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PROGRESS TOWARD USING HYDRAULIC DATA TO DIAGNOSE LOST CIRCULATION ZONES

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ABSTRACT

Several wellbore hydraulic models have been examined to determine their applicability in measuring the characteristics of lost circulation zones encountered in geothermal drilling. Characteristics such as vertical location in the wellbore, fracture size, effective permeability, and formation pressure must be known in order to optimize treatment of such zones. The models that have been examined to date are a steady-state model, a standpipe-pressure model, a raising-the-drill-bit model, a mud-weight model, a hydrofracture model, and several time-dependent models. None of these models yet have been found to adequately match the field data obtained from six loss zones in three geothermal wells. The development of these models is presented in this paper, and a discussion of their limitations is provided.

BACKGROUND

Lost circulation is a pervasive and costly problem routinely encountered in geothermal drilling. Between 10 and 20% of the cost of a typical geothermal well can be attributed directly to this phenomenon. These costs, in turn, increase the cost of geothermal power and contribute to a lower utilization of this environmentally favorable resource than would otherwise occur.

Consequently, the development of techniques for improving the effectiveness of lost circulation treatments is a priority of the drilling research program underway at Sandia National Laboratories. Sponsored by the U.S. Department of Energy, this program is examining various ways to reduce geothermal drilling costs. Because of the high-temperature, fractured-rock formations that must be penetrated to access geothermal resources, geothermal wells typically cost about twice that of petroleum wells drilled to the same depth.

In order to optimize the treatment of lost circulation zones, it is necessary to determine certain characteristics of the zones when they are encountered. For instance, the depth of the loss zone must be known in order to know where to emplace a treating fluid such as cement. Knowledge of the permeability of the zone and the formation pressure would enable the viscosity, density and setting time of the treating fluid to be optimized. If the fracture width could be accurately determined, bridging particles of the correct size could be added to the drilling fluid or cement to more effectively plug the zone.

Wellbore hydraulics models have the potential for providing the needed loss-zone characteristics. If flow tests could be run while measuring flow characteristics such as flow rates and pressures at the surface or downhole, it is possible that such models could provide estimates of the needed information with little additional rig time or cost. The purpose of this paper is to document the models that have been examined to date and discuss the limitations that have been discovered in their application.

STEADY-STATE-FLOW, NEWTONIAN-MUD

According to a steady-state-flow, Newtonian-mud model, the flow into a loss zone (wellbore inflow minus outflow) is related to the effective hydraulic conductance of the loss zone and the pressure across the loss zone by the equation

$$Q_i - Q_o = \frac{K_e}{\mu}(P_l - P_e) \quad . \tag{1}$$

For partial lost circulation, the pressure in the wellbore at the loss zone, P_l, is a function of the specific weight of the mud column, the frictional pressure drop in the annulus, and the depth of the loss zone:

$$P_l = \gamma_m D_l + \Delta p_3 D_l \quad . \tag{2}$$

Thus equation (1) becomes

$$Q_i - Q_o = \frac{K_e D_l}{\mu}\Delta p_3 + \frac{K_e \gamma_m}{\mu} D_l - \frac{K_e P_e}{\mu} \quad . \tag{3}$$

For complete lost circulation the pressure in the wellbore, P_l, is a function of the specific weight of the mud column, the depth of the loss zone, and the depth of the fluid level in the annulus:

$$P_l = \gamma_m (D_l - D_f) \quad . \tag{4}$$

In this case, equation (1) becomes

$$Q_i = \frac{K_e \gamma_m}{\mu} D_l - \frac{K_e \gamma_m}{\mu} D_f - \frac{K_e P_e}{\mu} \quad . \tag{5}$$

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This steady-state model assumes that the inlet flow, Q_i, is an independent parameter that can be varied and that outlet flow, Q_o, and fluid level in the annulus, D_f, are parameters that can be measured. The annular frictional pressure loss, Δp_3, must be determined either by modeling the flow through the annulus or empirically by measuring the pressure drop as a function of flow. The unknowns this model attempts to determine are depth of the loss zone, D_l, hydraulic conductance of the loss zone, K_e, and effective pressure of the formation at the loss zone, P_e.

