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DEVELOPMENT AND USE OF A RETURN LINE FLOWMETER FOR LOST CIRCULATION DIAGNOSIS IN GEOTHERMAL DRILLING

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ABSTRACT

This paper describes the development of a new drilling fluid outflow meter for use in the diagnosis and characterization of lost circulation experienced during the drilling of geothermal wells. The design and operation of the new meter, known as the rolling float meter, is described, and its laboratory and field performance data are presented. Considerations for using the rolling float meter with pump speed indicators for lost circulation characterization are discussed. Procedures for calibrating the flowmeters and data display and analysis techniques are outlined.

INTRODUCTION

Lost circulation occurs when drilling fluid is lost to the surrounding rock formation during the drilling of a well. Such fluid loss and associated problems with completing and producing the well generally make it imperative that one or more types of treatments be employed to plug the loss zone as soon as practicable. The costs associated with lost circulation problems and treatments represent an average of 10% of the total costs of drilling a well in mature geothermal areas [1], and often account for over 20% of the costs in exploratory wells and developing fields.

Rapid and accurate diagnosis of lost circulation is necessary to accomplish reductions in lost circulation treatment costs. It is necessary to know when lost circulation is occurring and its approximate severity to determine when and what type of lost circulation treatments are required. In severe cases where cement is required, it is necessary to know when the loss zone has been fully penetrated to avoid prematurely plugging only a partially-exposed loss zone at the bottom of the wellbore. It is also necessary to evaluate the effectiveness of any lost circulation treatment to optimize the treatment approach. Useful information related to these issues can be obtained by measuring and monitoring delta-flow (flow rate out of the well minus flow rate into the well) during drilling.

Flowmeters for measuring the inflow and outflow rates on drill rigs must meet a variety of criteria. They must be inexpensive, rugged, simple to install, use, and maintain, resistant to abrasive fluid, and reliable and accurate under a variety of field conditions. In addition, the inflow meter must not employ any intrusive probes that protrude into the flow stream because of the danger of the probe detaching, being pumped down the drillstring, and lodging in a bit nozzle downhole. The outflow meter must be capable of measuring fluid in a partially-filled pipe without disrupting the flow sufficiently for rock chips to fall out of suspension in the fluid. Flowmeters commercially available to the geothermal drilling industry meet many of these criteria, however, they lack the accuracy necessary for delta-flow measurements.

The industry standard device for measuring inflow rates is the pump stroke counter, which provides an indication of the number of pump strokes per minute. By multiplying this reading by the theoretical volume of fluid pumped per stroke and the pump efficiency, the approximate inflow rate to the well can be determined. Inaccuracies arise in this approach because of uncertainties and changes in pump efficiency. Although more accurate (and expensive) alternatives such as magnetic flowmeters do exist for measuring inflow rates, the pump stroke counter is often considered to have sufficient accuracy for drilling purposes.

The industry standard device for measuring outflow rates is the paddlemeter, which employs a single, spring-loaded paddle or vane that protrudes into the flow and is deflected upward by the force of the fluid impact. The magnitude of the deflection can be correlated with flow rate to provide an approximate measure of the outflow rate during drilling. This meter suffers from extreme inaccuracy in the field due to unsteady interaction between the paddle and the drilling mud stream (i.e., paddle bounce), which causes an unsteady and inaccurate meter reading [2]. Despite this inaccuracy the paddlemeter is used because it has been the only device that satisfies all the other criteria listed above. Its output is often displayed simply in terms of percentage of full flow and used more as a flow/no-flow indicator than as a quantitative measure of the outflow rate.

A project was undertaken to develop an alternative outflow meter that provides sufficient accuracy for lost circulation diagnosis and characterization. The new meter, known as the rolling flow meter, retains most of the simplicity of the paddlemeter while improving the interaction between the meter and the fluid stream. The result is a meter with greatly improved operation and accuracy that also meets all the other criteria discussed above. This paper describes the development of the rolling float meter and its use in diagnosing and characterizing lost circulation zones encountered in geothermal drilling.

ROLLING FLOAT METER DESIGN AND OPERATION

Drilling fluid enters the return flowline from the wellbore annulus and is accelerated by gravity to a point downstream where gravitational forces are directly offset by friction forces at the pipe walls and steady-state flow occurs. During the acceleration, the fluid velocity increases and the height of the fluid in the partially-filled pipe decreases. Because of the significant length of the accelerating-flow region for most practical applications, any outflow meter installed in the flowline will probably be installed in this region; therefore, the height and velocity of the fluid will depend on the location of the meter relative to the wellhead. The flow in the return line is also such that at any particular location the height of the fluid is a monotonic and repeatable function of flow rate in the pipe, while the velocity of the fluid reaches an asymptotic value with increasing flow rates. As such, a flowmeter that measures fluid height can, after installation in the return line, be calibrated to flow rate with an inflow meter to be used in the delta-flow measurements.

The rolling float meter was designed to measure height in a drilling fluid return line in a simple manner while avoiding problems associated with the conventional paddlemeter. A schematic and photograph of the meter are shown in Figures 1 and 2. The meter is easily installed in the return line, has little interference with the flow, and requires the monitoring of only one channel of data. The meter employs a rolling float that is counterbalanced so that it rides on the surface of the fluid. The angle of the float pivot arm (and, therefore, the height of the float) is measured with a pendulum potentiometer. The fluid accelerates as it flows under the spinning float, causing a lower pressure beneath the float that adheres it to the fluid surface through the Bernoulli effect. In this manner, the float accurately tracks the surface of the fluid, without bouncing free as it encounters waves on the fluid surface. Early prototype meters also included a transducer for measuring float spin rate, however, it was quickly apparent that the float velocity was not an accurate or repeatable measure of fluid flow rate. The original prototype also included an air dashpot to damp float fluctuations (Figure 2). During later laboratory testing it was found that the Bernoulli effect described above minimizes float bounce, so the dashpot is not necessary.

