ABSTRACT

Measurement of return mud flow is the single most diagnostic indicator of potential well control and lost circulation problems during drilling operations. To date, except for electromagnetic induction flowmeters, which can only be applied for conductive drilling fluids, it has not been possible to have access to accurate measurements of return mud flow rate over a wide range of drilling fluid properties and adverse conditions such as drilling through gumbo shale, gas cut mud and other non ideal conditions.

This paper describes the design, development and field testing of a full bore mass flowmeter based on the measurement of forces generated due to change in momentum of the return flow stream. This is accomplished by attaching a short J-shaped extension to the return flow line just before the shale shaker. This extension is instrumented with force sensors that measure forces caused by the flowing fluid.

The first generation prototype has been extensively tested in the laboratory and in the field over a range of flow rates up to 1700 GPM and over wide ranges of mud weights.

Results indicate that the flowmeter has performed successfully under adverse field conditions for extended periods of time without the need of extensive modification of the existing mud flow system.

INTRODUCTION

It is essential for the safety of the drilling operation that any influx of gas or liquid from the formations below or losses of drilling fluid are detected promptly and recorded accurately. Up to this date, however, flowmeters have not been able to accurately record the flow rate of the returning mud. The main reason for this difficulty is that mud is a dirty, sticky and non-linear-viscous liquid, and measured parameters such as mud level inside the return pipe, surface velocity of the mud, drag forces on immersed bodies, etc. are not directly convertible to flow rate over the practical range of mud properties.

Presently there are two exceptions; one being the electromagnetic flow meter\(^1\) and the second an ultrasonic doppler meter \(^2\). Two important disadvantages severely limit application of the electromagnetic flowmeter: it does not work with oil based mud because the fluid is non-conductive, and since one of the requirements for correct operation is a liquid-filled pipe, the return flow line needs to be of a U- tube shape.
Also, if the mud is gas cut to a certain extent the electromagnetic flowmeter will give erroneous readings.

The newly developed full bore flowmeter \[^2\] , which works both with water and oil mud, is based on two measurements: the liquid level in the return flow line and the velocity of the mud at a fixed distance from the bottom of the flow line. From these the flow rate is estimated assuming a fixed velocity profile. This meter is therefore subject to possible inaccuracies if the actual velocity profile deviates from the theoretical flow description.

In 1983 STATOIL initiated a project aiming towards the evaluation and testing of a new principle for recording mud flow rate, an idea patented by PETRECO. The principle can be applied to any flow of either gas, liquid or solids, and application to return mud flow measurements requires only minor modifications of the flow line. Preliminary laboratory tests during 1984-85 were promising and it was decided to build a prototype, test it and install it on the semi submersible ROSS ISLE for further field tests in the North Sea during 1986-87.

**DESIGN PRINCIPLE**

The principle upon which the flowmeter is based is the measurement of forces generated by changes in the momentum of the flowing mud caused by changing the direction of flow through a bend in the pipe. In the specific case of the return mud flowmeter the last 6 feet of the flow line is separated from the rest by a flexible universal joint. This last part of the flow line is formed like a "J".

The momentum force created by the fluid flowing in the bend of the pipe, is recorded by a load cell, as shown in fig. 1. The momentum force can be expressed as shown in equation (1):

\[
F_M = K_1 \rho V^2 \lambda
\]

where \( F_M \) = momentum force
\( K_1 \) = constant
\( V \) = velocity
\( A \) = cross sectional area
\( \rho \) = density
\( \lambda \) = filled portion of J-pipe

In equation (1) the liquid mass flow rate may in itself be expressed as

\[
Q = VA \lambda
\]

in which \( A \) is the cross section of the J-pipe. In order to know the amount of mass \( \rho A \lambda \) at any time in the J-pipe, the degree to which the pipe section is filled with mud \( A \lambda \) must be recorded. This is done by means of a weight sensor, and the resulting force is estimated in equation (3)

\[
F_W = K_2 g \rho L A \lambda
\]

where \( g \) = acceleration due to gravity
\( K_2 \) = constant
\( L \) = length of J-pipe

The density of the fluid must be known or measured either with a gamma ray densitometer or with a mud balance. Because of the low density of the gas in gas cut mud gas will not cause error in the flow readings if a pressurized density value is fed into the computer. The change of velocity in the x-direction, \( \Delta v_x \), depends on the angle of the "J" and the velocity itself as shown in fig. 1.

Based on these principles the first prototype was built with the objective to provide data and performance information so that the following tasks could be undertaken:

a) to build a full scale unit to be installed on a floating drilling rig;
c) to modify and improve both the mechanical construction and the electronic unit of the prototype, in order to achieve higher reliability and accuracy.

FLOWMETER DESIGN AND OPERATION

The unit described here is a version resulting from extensive tests and experience gained both in the lab and the field. The tests have resulted in development of a completely new electric unit and major changes of the mechanical design.