For equation (3), if loss circulation is plotted as a function of Δp_3, the slope and intercept are

$$\text{Slope: } \frac{K_e D_l}{\mu} \quad \text{Intercept: } \frac{K_e \gamma_m}{\mu} D_l - \frac{K_e P_e}{\mu} .$$

For equation (5), if loss circulation is plotted as a function of D_f, the slope and intercept are

$$\text{Slope: } -\frac{K_e \gamma_m}{\mu} \quad \text{Intercept: } \frac{K_e \gamma_m}{\mu} D_l - \frac{K_e P_e}{\mu} .$$

If it is possible to vary Q_i so that data can be taken for both partial and complete lost circulation conditions, then knowing these slopes and intercepts, the depth of the loss zone, D_l, the hydraulic conductance of the loss zone, K_e, and the effective pressure of the formation at the loss zone, P_e, can be solved for algebraically.

Problems with applying the steady-state-flow, Newtonian-mud, lost-circulation model as outlined above are that: 1) it is difficult to calculate Δp_3 accurately enough to solve for the unknowns because of mud rheology effects, eccentricity of the drill pipe in the hole, Couette flow (angular drag of rotating the drill pipe), drill pipe vibrations, downhole temperature effects, hole diameter variations, hole roughness, thinning or thickening of the mud, friction or viscosity or density effects of the cuttings, and flow regime transitions; and 2) the flow may be insensitive to Δp_3 because it is much smaller than the other pressure drops in the system, making it difficult to determine Δp_3 empirically from surface data. Thus downhole pressure measurements would be required in order to determine Δp_3 as a function of flow. While technically feasible, this limits the practical applications of the steady-state model.

STANDPIPE-PRESSURE MODEL

The relationship between depth of the loss zone and the standpipe pressure can be determined as follows. Summing the pressure changes in the annulus, the bottom hole pressure is

$$\Delta p_3 \left(D_l - D_f\right) + \Delta p_2 \left(D_b - D_l\right) + \gamma_m \left(D_b - D_f\right) . \quad (6)$$

Summing the pressure changes in the drill pipe, the bottom hole pressure is

$$P_s - \Delta p_1 D_b + \gamma_m D_b - \Delta p_b . \quad (7)$$

Equating these and solving for the depth of the loss zone gives

$$D_l = \frac{P_s - (\Delta p_1 + \Delta p_2) D_b - \Delta p_b + (\Delta p_3 + \gamma_m) D_f}{(\Delta p_3 - \Delta p_2)} \quad (8)$$

In general the depth of the loss zone, D_l, is not sufficiently sensitive to the standpipe pressure, P_s, to determine D_l from measurements of P_s. Under certain circumstances this model may be useful (e.g., severe lost circulation in slim holes), but its application requires calculating or measuring the Δp's as a function of flow and accounting for the yield stress of the mud. Because of these limitations, other means of diagnosing lost circulation are more likely to be useful.

RAISING-THE-BIT MODEL

For slim holes, most of the pressure drop is in the annulus, and a simple method may be applicable to determining the depth of lost circulation. In this technique, the inflow rate is adjusted so that the fluid in the annulus is just at the surface ($D_f = 0$) or at a constant depth below the surface, and the drill pipe is rotated to shear the mud in the annulus; thus $\Delta p_3 \sim 0$ and $P_l \sim \gamma_m D_l$. As long as these conditions are maintained, the pressure at the loss zone, P_l, will be almost constant and any changes observed in standpipe pressure, P_s, and inflow rate, Q_i, should be indicative of changes in the flow between the bit and the loss zone. As an example, Figure 1 shows the standpipe pressure, P_s, as a function of the depth of the bit, D_b, for three different depths of lost circulation, D_l. The standpipe pressure, P_s was calculated by equating expressions (6) and (7) and solving for P_s. Note that there is a very significant change in slope when the bit is at the loss zone, $D_b = D_l$. Thus, by plotting standpipe pressure, P_s, vs. bit depth, D_b, it may be possible to determine the depth of lost circulation graphically.