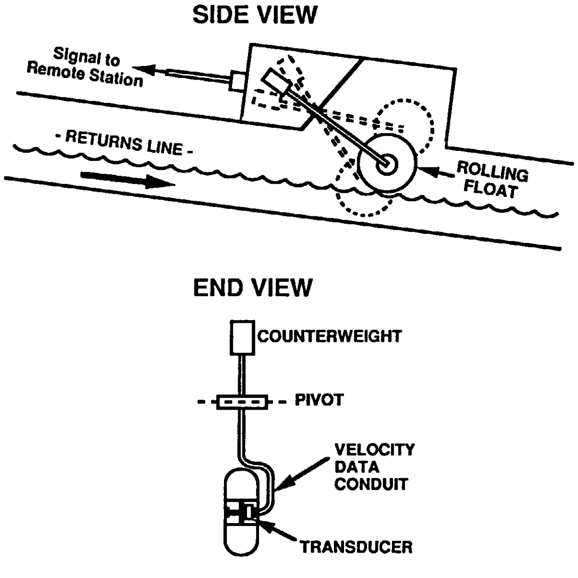

Figure 1 - Schematic of the rolling float meter.

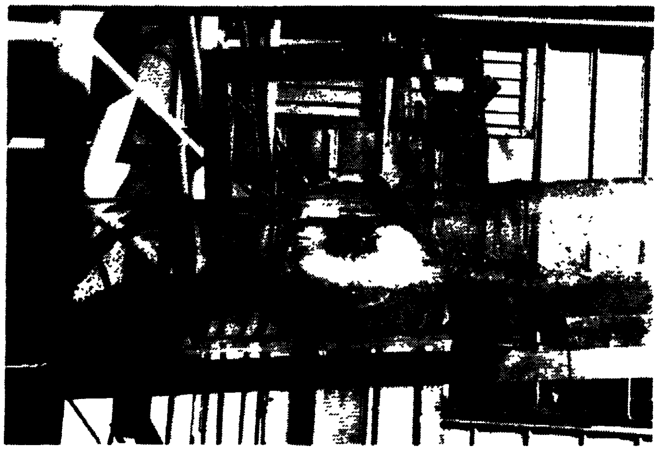

Figure 2 - Photograph of laboratory prototype rolling float meter.

LABORATORY TESTING

A laboratory test facility was built to provide full-scale simulation of a drilling fluid return line for testing of the rolling float meter. The facility employs a 1000-gpm centrifugal slurry pump, which pumps fluid from a mud tank, into a simulated wellbore, and down a 12-ft-long return line. The return line can be adjusted to any angle between 0 and 12.5° with respect to horizontal. During laboratory testing, both a 10-inch, transparent plastic pipe and a 12-inch steel pipe were used as the fluid return line.

During initial development, the rolling float meter was extensively tested in the laboratory. Details of this testing can be found in Refs. 2 and 3; the results will be summarized here. The effects of different rolling float design parameters were evaluated to determine designs for further prototype meters. These parameters included: float cross-sectional shape and traction, pivot arm length, counterbalance weight, and dashpot setting. The meter was tested for response and repeatability under a variety of conditions. After laboratory testing, a field prototype meter was designed. The field prototype meter employs a 3-inch wide oval-shaped float with tread that provides traction; the counterbalance on the float is set with an effective float weight of 20 g. In addition, the length of the pivot arm was found to have little effect of the meter performance, so the field prototype used an arm length suitable for the size of pipe in which it was installed.

Laboratory testing was performed using a transparent plastic return line so that interaction of the meter with the flow could be seen. The rolling float meter was found to have little effect upstream of its location. Downstream, the float produces a plume of fluid as it spins; however, this effect is slight and affects only the fluid within approximately two feet of the meter. The paddlemeter, on the other hand, affects the flow in the return line both upstream and downstream of its location. The paddle protruding into the fluid causes enough flow obstruction to block the flow upstream and accelerate the flow downstream of the meter. At high flow rates, the paddle obstructs the flow area enough that the fluid upstream of the meter completely fills the pipe.

The response of the rolling float meter was tested in both water and drilling mud. In addition, drilling fluid properties were varied and rock chips were added to the flow to determine their effects on the meter height measurements. The rolling float meter height measurements as a functions of flow rate are shown for a variety of drilling fluid viscosities and densities in Figure 3. Changes of fluid properties in this range have very little

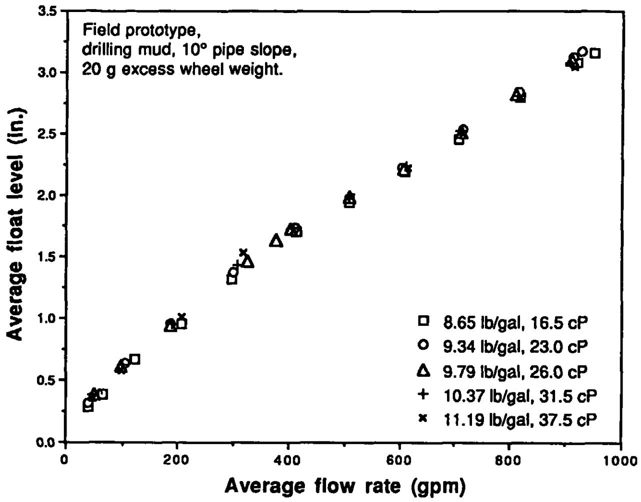

Figure 3 - Rolling float meter response in a variety of drilling muds.

effect on the height measurements. In addition, it was found that the addition of rock chips to the fluid (simulating drill cuttings) also has little effect on the measurements. Although the rolling float meter must be initially calibrated upon installation in a return line, this calibration is independent of fluid properties, which often change over the course of drilling.

