the interpretation of formation temperature, since the three others either do not have enough data or there has not passed enough time from when the well was closed to the measurement (shut-in time). Those six profiles are the latter measurement from 16 September 2002, from 10 October 2002, 18 August 2003, 22 August 2003 and the two from 7 September 2004. A feed zone is visible at 1900 m depth in the injection profile from 4 September, [1].

7. Result and Discussion

The back pressure is the most important key in maintaining pressure regime. At some point, gas and liquid tend to split up the quality of 0.8 (percentage of gas in the fluid). If the quality is above 0.8, then the worst will happen as the separation of gas and liquid, emerging slugs of water and can cause pressure surges in the hole, as well as gas or air can be a continuous phase so that the cutting cannot be lifted to the surface. figure 3 shows the operating zone that is the zone that can be safe in the process of aerated drilling.

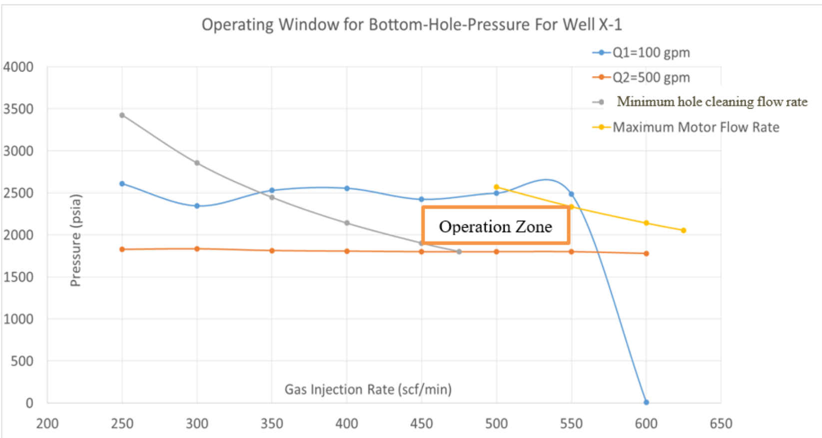

Figure 3. Operating Window for Bottom-Hole-Pressure for Well X-1

The modeling was done using two different pump flow rate. The first uses a flow rate of 100 gpm with gas injection rate variation ranges from 250-600 scf/min. Secondly, by using a flow rate of 500 gpm pump with gas injection rate variation of the same. Should be noted that the flow rate of the pump is at the minimum or maximum interval desired pressure and is under formation pressure (underbalanced drilling). figure 4 shows the gas injection rate required for each increase in temperature that will be encountered. the higher the temperature, the less for gas injection is needed.