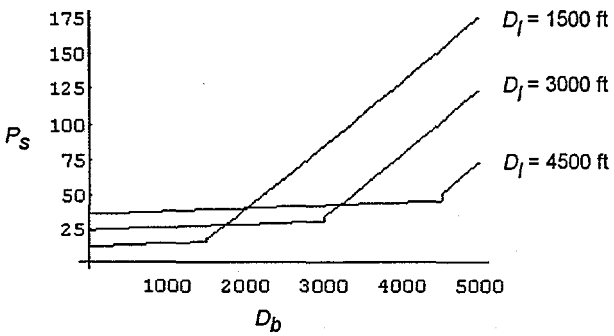

Figure 1: P_s (at point when fluid is about to drop below the surface assuming τ_0 is insignificant) as a function of D_b (depth of bit).

Problems with applying this approach to large diameter wells is that downhole pressures would probably have to be used instead of standpipe pressure, and rotating the drill pipe will not adequately shear the mud. Even for slim holes a question related to this approach is whether rotating the drill pipe really makes $P_l \sim \gamma_m D_l$. Furthermore, a rate of rotation high enough to shear the mud may introduce other problems, e.g. drill string vibrations.

NONUNIQUENESS OF HYDRAULIC DETERMINATION OF DEPTH OF LOST CIRCULATION

It can be shown that under certain conditions, the depth of lost circulation is nonunique with respect to surface measurements of pressure and flow. Specifically, if (1) the steady-state-flow, Newtonian-mud model applies, (2) the weight of the mud is much larger than annular frictional pressure losses, and (3) the pressure gradient in the formation is close to the specific weight of the mud, then the surface pressure and flow will be insensitive to the depth of the loss zone. These conditions are sufficient, but not necessary, for nonuniqueness. This potential nonuniqueness implies that pressure or flow data from within the loss zone or data other than pressure or flow may be needed to determine the location of the loss zone.

MUD WEIGHT AS A PARAMETER

In the models considered so far, the parameters have been Q_i, Q_o, Δp_3, D_f, and P_s. The one that is an independent parameter, i.e., can be varied, is Q_i. The others are functions of Q_i. The unknowns are K_e, D_l, and P_e. If mud weight, γ_m, is considered an independent parameter that can be varied, then γ_m can be used to obtain information about the loss circulation zone. If the formation pressure is not too high, then when the mud pump is turned off, the fluid level in the annulus will drop to a level D_f given by

$$D_f = D_l - P_e / \gamma_m \qquad (9)$$

provided the mud has zero yield stress. If γ_m is varied and D_f is plotted as a function of $1/\gamma_m$ then the intercept will be D_l and the slope will be $-P_e$. Using the mud weight as a parameter removes the nonuniqueness and allows a simple way of determining the depth of the lost circulation zone. In practice, however, γ_m probably cannot be varied sufficiently for this technique to be practical. Furthermore, the entire column must have the same mud weight, i.e., water cannot be just dumped on top of the mud.

When the mud has non-zero yield stress, the above expression may in theory be generalized to include yield stress, but in practice this may be difficult.

APPLICATION OF STEADY-STATE MODEL TO FIELD DATA

Figure 2 shows actual standpipe pressure and flow for a "typical" lost circulation zone. The first observation from the figure is that there is a sudden change in lost circulation as a result of changing the mud pump rate. The stability of the data before and after this change suggests the steady-state model may be appropriate. However, the question must be asked: "Is this really typical and can lost circulation zones be considered to be steady-state?" Data taken before that shown in Figure 2 and data from other lost circulation zones suggest time dependence associated with drilling into the lost circulation zone and the build-up of cuttings and/or mud cake at the entrance to the loss zone. However, data showing time-dependent effects of flow through the loss zone (analogous to time dependence observed during build-up or draw-down tests performed to determine reservoir properties) were not observed. This conclusion is based on examining 6 lost circulation zones in three different geothermal wells. Figure 3 shows lost circulation data from one of these other zones. Note the rapid changes in loss rate. Examination of various models of time-dependent effects of flow through a loss zone (moving boundary of the mud, compressibility of mud or rock matrix, etc.) suggests that time dependence should be observable on the time scale of Figure 2. If such time dependence is important it should be observed in association with changes in mud pump rate.