FIELD TESTING

The field prototype of the rolling float meter was tested under actual drilling operations during the phase-2 drilling of a joint Department of Energy-State of California exploratory well in Long Valley near Mammoth Lakes, California. Several other commercial inflow and outflow meters were also tested. These included: magnetic flowmeters, pump stroke counters, pump rotary speed transducers, and a Doppler ultrasonic meter on the inflow line; and an acoustic level meter and the conventional paddlemeter on the outflow line. Details of the field testing results can be found in Refs. 2 and 3. Only the outflow meter results will be discussed here.

Since the three outflow meters tested do not directly measure flow rate, they required calibration. The meters were calibrated against the magnetic inflow meters at flow rates ranging from 0-950 gpm. The calibrations were conducted prior to the beginning of drilling, and again after any meter parameter had changed. These calibrations were conducted when pit level indicators showed no loss or gain of fluid.

A calibration of the paddlemeter is shown in Figure 4. The paddlemeter reading was erratic due to the tendency of the paddle to respond to waves in the flow. The apparent scatter in the calibration data was as much as 35% of the average reading. In addition, the paddlemeter response was insensitive to flow rates above 700 gpm. As a result, it was not possible to obtain an accurate calibration with the paddlemeter. The acoustic level meter and rolling float meter did not exhibit these scatter and sensitivity problems, enabling accurate calibrations to be obtained with these meters.

Typical results obtained from the outflow meters under normal drilling conditions are shown in Figure 5. Shown are the measured flow rates from each of the three outflow meters and the magnetic inflow meter. The accuracy of the rolling float

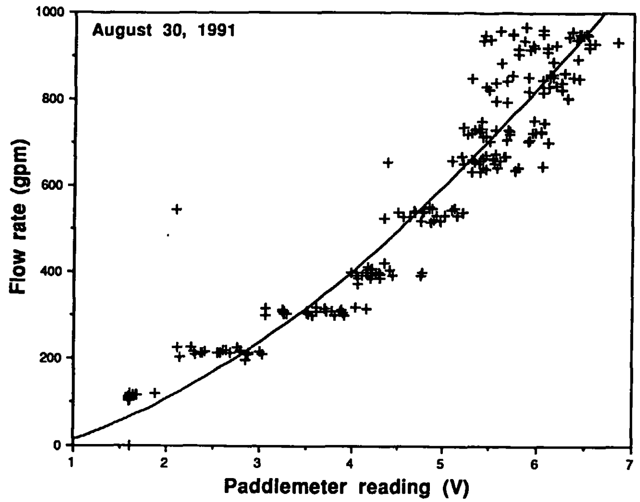

Figure 4 - Paddlemeter calibration against magnetic flowmeter in the field.

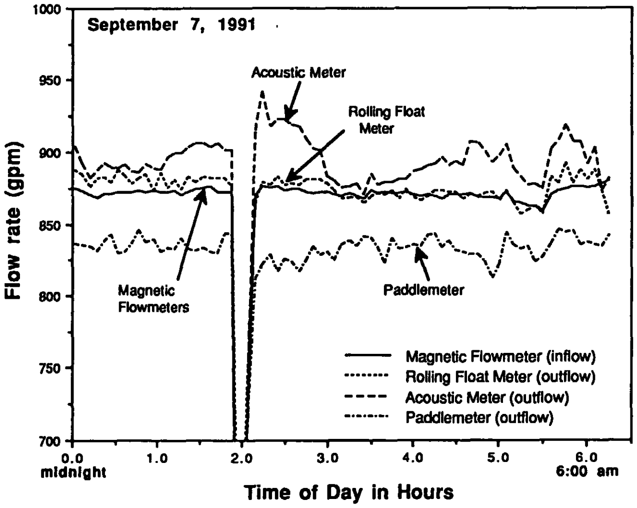

Figure 5 - Comparison of inflow and outflow rates during normal field drilling.

meter was typically within 1/2-2%, and often read within 5 gpm of the magnetic inflow meter at total flow rates over 900 gpm. With regards to the acoustic level meter, the sonic velocity of the air between the flowing mud surface and the acoustic transducer changes with temperature and gas composition. Therefore, while the acoustic meter would read accurately immediately following a calibration, after periods of drilling the meter readings were consistently 2-8% high. To obtain accurate flow rate measurements with the acoustic meter, it would be necessary to monitor the temperature and air composition in the return line. The poor performance of the paddlemeter (±5-15%) was due to scatter in readings and its insensitivity at the higher flow rates as discussed previously.