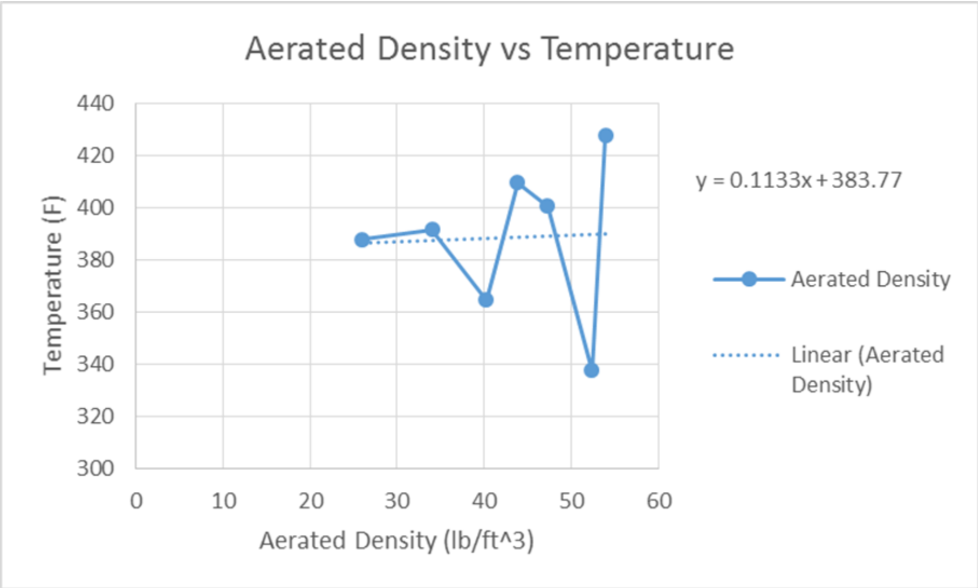

Figure 4. Aerated Density vs Temperature for Well X-1

figure 5 is a curve between the cutting size of the rock with the circulating pressure. In this study used the assumption that the density of the rock is ranging for 2.80 - 2.83 (SG). The size of cutting which can be lifted to the surface in the operating zone is 2.5 to 4-in.

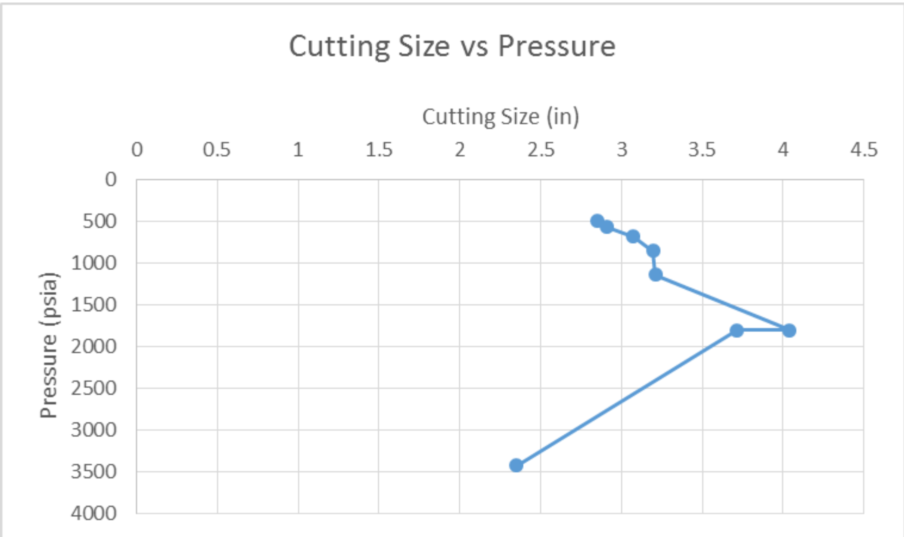

Figure 5. Cutting Size vs Pressure for Well X-1

Gas injection rate is very important on several factors such as pressure drop in the well, changing in the flow pattern, and the viscosity of the fluid phase and the charges. There are always limitation on how much gas can be added to the system to reduce the pressure as well. In figure 3 we can see that there are two limitations that cuts the respective curve given flow rate is currently 100 gpm and 500 gpm. The first limitation is the minimum flow rate to clear the hole of the cutting. The second limitation is the maximum flow rate that can be generated by the provided pump. Also in figure 6 can be seen that the higher the flow rate of gas that is injected, the maximum cutting required cutting settling velocity and transport velocity will increase. There are anomalies which can be seen on the profile of the maximum cutting settling velocity that is after the injection rate of 500 gpm maximum cutting settling velocity will continue to decline.