Mechanical design

A typical J-meter is composed of five main parts. These are the load cells, the flange end, the universal joint with flexible seal, the cover and finally the J-pipe as shown in fig. 2. The dimension of the J-pipe is 12" ID, which matches the flow line on the ROSS ISLE drilling rig.

As shown in fig. 3, the universal joint that connects the J-pipe with the flange end consists of four blade springs, a flexible seal and a universal link or chain ring. Two of the blade springs connect the flange end with the ring, and the other two connect the ring further to the J-pipe. The springs are mounted so that each plane through two of the blades is perpendicular to the direction of each of the forces; gravity and momentum force.

The steel cover protects the J-pipe, the load cells and their wiring, and also extends the base of the load cells to the flange end. The cover is connected to the flange end with three bolts.

Two forces are recorded by strain gage load cells with a range of 0 - 500 N (112.4 lbf) for the momentum force and 0 - 2000 N (449.6 lbf) for the weight. This enables the measurement of a water flow rate of approximately 5000 l/min (1321 GPM), and for mud of density 2.0 kg/l (16.7 PPG) a flow rate of 2500 l/min (660 GPM). Since the sensors should not be exposed to excessive forces the instrument is equipped with over-load safety bolts which block the J-pipe when the full scale force is reached.

The mechanical design of the J-meter is very simple. However, the development and testing has shown that the repeatability and accuracy is greatly affected by some vital details.

The mounting of the J-meter should in essence be horizontal, however, slopes of 1 - 10 degrees will not alter its accuracy with any significance.

Electronic system

The first version of the electronic unit was found to be unsuited for field use during the preliminary tests. Any changes or adjustments of the hardware (universal joint, load cells) after a calibration procedure, required the software to be reprogrammed; besides, too many manual operations were necessary during adjustments in the electronics. Based on this experience and some of the experience gained from a shallow gas blowout, some important design principles for the electronic package were identified.

1. All changes of operational type should possibly be carried out through software.
2. It should be possible to receive at least 6 analog input signals.
3. Changes in signal processing should be carried out via the computer program.
4. Continuous memory is required in case the electric power on the rig should fail.
5. A printer for continuous storing and dumping of signals is required.
6. For ease of interpretation the flow data should also be displayed as histograms showing the difference between flow in and out versus time.
7. A "flight recorder" function should store the last 48 hrs of data and automatically dump the last 1/2 hours of flow rate data to a printer in case of alarms.

An overview of the electronic system is shown in fig. 4. The load cells, filters and amplifiers are standard equipment (Bofors Electronik). The load cells are connected to the amplifiers via a six conductor cable protected with Zener-barriers. Amplifiers and Zener-
barriers are mounted in a separate box outside explosion hazard Zone 1. The output from the amplifiers is 4 - 20 mA, which corresponds to the lowest and highest force on each of the two load cells. The two signals are collected by the computer AWACS (Analog Warning And Control System).

The front and back panel of the computer are shown in fig. 5. On the back panel several multi-pin terminals are seen. AWACS receives the signals from the load cells, the densitometer and the pump flowmeter and converts them to digital values. The AWACS is designed in a modular form and may easily be expanded to other purposes by building more modules into the computer or just plugging more external units to it as indicated in fig. 4 and fig. 5. The AWACS is equipped with a long lasting back-up battery package in order to maintain its continuous memory.

When the AWACS is turned on the main menu appears, displaying the following sub menus:

- Alarm reset
- Operation menu
- Display menu
- System menu 1
- System menu 2

It takes about 15 minutes for a new user to become familiar with the use of AWACS. The same goes for calibration of the J-meter on location. This is done by setting the appropriate constants into AWACS using the menus. A menu or a function in the sub menu is chosen by moving the cursor with the arrow keys and pressing ENTER when appropriate.

By choosing Alarm reset all the alarms are shut off. The alarms are activated when a preset difference between pump rate (flow rate in) and return flow rate is exceeded. Via the relay outputs, different alarms may be selected such as horns or flashing lights. The word ALARM is simultaneously displayed.

The Operation menu lists the operations that the user most commonly undertakes:

- set time constant
- set alarm
- set alarm delay
- print
- stop print

The set time constant may be chosen as a value between 1 and 100 seconds and indicates the time period over which the signal representing the flow difference should be averaged. If the difference between the return flow and the pump rate is larger than the alarm limit, then the alarm activates after a preset delay. The alarm delay is important when changing the pump rate. This change will normally cause a temporary large difference between flow in and out, and without the delay the alarm would be triggered unnecessarily.

All data concerning flow in and out of the well over the last 48 hours are logged twice every minute and stored in the AWACS. By choosing print, these data will be printed out. If an alarm condition should occur, this also causes the flow information for the last half an hour to be printed out automatically.