The rolling float meter successfully detected very small gains and losses of wellbore fluids. Results from each outflow meter during a lost circulation event on August 30-31, 1991, are shown in Figures 6-8. Both the rolling float meter and the acoustic level meter measured a drop in flow rate relative to the magnetic inflow meter readings. According to these meters, the loss began at approximately 6:30 pm on August 30 and ended just after 4:00 am on August 31. Loss rates as high as 56 gpm, or 6% of the inflow, were detected. (The abnormally high rolling float measurement between 4:00 and 6:00 am on August

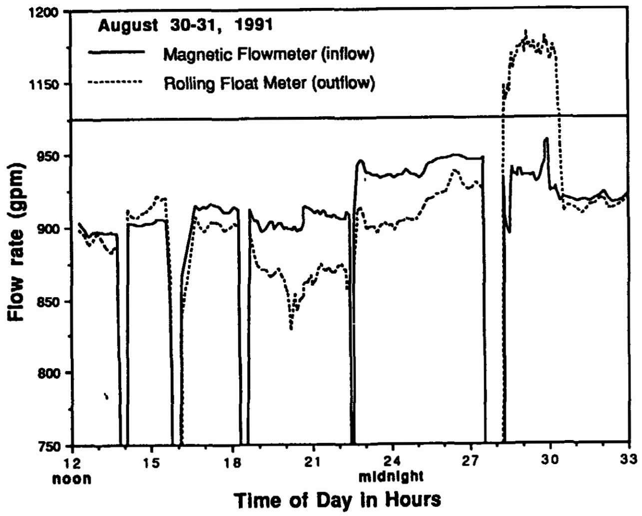

Figure 6 - Rolling float meter response during lost circulation.

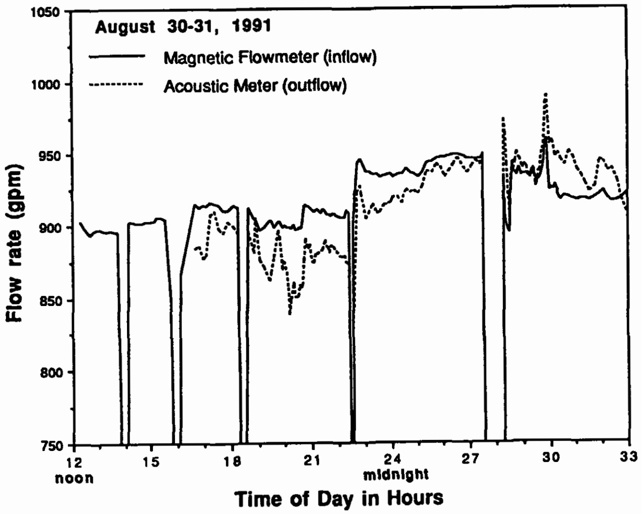

Figure 7 - Acoustic level meter response during lost circulation.

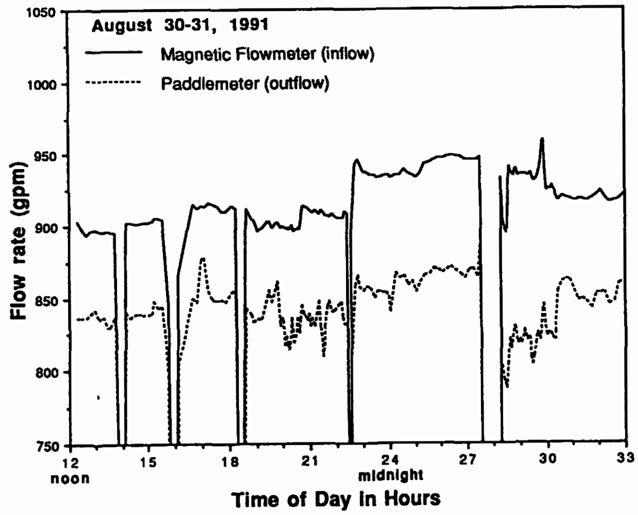

Figure 8 - Paddlemeter response during lost circulation.

31 was due to siezing of one of the float bearings) The drilling crew noted a drop in mud pit level at approximately 9:00 pm, 2 1/2 hours after the outflow meters first detected a loss. The paddlemeter measured a lower flow rate than the magnetic flowmeter throughout this entire time period. The actual loss and subsequent recovery of circulation were not detected by the paddlemeter.

Wellbore fluid production during drilling was detected on September 6 and 7, when the mud logger's pit level report indicated an increase of 200 bbl. The rolling float meter response is shown in Figure 9. The measurements indicated up to 5-6% greater outflow than inflow starting at approximately 2:00 pm and ending near midnight on September 6. Since the acoustic level meter read as much as 7% high throughout the day, the wellbore production of fluid was not distinctly detected with this meter. The same is true for the paddlemeter, which read approximately 5-7% low throughout the entire time period.

Problems with the rolling float meter were encountered during the field test due to its prototype status; however, these problems were addressed during further laboratory development and testing. When the return mud temperature reached approximately 145°F, the sidewalls of the polyethylene float softened sufficiently to warp and become disengaged from the hubs and bearings. To solve this float durability problem, the original polyethylene float was used to fabricate solid polyurethane foam floats of the same size and shape as the original. The foam float has been successfully tested in the laboratory in drilling mud at temperatures up to 195°F. One of the float's bearings also experienced periodic sticking toward the end of the field test period, causing erroneous readings. To address this, a simple, light-weight mud splash guard was incorporated into the axle design to prevent mud from splashing into the bearing regions and causing a potential problem. By preventing mud from accumulating on the bearings, the bearings should have long life since they are subjected to very little load. During laboratory testing, the bearing assembly survived 20 days of continuous spinning in drilling mud at temperatures up to 183°F.

