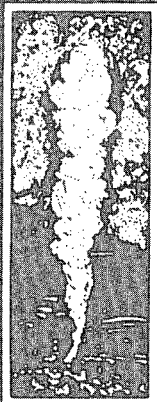


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THE DEVELOPMENT AND USE OF A HIGH TEMPERATURE DOWNHOLE FLOWMETER FOR GEOTHERMAL WELL LOGGING

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ABSTRACT

This paper discusses the development and use of a high temperature (300°C) downhole flowmeter for geothermal well logging. The availability of the instrument gives the reservoir engineer a powerful tool for formation evaluation and studying wellbore dynamics. The instrument components, their function, and temperature limitations are discussed in detail. Several field examples of spinner log interpretation are also presented.

INTRODUCTION

The Earth Sciences Division at the Lawrence Berkeley Laboratory has developed a reliable high temperature (300°C) downhole flowmeter. The utility of downhole flowmeters for locating production and injection zones in petroleum reservoirs has resulted in their use for many years. The high temperatures, corrosive brines and very high fluid velocities encountered in geothermal wells prohibited the use of conventional downhole flowmeters. In the mid 1970's both the U.S. government and private industry put a significant effort into developing high temperature instruments (including downhole flowmeters) suitable for use in geothermal wells (Veneruso et al, 1979; Lawton et al, 1982). This ongoing effort has resulted in the development and testing of high temperature components and instruments. However, the difficulty in making reliable high temperature instruments persists. Using a very simple design concept and a minimum of downhole electronic components, a successful design for a reliable high temperature (300°C) downhole flowmeter (spinner) has been realized. The availability of a high temperature spinner has demonstrated its use for several purposes:

- 1) Locating production and injection zones;
- 2) Indicating changes in production and injection zones resulting from acidizing or fracturing;
- 3) Locating the flashpoint or bubble point in a wellbore;
- 4) Reflecting scale buildup, casing damage, plugged perforations or thief zones.

To make downhole measurements, the flowmeter is attached to a high temperature single conductor armored logging cable. It is lowered into the well with a conventional logging hoist. As the flowmeter is lowered into the well, the vertical fluid velocity causes an impeller to rotate. The rotational speed is sensed and recorded at the surface. Changes in the vertical fluid velocity can be used to indicate the items previously mentioned.

BACKGROUND

A general utility geothermal downhole flowmeter should have a temperature rating of at least 300°C and an operating pressure of 10,000 psi. In 1977, when research in this area began, the only high temperature downhole flowmeter available was a subsurface recording unit with a temperature rating of 260°C (Kuster). A stylus would scribe a number of marks on a metal chart located inside the body of the flowmeter. Each mark on the chart represented a certain number of turns of the impeller. A survey would require making stops of equal length in time at various well depths, never knowing if the instrument was still functioning or if zones of interest had been located and properly identified. Other downhole flowmeters had been used extensively in oil wells but were not well suited for the high temperatures in geothermal wells. Most of these

used pivot bearings and had rather sophisticated downhole electronics. The downhole electronic packages typically had a maximum temperature rating of 177°C. Due to the high wellbore velocities, thermal and mechanical shock, scaling and the corrosive nature of geothermal fluids, conventional pivot bearings and unprotected ball bearings were unreliable.

FLOWMETER

The basic concept of the spinner is that the fluid flowing up or down a wellbore and passing through the flow passage of the instrument will rotate the impeller inside the flowmeter at a rate that is proportional to the fluid velocity. The impeller in turn rotates a magnet assembly. The rotating magnet opens and closes a reed switch, thus generating a frequency signal which is recorded electronically at the surface. The frequency signal is proportional to the number of revolutions per minute at which the impeller is rotating. The spinner rotates at approximately 150 revolutions per minute for each foot per second of fluid velocity (for liquid water). The volumetric flowrate is calculated by multiplying the measured fluid velocity by the cross-sectional area of the bore. A photograph of the flowmeter is shown in Figure 1. The total length of the instrument is 2 feet and its maximum outside diameter is 2 inches without the centralizer. The flowmeter makes a pressure tight connection to a high temperature cablehead with the aid of metal to metal seals and high temperature elastomer o-ring seals.

Components

Table 1 lists the major components used in the instrument. The advantages of these components in hostile downhole conditions are discussed below. Downhole geothermal environments are particularly harsh on instruments due to:

- 1) High temperatures;
- 2) Corrosive liquids and gases;
- 3) Scale formation;
- 4) Sand production;
- 5) Very high fluid velocities in the flash zones.

To design and fabricate a high temperature flowmeter that will function reliably under these conditions, several design criteria must be met. First, the downhole electronics should be simple and function reliably at high temperatures. Second, the bearings must be shock resistant, have a high operating temperature and be protected from the geothermal brine. Finally, all components exposed to the brine must be corrosion and abrasion resistant in the operating environment.

The first objective was accomplished by using a reed switch* to sense the rotation of the impeller. This simple device eliminates the need for any active downhole electronics such as voltage regulators, voltage to frequency converters or signal amplifiers which may be temperature sensitive. The reed switch assembly operates in the following manner. The reed switch, enclosed in a stainless steel tube, is placed in close proximity to a magnet which is fastened to the top of the shaft (Figure 2). As the impeller rotates it opens and closes the reed switch. This creates a frequency signal which can be monitored and recorded at the surface. Two types of bearings are frequently used in downhole flowmeters, pivot bearings and ball bearings. Pivot bearings are more commonly used in conventional flowmeters but for the reasons discussed previously they may not be best suited for geothermal applications. Ball bearings, if kept clean and well lubricated will function extremely

*A reed switch is a passive electronic device. It has electrically insulated contacts that can be made to close by passing a magnetic field in close proximity of the device, and will open when the magnetic field is removed.