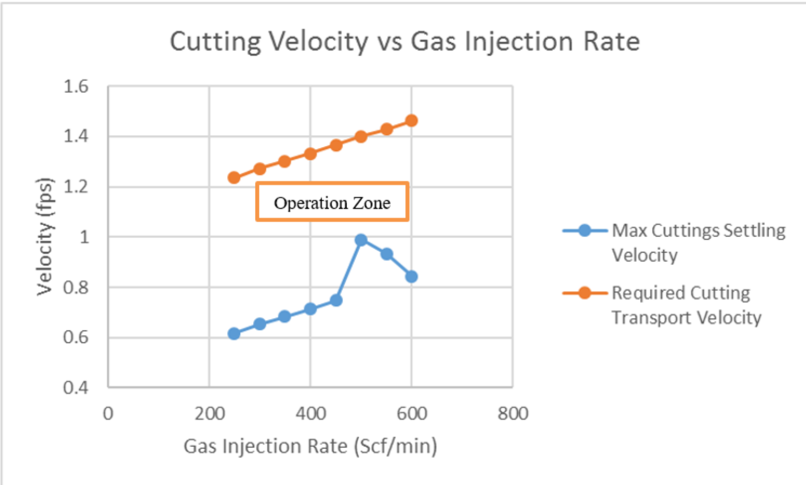

Figure 6. Cutting Velocity vs Gas Injection Rate for Well X-1

There is a different operation zone if the temperature is stated as constant. As shown in figure 7, the operation zone is limited to the small gas injection rate but the higher pressure required in circulating drilling mud.

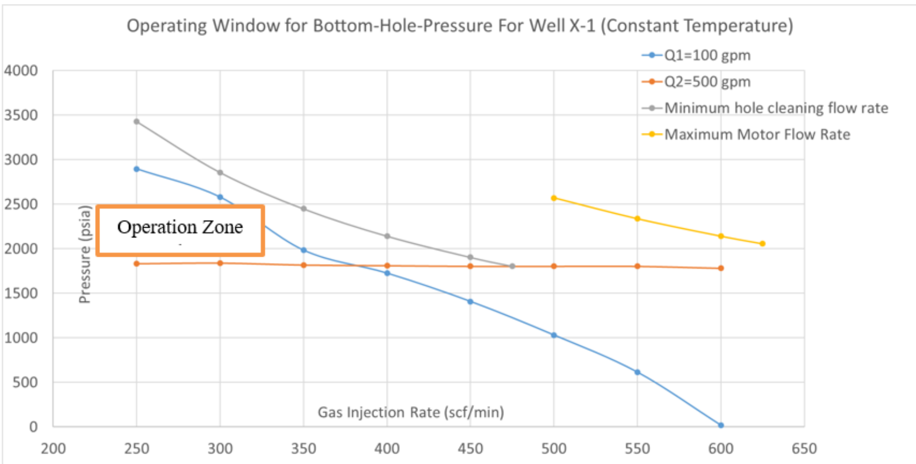

Figure 7. Operating Window for Bottom-Hole-Pressure for Well X-1 (Constant Temperature)

8. Conclusion

From this study, there are several lessons learned. Cutting-carrying capacity is depending on how much the gas is injected to the system of the drilling mud. Also, temperature and pressure play the role to create the large operation zone which is the safe zone for applying aerated drilling method. The operation zone is the range of required gas to be injected as well as the cutting will be effectively lifted to surface with the desired cutting size and the pump power which is available.

Nomenclature

$V_{sl} = Cutting\ Terminal\ Settling\ Velocity\ (fps)$
$D_c = Cutting\ Diameter\ (in)$
$\rho_c = Cutting\ Density\ \left(\frac{lb}{ft^3}\right)$

$\rho_f = Fluid\ Density\ \left(\frac{lb}{ft^3}\right)$
$R = Rate\ of\ Penetration\ \left(\frac{ft}{h}\right)$
$V_t = Cutting\ Transport\ Velocity$ (fps)
$C_c = Cutting\ Concentration$ (%)
$A = Surface\ Area\ (in^2)$
$d_b = Wellbore\ Diameter\ (in)$
$Q_l = Volumetric\ Flow\ Rate\ of\ Liquid\ (gpm)$
$Q_i = Volumetric\ Flow\ Rate\ of\ influx\ (gpm)$
$Q_m = Mud\ Flow\ Rate\ of\ Liquid\ (gpm)$
$Q_{air\ inj} = Air\ Injection\ Rate\ (gpm)$
$P = Pressure\ (psia)$
$T = Temperature\ (F^o + 460)$
$V_f = Average\ Velocity\ in\ the\ top\ of\ the\ drill\ collar$

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