USE OF THE METER IN GEOTHERMAL DRILLING

Optimal use of the rolling float meter would require accurate measurement of inflow rates with a precision magnetic

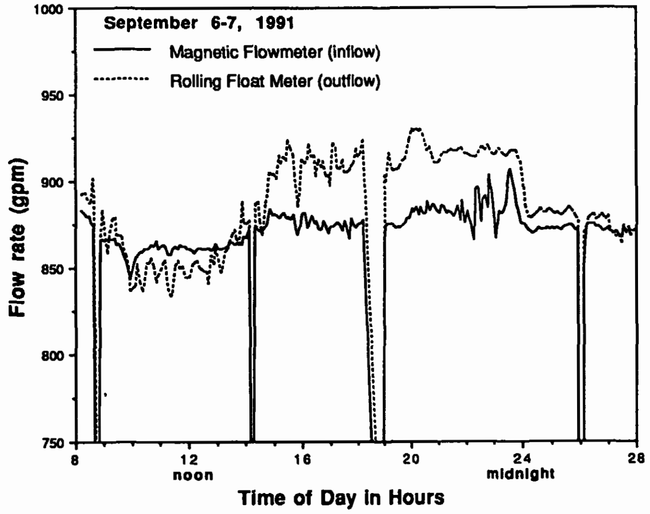

Figure 9 - Rolling float meter response during wellbore fluid production.

flowmeter. The cost of such flowmeters, however, may make them impractical for routine use in geothermal drilling at the present time. Pump speed indicators, such as pump stroke counters and rotary speed transducers, suffer from uncertainties and changes in pump efficiency and, as a result, can sometimes be inaccurate in measuring inflow rates. Clearly, an alternative inflow meter is needed, but until one is available, the only practical alternative for measuring inflow rates during geothermal drilling is the pump speed indicator. The following discussion presents some considerations for using these indicators with the rolling float meter to detect and characterize lost circulation zones encountered in geothermal drilling.

Inflow Rate Measurements

Pump speed indicators provide a measure of the number of pump strokes or rotations per unit time. The volume of fluid pumped with each stroke or rotation is a function of the pump design, which is known, and the pump efficiency, which is generally unknown. Moreover, pump efficiency changes with time. Both stroke counters and rotary speed transducers suffer this same problem; however, it is recommended that rotary speed transducers be used instead of stroke counters whenever possible. The greater resolution offered by a rotary speed transducer results in an inflow rate reading that responds more quickly to actual changes in pump speed. This can be helpful during flowmeter calibration and flow testing operations.

Shown in Figure 10 is the calibration obtained with a drill rig mud pump fitted with a rotary speed transducer and a magnetic flowmeter on its inlet line. The data are linear and exhibit very little scatter. An overall pump efficiency of 96.4% can be derived from this data by comparing the actual flow rate with the theoretical flow rate based on pump speed and finding the least-squares fit of the data. Local variations in pump efficiency range from 93.8% to values greater than 100%. Instantaneous efficiencies greater than 100% are due to transducer measurement error, as well as to the surging nature of the flow. The calibration of a mud pump 22 days later is shown in Figure 11. The pump had been run almost continuously during this drilling period and had been subject to normal maintenance procedures. Although the mean data are still linear, the scatter is significantly greater. The pump efficiency in this case was 92.8% with local variations ranging from 83.5-99.8%.

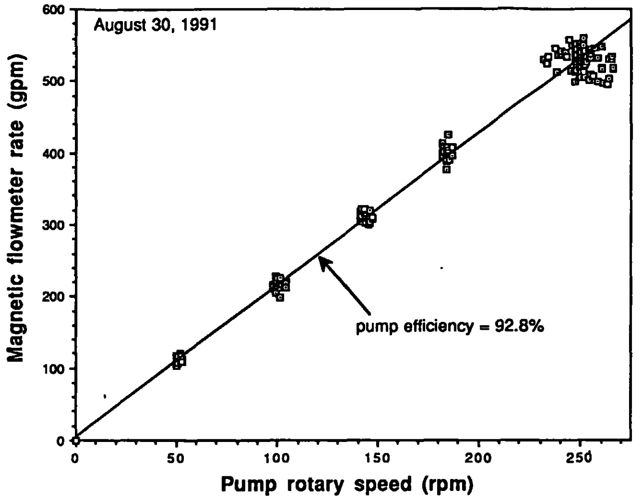

Figure 11 - Pump speed indicator calibration after 22 days of drilling.

The scatter in the calibration data is due to a variability in the efficiency of each stroke, caused by local changes in mud properties, pressure transients, and the interaction of two or more pistons in each pump. This scatter is also apparent in Figure 12, which is a plot of pump efficiency during a twelve-hour drilling period shortly following the calibration shown in Figure 11. A sampling rate of 1 data point per five minutes was used. Note that the scatter in the efficiency is approximately the same as that experienced during the calibration. The data oscillate about a roughly mean level for several hours. Changes in the mean efficiency occur periodically and can be on the order of several percent. Several factors can account for such changes in the mean efficiency, including pump seal wear, general changes in mud properties, and (in the case of worn seals) changes in standpipe pressure.

Each one-percent change in efficiency represents slightly more than a one-percent change in apparent flow rate. A decrease in pump efficiency will be manifested in the delta-flow measurement as an apparent fluid loss. Improved pump efficiency resulting from actions such as rebuilding the mud pump will appear as apparent wellbore fluid production. It is

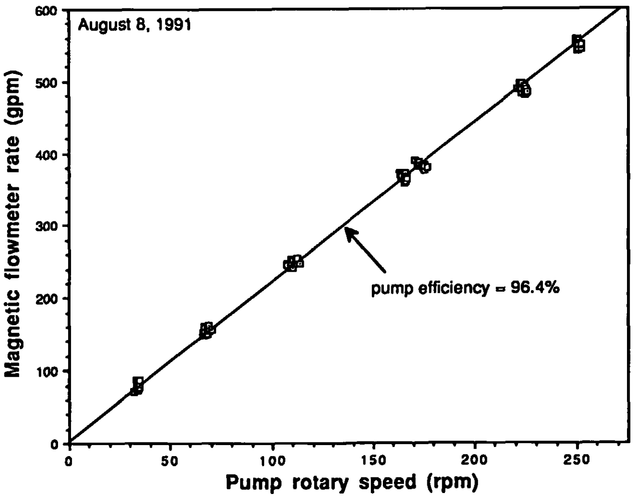

Figure 10 - Pump speed indicator calibration at the beginning of drilling.