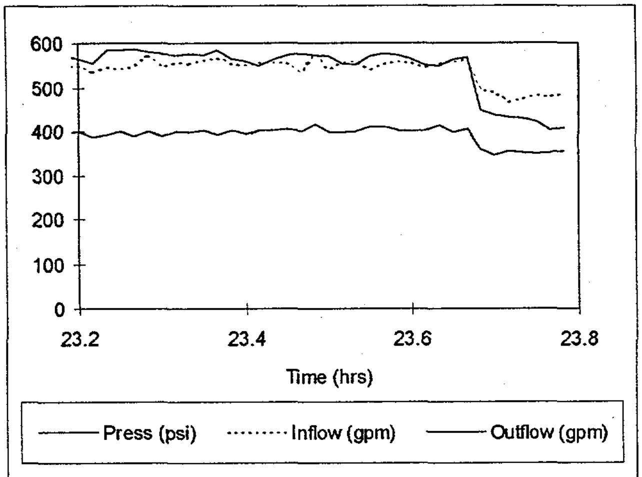

Figure 2: Pressure and flow vs. time for lost circulation zone.

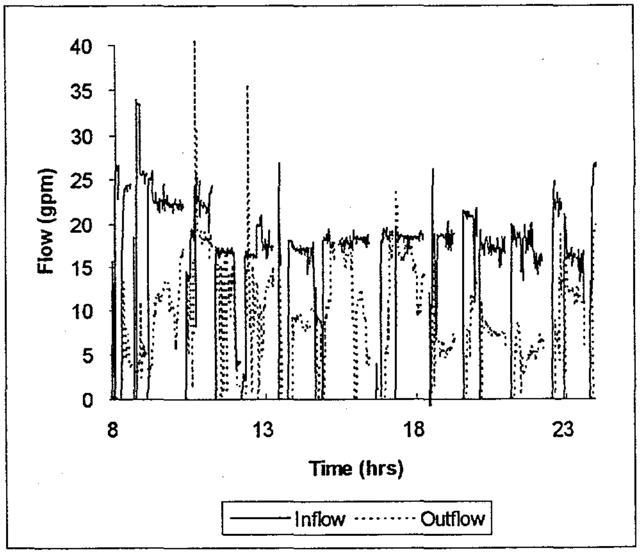

Figure 3: Example lost circulation data.

As shown in Figure 4, the steady-state lost circulation model can be understood as a channel or porous zone connected to a "reservoir." Whether the channel is one dimensional (as shown on the figure) or two dimensional (planar fracture) should be important only if one is trying to compare the measured K_e/μ with a geometric model of the loss circulation zone. The channel must be short enough that the mud completely fills or flows across the channel in a time less that the minimum time of interest, otherwise the flow will not be steady-state. Also the "reservoir" must have sufficient capacity that the volume of mud that has entered the "reservoir" has no effect on the pressure of the "reservoir," P_e.

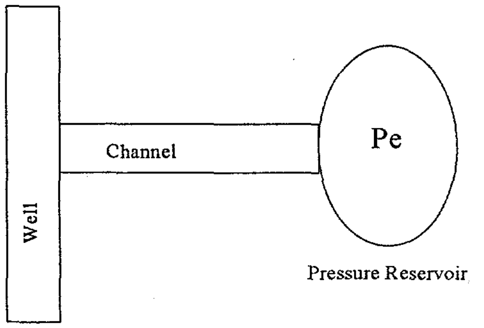

Figure 4: Steady-state lost circulation model

Considering the two different lost circulation conditions shown on Figure 2, the steady-state Newtonian-mud lost-circulation model implies that

$$\Delta Q_l = \frac{K}{\mu} \Delta P_l \qquad (10)$$

provided P_e is constant. From the change in lost circulation rate observed on Figure 2 and hydraulic calculations using ANFLOWPC,[1] the change in wellbore pressure at the loss zone, ΔP_l, was estimated to be about 0.025 psi, and K_e/μ was estimated to be 1000 gpm/psi.