After selecting the Display menu one may choose between four ways of graphically presenting the delta-flow vs. time histogram.

Using System menu 1 all the constants necessary to calibrate the J-meter, the pump rate and the fluid density are set. Through the sub menu, "Autozero", the load cells on the J-meter are zeroed automatically.

In System menu 2 it is possible to choose between two serial or parallel type printers, to set the time and to display the four analog signals overlaying the histogram presentation of delta flow. The latter function is very handy when checking the functioning of sensors and electrical connections, drift and variations, and also for adjusting the J-meter.
TESTING OF THE J-METER

In order to test the J-meter after proving the feasibility of the concept, it was decided to put it out in the field as early as possible, in this way gearing the development quickly towards the tough offshore environment, and gaining general field experience. To make preliminary tests of the prototype and later tests during the progress of the instrument, two laboratory flow loops were built one of which, in fact, was a full scale copy of the return flow line on ROSS ISLE.

Laboratory flow loop and tests

A sketch of the flow loop is shown in fig. 6. The mud pump is a centrifugal pump with a maximum flow rate of 6434 l/min (1700 GPM) at 2 bar (30 psi). To control the function of the J-meter a 6" electromagnetic flowmeter working on a filled section of the pipe was used. Variations in the returning flow rate sometimes occurring on a floating rig were simulated by regulating the pump flow rate with a computer controlled air operated butterfly valve. By injecting batches of compressed air into the loop ahead of the surge tank it was possible to simulate gas bubbles migrating through the mud and pushing out large volumes of mud down the flowline.

The laboratory tests were performed with flow rates from 0 to 6434 l/min (0 to 1700 GPM), and with mud weights from 1.0 to 1.5 kg/l (8.5 to 12.5 PPG). The laboratory tests showed that the J-meter measured the flow rate with an absolute accuracy of ±50 l/min (13.2 GPM) over the whole range of flow rates. This is of the order of ±1%.

Tests on board ROSS ISLE

The rig: The first prototype J-meter was installed on the semisubmersible ROSS ISLE in 1985. However, because of problems with the AWACS it was then operated using an off the shelf PC. The last section of the return flow line was slightly altered to allow for the extra curve in the J-pipe. In the beginning of the first test period practical problems were encountered because no person on board the rig was assigned to the job of maintaining the J-meter. Mechanical failures, such as a broken link between J-pipe and the load cell led to breakdown of the meter. However, since this caused no changes in the flow, the J-meter was just left alone until PETRECO personnel again visited the rig. The technical side of the problem was quickly solved by changing the link, and the administrative side was solved after involving the mud logging company on board Ross Isle in the evaluation study.

Calibration and testing: After field installation of the J-meter the next task was to accurately calibrate the instrument. Initial measurements on the rig gave results that were not of the same quality as those observed in the lab. The inaccuracy was found to be caused by the different flow path and liquid fill-up inside the J-pipe compared to when installed in the laboratory flow loop. The flow characteristics will vary slightly as a function of slope of the flow line, type of bend, the number of branches, valves etc. The slope difference between the rig and the lab installation of only a few degrees was sufficient to cause different results. This caused no further problems as the flow rate could easily be calibrated against the mud pump and/or an electromagnetic flowmeter on the stand pipe. The field installation is shown schematically in fig. 7.

Due to rig motions and the absence of filtering of the raw signal from the load cells prior to the calibration, it was a time consuming process to adjust the zero values of the transducers. Hence, this operation gave valuable input to the design of the second generation AWACS which includes the filtering capability.

After calibrating the J-meter it was tested for a variety of flow rates, and mud weights during the next months with both oil and water based muds. In fig. 8 and fig. 9 typical readings from the J-meter are shown and compared to the mud flow into the well. Variation in flow out of the well during a stable drilling period (fig. 9) is interpreted in fig. 10, which is an enlarged section of fig. 9. Here it is indicated that the main reason for delta flow is the flow lag time through the well and the flow line. Set alarm delay will suppress alarms caused by these high frequency variations. In fig. 11 a similar comparison as in fig. 8 is made for the paddle type return flowmeter.
Given the crew's typical skepticism to new equipment, two different tests were performed to test the meter's sensitivity and accuracy. During the first test the pump speed was increased by an unknown number of SPM's. The object of the test was to determine the pump speed by means of the J-meter. Based on the J-meter return flow and the volume per stroke, the pump speed was calculated to be 224 SPM. Readings on the drill floor showed 226 SPM.

The second test was performed after simultaneously starting two stop watches, one on the drill floor the other in the mud logging unit. The pump speed was to be changed at some unknown time from 112 SPM to 114 SPM. This change was detected by the J-meter down in the mud logging unit 2 min and 17 s after time zero. The actual change had taken place at 1 min and 40 seconds. Considering the small flow rate change of only 27 l/min (7 GPM) and that the signal was filtered with a time constant of 30 seconds, this behavior was found to be quite impressive.