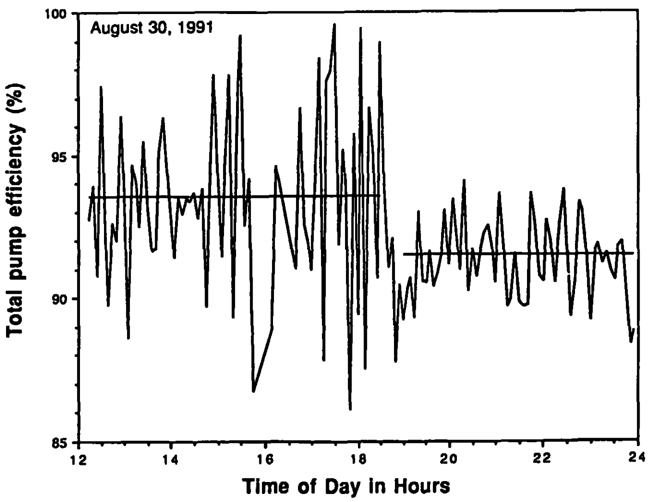

Figure 12 - Typical rig pump efficiency variations during drilling.

essential that significant long-term changes in pump efficiency be factored out of the delta-flow measurements through frequent recalibration.

Flowmeter Calibration for Delta-Flow Measurements

Calibration of the rolling float meter must be performed when no significant fluid loss or gain is occurring. The most certain times for guaranteeing this condition is at the completion of casing runs, before the cement is drilled out of the bottom of the casing. Other calibration opportunities arise during non-drilling periods under stable circulating conditions when mud pit level indicators show no long-term changes in pit level. The rolling float meter does not experience significant long-term drift, but frequent calibration is desirable because of changes in pump efficiency over time. The more often accurate calibrations can be performed, the more sensitive and accurate the detection of loss circulation will be.

The rolling float meter is calibrated against the pump speed indicator by recording the response of both devices at several flow rates over the range of interest. The following calibration procedure is recommended:

1) Select a suitable calibration period according to the criteria discussed above.

2) Select at least four calibration flow rates within the range of inflow rates expected during drilling. The first calibration point should be zero flow, and the last calibration point should be the maximum expected inflow rate The remaining calibration points may be evenly distributed over the range, or they may be clustered in the flow-rate range where most drilling is expected to occur. Although four calibration points are considered necessary for acceptable accuracy, improved accuracy may be attainable in some cases by increasing the number of calibration points beyond four.

3) For each of the selected calibration flow rates (including zero):
   a) Set the mud pump speed to the corresponding level and allow several seconds for flow transients to dissipate.
   b) Record both the pump speed indicator and the rolling float meter responses over several seconds. A data-recording frequency of one data point per channel per second and a recording period of 30 seconds for each calibration flow rate have been successfully used in the past (resulting in 30 calibration points at each nominal flow rate).

4) Assume a nominal pump efficiency (e.g., 0.92) and convert the pump speed indicator data to inflow rates, Q_i, and outflow rates, Q_o, according to the equations:

$$Q_i = \eta \, F_p R_p \; , \qquad (1)$$

$$Q_o = Q_i \; , \qquad (2)$$

where η is the pump efficiency, F_p is the conversion factor between speed and flow rate (e.g., gal/stroke or gal/rev), and R_p is the pump speed indicator reading (e.g., strokes/min or rev/min). The nominal pump efficiency selected is unimportant. An efficiency of one (i.e., 100%) may be assumed, but a slightly lower efficiency is more realistic.

5) Using any available curve-fitting program, fit a third-order polynomial equation to the data of the form:

$$Q_o = A + B\,R_R + C\,R_R^2 + D\,R_R^3 \; , \qquad (3)$$

where R_R is the rolling float meter reading (volts), and A, B, C, and D are constants determined by the curve-fitting program. An example of a calibration curve determined in this manner is shown in Figure 13.

During subsequent operation of the flowmeters, the inflow rate, Q_i, is determined using the pump speed indicator reading and Eq. 1. The outflow rate, Q_o, is determined using the rolling float meter reading and Eq. 3.

The above procedure required approximately 10-15 minutes in the field when using ten calibration flow rates. It is believed that 4-point calibrations could be conducted in less than 5 minutes once they become routine to the driller.

Delta-Flow Rate Monitoring

The detection of lost circulation is best accomplished by plotting the delta-flow rate, ΔQ, from the equation

$$\Delta Q = Q_o - Q_i \; . \qquad (4)$$

The delta-flow rate is therefore positive during wellbore fluid production and negative during lost circulation. This plot should be large enough to allow small point-to-point variations (i.e., scatter) to be easily seen. During normal, steady-state drilling with full fluid returns, ΔQ should oscillate about zero or some other small value, depending on the precision of the calibration at the prevailing flow rate. By examining a long-term plot of ΔQ, sudden and even gradual changes of significance in the delta-flow rate can be visually recognized. Such changes can be caused by three possible conditions: 1) a net gain or loss of fluids downhole; 2) a change in pump efficiency; or 3) drift in the rolling float meter calibration. The character of the delta-flow rate plot should provide some insight to the probable cause.