Knowing K_e/μ it is possible to determine the length of a channel and the time for the mud to fill the channel as a function of effective channel diameter. For a one dimensional channel

$$\frac{K_e}{\mu} = \frac{\pi a^4}{8 \mu L} , \qquad (11)$$

where a is the effective channel diameter and L is the effective channel length. Given K_e/μ is 1000 gpm/psi, if L is to be several feet or more long, then the effective channel diameter must be at several inches or more. Such a channel would fill quickly, meeting the requirement that the channel be filled in less than the time between measurements. For radial flow the thickness of the disk would only have to be a fraction of an inch or more for the length of the channel to be several feet long or more. Again the disk would fill quickly. Thus the "channel" dimensions suggested by the K_e/μ are reasonable, though the length would be surprisingly short.

Once K_e/μ was determined, $(P_l - P_e)$ was estimated to be 0.15 psi and 0.13 psi for the two flow conditions. This is so small that slight changes in P_l would cause large changes in the rate of lost circulation. For example a 0.02% reduction in mud weight (0.002 lb/gal) or lowering the flow line to the mud pit only 4 inches could stop the loss circulation. This seems unlikely and calls into question the reasonableness and utility of the steady-state loss-circulation model.

NON-NEWTONIAN MUD

For simplicity the steady-state model presented above assumes a Newtonian mud. Extensions of the model have been examined to consider a power-law fluid and yield stress. While these effects introduce nonlinearities that help, they only increase the pressure differences about a factor of two. Thus it is concluded that the problem with applying the steady-state model to the data of Figure 2 is not due to the assumed non-Newtonian behavior of the mud.

HYDROFRACTURE LOST CIRCULATION

Another mechanism for lost circulation is for the formation to be "hydrofractured" by the mud. In this case, the fracturing of the rock creates the volume into which the mud flows. In hydrofracturing, a pressure drop occurs both at the fracture face and through the fracture, i.e., the flow from the wellbore out to the fracture tip. The pressure drop at the fracture face is a quasi-steady-state process. Early in time, the pressure drop through the fracture will be small and the pressure vs. flow behavior should be governed by the fracture face. Late in time, the pressure drop through the fracture may become dominant.

An early time analysis of a fracture model supplied by N.R. Warpinski (Sandia National Laboratories), resulted in a pressure difference of less than one psi, again unreasonably small. Hence, while the hydrofracture model appeared more reasonable than the steady-state model shown in Figure 4, it was concluded that the problem is not resolved by replacing the steady-state model with a hydrofracture model. This is not to imply that hydrofracture is not a significant cause of lost circulation. The hydrofracture model did not include non-Newtonian effects.

OTHER POSSIBILITIES

It may be that even though ANFLOWPC accurately predicts the frictional pressure drop, the calculated pressure drop is not representative of field conditions. Two possible problems could be temperature and cuttings effects. The bottomhole pressure due to the mud weight was about 680 psi for the loss zone shown in Figure 2, thus the frictional pressure difference calculated by ANFLOWPC is only .000034 of the bottomhole pressure. To mask a 10-psi pressure difference, a more reasonable pressure difference between the wellbore and the lost circulation zone "reservoir," a 127 °F temperature change would be needed in the downhole fluid at the two flow rates. Certainly the temperature changed with circulation rate but probably not 127 °F. Thus, the change in mud density with temperature is probably not the problem. Temperature can also change the mud properties. No data was available to address this question.