Mechanical problems: In the Central North Sea, gumbo shales are often encountered, and the flow line often gets plugged. To clean out the clay, once the J-meter had to be subjected to what could be called severe mistreatment. The wire connecting the load cell to the J-pipe broke off and one load cell was permanently bent. After having made a new link between the load cell and the pipe from a chain as well as adjusting the over-load safety bolts, the J-meter was tested again. Even though the momentum cell was permanently bent, showing a force of 105 N at zero load, this offset was zeroed out and the J-meter was back in operation after only 30 minutes of work. The overload safety bolts were then tested by having a man standing on top of the J-meter.

At one time the J-meter showed gradually increasing flow rate, caused by a slow build up of dried mud on the outside of the J-pipe. This problem has now been solved by using an extended cover to protect the J-pipe from splashing mud. No serious build up of material has been observed inside the pipe.

After the modifications, the J-meter functioned well even with large amounts of gumbo clay coming through. At one occasion, however, large quantities of gumbo clay was being produced and accumulated on top of the shale shakers to such an extent that the flow also went backwards and in between the cover and J-pipe. This was not cleaned properly at first and the flowmeter showed erroneous flow values.

Problems Related to Offshore Operations: During periods with heave, pitch (1.5 degree) and roll, the instantaneous flow rate was observed to vary significantly since the flowline axis is perpendicular to the rig's longitudinal axis. However, the accuracy of the average flow rate was unaffected due to the use of filtering and averaging of the raw signal.

Summary: After almost two years of field testing was found that the following modifications were necessary to implement a better instrument, especially with respect to the reduction of mechanical problems.

1. The weight of the J-pipe should be minimized to further reduce sensitivity to heave, pitch, and roll.
2. The J-pipe must be protected against mud accumulations on the outside due to splashing.
3. The load cells should be standardized, resulting in easier maintenance.
4. Better overload safety system should be designed.
5. Stainless steel construction is necessary to increase the instrument's life and reduce corrosion related problems.

These modifications have been implemented in a second generation prototype which is currently being field tested in the North Sea.

Further applications:

Other potential applications for the flowmeter, besides detecting volumetric instabilities in the flow system, include keeping track of the mud return volume during a cement job. Volumetric control during a normal primary cement job is inadequate since currently the return flow rate is not monitored. It is difficult to detect if some of the cement slurry is lost due to fracturing of the formation. This is especially the case when cementing liners. With an accurate
flowmeter on the return line, the quality of the cement job could be better evaluated.

CONCLUSIONS

A new flowmeter for measuring and recording the return mud in an "atmospheric" flow line has been developed. The existing flowmeter is now of an industrially acceptable standard and can be installed on existing mud return flowlines with only minor modifications. Extended field tests have proven the meter to be adequately rugged and easy to maintain.

The overall accuracy of the flowmeter is approximately ± 1% of the full range flow rate, the full range being 1700 GPM for mud weights in the range between 1.0 and 1.5 kg/l (8.5 and 12.5 PPG). This accuracy, however, is hard to confirm on a platform where the reference flow readings in some cases are of uncertain quality.

Field tests have shown that the instrument has adequate sensitivity to detect small changes in return mud flow associated with normal drilling operations such as making connections and reciprocating pipe as well as small variations due to changes in pumping speed.

After field calibration, the instrument readings compare favorably with measurements obtained from electromagnetic flowmeter installed at the standpipe.

Signal filtering and averaging has proven effective in reducing the sensitivity of the meter to vessel motions.

ACKNOWLEDGEMENT

The Authors express their gratitude to STATOIL for supporting this research and for permission to publish this information.

REFERENCES


Fig. 1—Vertical and horizontal projections of the J-meter showing the design principle.

Fig. 2—Vertical projection of the J-meter showing supports and connection to the return mud flowline.

Fig. 3—Section through the universal joint.

Fig. 4—Block diagram of the electronic system.

Fig. 5—Schematic diagram of the front and back panels of the sensing warning and control system (AWACS). The letters C and E on the panel mean clear and enter, respectively.
Fig. 6—The laboratory flow loop.

Fig. 7—Rig schematic showing location of the J-meter and the electromagnetic flowmeter used in the field tests.

Fig. 8—Comparison of mud flow in (electromagnetic) and mud flow out (J-meter) showing sensitivity to lost circulation.
Fig. 9—Typical flow recordings by means of the J-meter on board ROSS ISLE, compared with the pump flow rate (electromagnetic flow meter) during a stable drilling period.

Fig. 10—Enlarged portion of J-meter flow, taken from Fig. 9 at approximately 12:20 hours.