If the delta-flow rate plot shows a significant, sudden change during drilling, it is probable that a fluid production or loss zone has been encountered. An example of a loss-zone

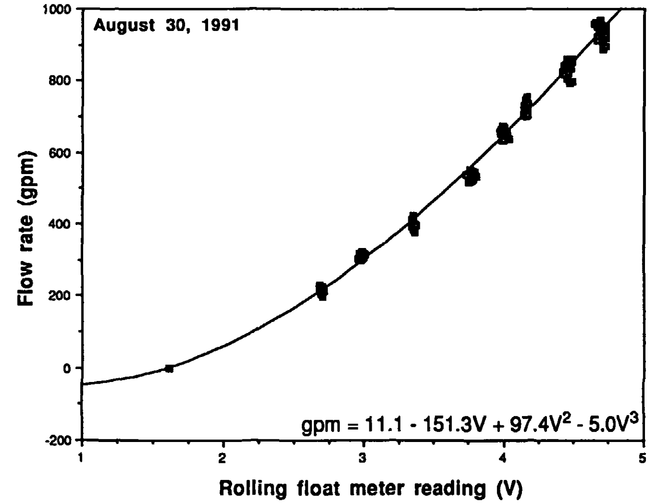

Figure 13 - Rolling float meter calibration against magnetic flowmeter in the field.

encounter is shown in Figure 14. "Significant" in this context means of a magnitude larger than the prevailing scatter in ΔQ and larger than recent changes in the mean ΔQ. In most cases, this probably means changes in ΔQ of 10% or more. "Sudden" in this context means over a period of a few hours or less. Even a single, relatively thin fracture is capable of sustaining a high fluid flow rate if it is permeable and is connected to a formation interval with a pore pressure different from the hydrostatic pressure in the wellbore. At typical drilling rates, once a loss or production zone is first encountered, very little time may be required to penetrate the zone sufficiently to cause significant changes in the delta-flow rate. This contrasts with formation intervals with matrix-dominated permeability, where long intervals may be required to be drilled through before significant losses occur. In either fracture- or matrix-dominated loss or production zones, however, the magnitude of the delta-flow rate should continue to increase as long as penetration of the zone is underway. Once the entire zone is penetrated, the delta-flow rate should stabilize again at some relatively constant level, as seen in Figure 14. This information is useful in severe loss zones because it is generally desirable to drill through the entire loss-zone interval before attempting to seal the zone with a cement plug.

A delta-flow plot which illustrates wellbore fluid production is shown in Figure 15. Fluid production gradually increases over a four-hour period, corresponding to the drilling interval associated with uncovering the production zone. After approximately eight hours of stable fluid influx, changes in formation pressures or drilling fluid weight cause the fluid production to gradually decrease until the zone is no longer producing significant fluid.

Significant, sudden changes in the delta-flow rate are less likely to be caused by changes in pump efficiency or flowmeter calibration drift because these conditions tend to evolve rather slowly. However, at least two exceptions to this rule exist:

1) Sudden changes in pump efficiency due to mud problems (e.g., foaming) or pump problems (e.g., plugged inlets or seal wear). Such problems generally cause a reduction in pump efficiency, which is manifested in the delta-flow rate as a fluid loss. An example from actual field data is provided in Figure 16, where foaming of the mud caused dramatic reductions in the ability of the pump to efficiently pump the mud. Such problems are generally accompanied by reductions in the standpipe pressure because of the lower pressure drops throughout the pumping system resulting from the reduced inflow rates.

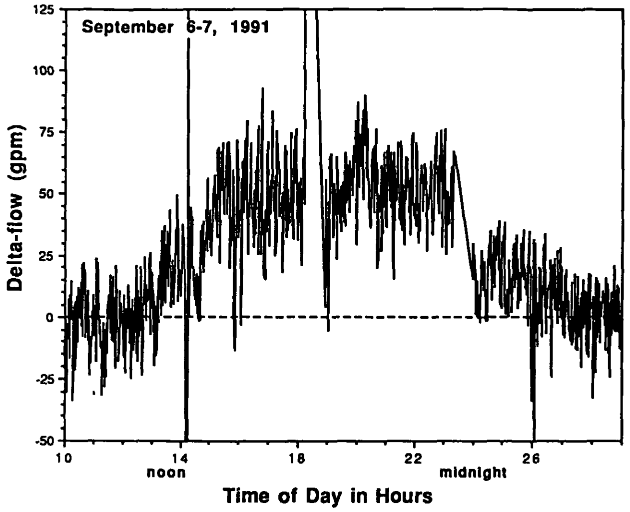

Figure 15 - Delta-flow rate measurements during wellbore fluid production.

2) Sudden seizing of a bearing on the rolling float meter. When this happens, the float stops spinning and tends to ride higher in the fluid, producing a higher reading than the actual flow rate. In the first field test with the rolling float meter, this problem was periodically encountered for brief periods with a bearing that was possibly damaged during installation. In those cases, the rolling float meter reading underwent a sudden 20% increase that was quite distinct on the flow rate record, as seen in Figures 6 and 14. This condition is therefore easily recognizable and in any case produces a flowmeter response opposite to that experienced with lost circulation. The condition could more easily be mistaken for a sudden influx of fluid into the wellbore.

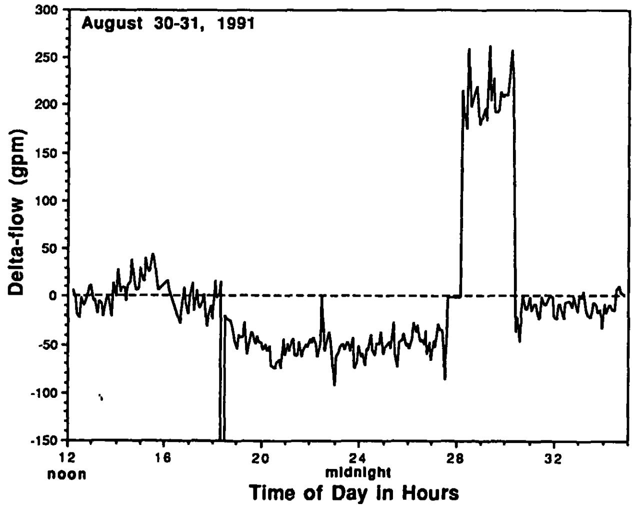

Figure 14 - Delta-flow rate measurements during lost circulation.