For cuttings with a specific gravity of 2.5, it would take only a 1% change in the cuttings volume fraction to mask a 9-psi pressure difference. A 1 % change in cuttings volume fraction may be reasonable based on the work of Clark and Bickham[2] and laboratory experiments in a flow loop at the University of Tulsa (Troy Reed, Reed Analytics & Consultants, personal communication). Furthermore, it has been shown that the build up in cuttings can add to the mud weight sufficiently to increase bottom hole pressure above the formation fracture pressure and thus cause lost circulation by fracturing the formation.[2]

It is also possible that the bottomhole condition changed between the two different flow conditions on Figure 2 because the weight on bit changed. Thus, the change in lost circulation rate may have been due to a change in bottomhole condition rather than the change in inflow rate. However, similar changes in lost circulation rate in association with changes in inflow rate have been observed in the other lost circulation data examined. Thus, the issues raised by trying to analyze the data presented in Figure 2 are of general concern and not just associated with some change in drilling operations.

CONCLUSIONS

Wellbore hydraulics studies have been conducted, starting with a steady-state-flow, Newtonian-mud model, to develop analytical and/or numerical models to diagnose lost circulation problems encountered in geothermal drilling. Examination of field data suggests that lost circulation is a quasi-steady-state process. Evidence of transient flow (pressure build-up or draw-down) was not observed.

A steady-state-flow, Newtonian-mud model was found to raise serious questions as to whether the depth of the loss zone can be determined if the only data available are standpipe pressure, inlet flow, and outlet flow. Other models, standpipe-pressure, raising-the-drill-bit, and mud-weight-as-a-parameter, were not found to be significant alternatives. From the work done on the standpipe-pressure model, it is unlikely that pressures can be calculated or measured accurately enough to use standpipe pressure as a diagnostic tool.

Application of the steady-state-flow, Newtonian-mud model to field data using calculated pressure changes led to unreasonable results. Examination of non-Newtonian mud effects and a hydrofracture lost-circulation model showed that these could not explain the discrepancies. Most likely the problems are due to not including temperature effects and cuttings effects in the calculations of pressures changes. It thus appears that it will difficult to calculate pressure changes accurately enough to apply a steady-state-flow model. This implies that downhole pressure data or another source of information will be needed to diagnose lost circulation.

ACKNOWLEDGMENT

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2. Clark, R.K., and Bickham, K.L.: "A Mechanistic Model for Cuttings Transport," SPE 28306, SPE 69th. Annual Technical Conference, New Orleans LA, 25-28 September 1994.

NOMENCLATURE

a Effective channel radius, ft,
d_i Drill pipe inside diameter, ft,
d_o Drill pipe outside diameter, ft,
d_w Hole diameter, ft,
D_b Depth of bit, ft,
D_c Depth of casing shoe, ft,
D_f Depth of fluid level in annulus, ft,
D_{fd} Depth of fluid level in drill pipe, ft,
D_l Depth of lost circulation zone, ft,
K_e Effective hydraulic conductance of the loss zone, gpm-cP/psi,
L Effective channel length, ft,
P_e Effective pressure of formation at loss zone, psi,
P_{eb} Effective pressure of formation at loss zone at bit, psi,
P_{ec} Effective pressure of formation at loss zone casing shoe, psi,
P_l Annular pressure at loss zone, psi,
P_s Standpipe pressure, psi,
P_{ys} Pressure in annulus necessary to overcome yield stress of mud, psi,
P_{ysd} Pressure in drill pipe necessary to overcome yield stress of mud, psi,
Q_i Wellbore inflow rate, gpm,
Q_o Wellbore outflow rate, gpm,
ΔP_l Change in annular pressure at loss zone, psi,
Δp_b Frictional pressure drop at bit, psi,
Δp_1 Frictional pressure drop in drill pipe, psi/ft,
Δp_2 Frictional pressure drop in annulus below lost circulation zone, psi/ft,
Δp_3 Frictional pressure drop in annulus above lost circulation zone, psi/ft,
ΔQ_l Change in lost circulation rate, gpm
γ_m Specific weight of the mud, psi/ft
μ Viscosity, cP, and
τ_o Yield stress, lb/(100 ft^2).