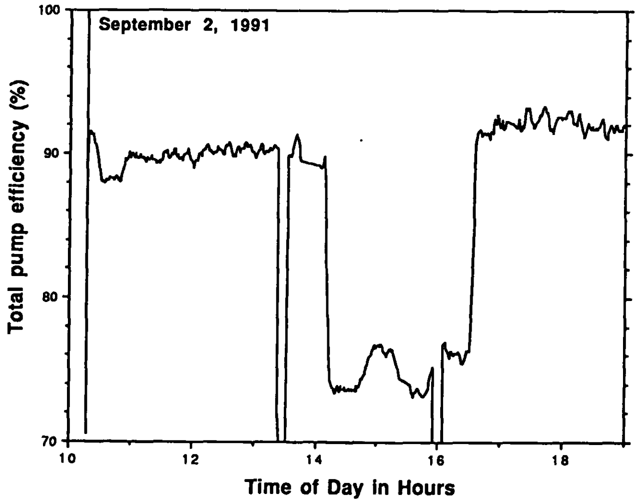

Figure 16 - Pump efficiency variations due to mud foaming.

However, the mud splash guards previously described were added since the first field test and have been shown to prevent long-term bearing degradation in high-temperature muds, so this condition should not be frequently encountered.

Gradual but significant changes in the delta-flow rate are more difficult to diagnose. To rule out inaccuracies in the calibration equation as the cause, the mud pump should be run at a speed corresponding to a calibration flow rate in the most recent calibration. If the indicated delta-flow rate is still significant, careful monitoring of the mud pit level indicators will determine whether the fluid loss is real or changes in pump efficiency or flowmeter calibration have occurred. Recalibration of the rolling float meter may be in order if either of the latter two causes are deemed responsible for the delta-flow rate.

In addition to detecting the onset of lost circulation and providing an indication of when a loss zone has been fully penetrated, the delta-flow measurement can be used to help evaluate the effectiveness of lost circulation treatments. Lost circulation materials (LCMs) added to the drilling mud are capable of providing sealing of porous and finely fractured loss zones. Because the bridging process is rapid once the LCM particles reach the plugging site, the successful development of such a plug should result in a sudden change in the delta-flow rate measurement. A trial-and-error approach starting with smaller bridging particles, evaluating any changes in delta flow, and progressing to the largest particles that can be pumped through the bit nozzles may be successful in providing a temporary or permanent plug under favorable conditions. Selection criteria for LCM bridging particles are discussed in Ref. 4.

Under extreme lost circulation conditions, the effectiveness of a cement plug is generally tested after the cement has set and before the open-end drill pipe is tripped out of the hole. This is done to determine the need for a second cement plug before drilling proceeds. A comparison of delta-flow measurements obtained before encountering the loss zone with those obtained before and after setting of the first cement plug can help in this evaluation. As with all the applications discussed above, changes in the delta-flow rate measurements are more important than the absolute values of the delta-flow rate itself.

SUMMARY

A meter has been developed for measuring fluid flow rates in the return line of a drilling rig. The meter employs a rolling float that rides on the surface and tracks the height of the fluid in the line, which can be calibrated to fluid flow rate. The meter was extensively tested in a laboratory facility simulating a full-scale drilling fluid return line. Several design parameters were optimized during laboratory testing to develop a field prototype of the meter. The prototype rolling float meter, as well as several other commercial inflow and outflow meters, were tested during actual drilling operations at the Long Valley Exploratory Well near Mammoth Lakes, California. The rolling float meter proved to be more accurate than both an acoustic level meter and a paddlemeter, and the rolling float meter distinctly captured periods of minor lost circulation as well as wellbore fluid production. Rolling float meter design problems apparent during field testing were solved during subsequent laboratory development and testing.

A method for utilizing the rolling float meter outflow measurements combined with pump speed inflow measurements has been proposed for use in diagnosing lost circulation in geothermal drilling. The rolling float meter is initially calibrated against the inflow rate measurements from the pump stroke rate using an assumed pump efficiency. Delta-flow (outflow minus inflow) is then monitored; abrupt losses or gains of fluid are readily apparent, as well as the loss and subsequent recovery or continual loss. This information can be used to detect the onset of lost circulation, estimate the relative severity of the loss zone, determine when the loss zone has been fully penetrated, and provide an immediate indication of the degree of success of treatments such as LCM pills and cement plugs. Meter recalibrations are periodically performed to account for long-term drift in the response of the flowmeters.

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NOMENCLATURE

A	constant in rolling float meter calibration equation
B	constant in rolling float meter calibration equation
C	constant in rolling float meter calibration equation
D	constant in rolling float meter calibration equation
F_p	pump conversion factor, gallons/stroke or gallons/rev
η	mud pump efficiency (actual/theoretical volume per stroke or volume per revolution)
Q_i	well inflow rate during drilling, gpm
Q_o	well outflow rate during drilling, gpm
ΔQ	delta-flow rate (outflow-inflow), gpm
R_p	pump speed indicator reading, strokes/min or rev/min
R_R	rolling float meter reading, volts

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