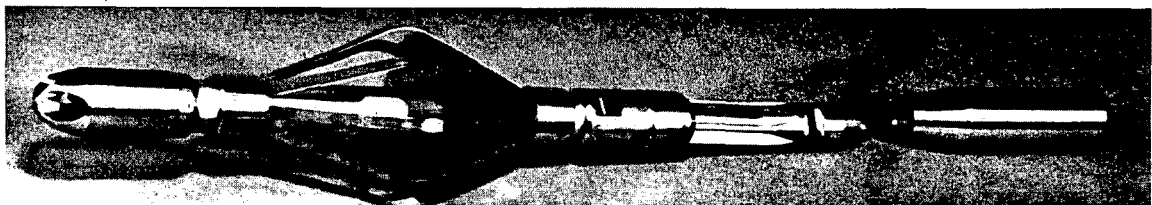
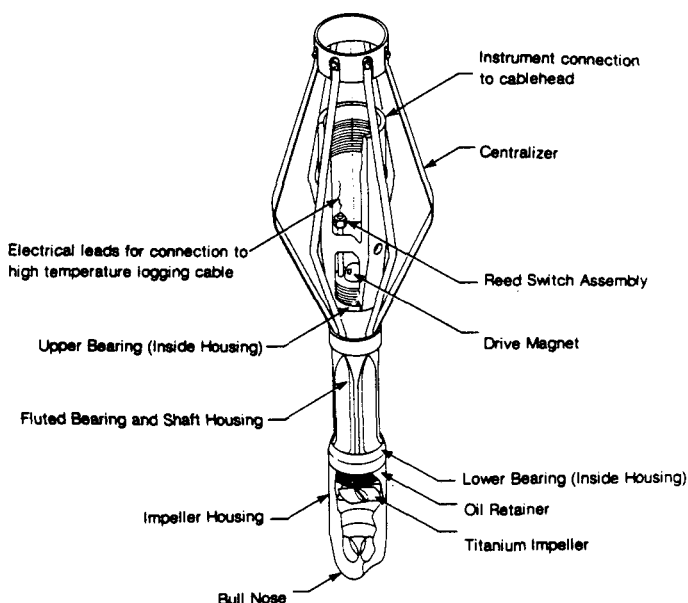


Figure 1. Photograph of the downhole flowmeter.

reliably at high temperatures and high rotational speeds. In addition, their successful use in the early subsurface recording units made them a logical choice. Two bearings are used (shown in Figure 2), one close to the impeller and the other near the top of the shaft. The two precision bearings let the 1/8 inch diameter impeller shaft rotate freely. They are protected from the corrosive wellbore fluid by an oil bath reservoir. The oil is prevented from leaving the enclosure at the lower bearing by capillary action due to the close fit of the impeller shaft and the shaft exit port located below the bottom bearing. After the flowmeter is lowered into a well, the higher specific gravity and the pressure of the brine prevents the turbine oil from leaving the enclosure.

To protect the instrument from the corrosive and abrasive downhole environments in geothermal wells the body was fabricated of type 304 stainless steel. A titanium impeller was chosen and fabricated because of the very high strength to weight ratio and high resistance to corrosion in geothermal brines. The aluminum and plastic impellers used in many downhole flowmeters are usually destroyed within a short time by the brines and high temperatures.

The fluid in production wells enters the flowmeter through the holes in the bullnose, rotating the impeller, and escapes through the externally fluted area of the bearing and shaft housing (see Figure 2). During use in injection wells, a collapsible funnel is usually attached at the fluted area of the bearing and shaft housing, which diverts the well fluid through the impeller housing, rotating the impeller and exiting at the bullnose.



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Figure 2. Schematic of the downhole flowmeter.

EXAMPLES

Downhole flowmeters have many applications in geothermal well testing, formation evaluation, and wellbore dynamics. In the following section three examples are given which demonstrate their utility and illustrate some of the difficulties with the interpretation of spinner logs. In theory, interpretation of spinner logs is very straight forward, but in practice it is often complicated by bore diameter variation and erratic

Table 1. Spinner components and temperature ratings.

Component	Type	Temperature Rating
Bearings	Shielded Precision Ball Bearings (many manufacturers)	480°C
Reed Switch	Hermetically Sealed (many manufacturers)	300°C*
Lubricating Oil	High Temperature Turbine Oil (Union 32 or equivalent)	300°C
Magnet	Alnico 5 or Alnico 8	400°C

*No temperature rating given. This value was determined experimentally and the true value may be significantly higher. The only reed switch tested is manufactured by the Calctro Company.

fluid flow near fractures or perforations. Methodical evaluation of the spinner log can resolve some of these complications and result in quantitative evaluation of production and injection zones. The first two examples are spinner surveys obtained from wells in the Imperial Valley, Calif. The first one demonstrates a conventional interpretation of a spinner survey from a well completed in a sandstone and shale reservoir. The second demonstrates flash point location in a very hot well which produces highly saline brine. The last example demonstrates the interpretation of a spinner log in a well with an openhole completion.

Flowmeter logs are obtained by lowering the instrument into the well. The log can be obtained while the instrument is lowered down the bore at a constant rate or with stops made at regular intervals. Logging at a constant speed has the advantage that the line speed can be sufficient to overcome the starting velocity (0.25 ft/s) of the spinner. On the other hand, it has been found that the precision of the survey is far greater if stops are made. During logging runs it is also important to ensure that the instrument is adequately centralized in the bore throughout the survey. This can be a problem in large diameter wells or wells with significant bore diameter changes. In that case the centralizer is chosen to fit the region of major interest.

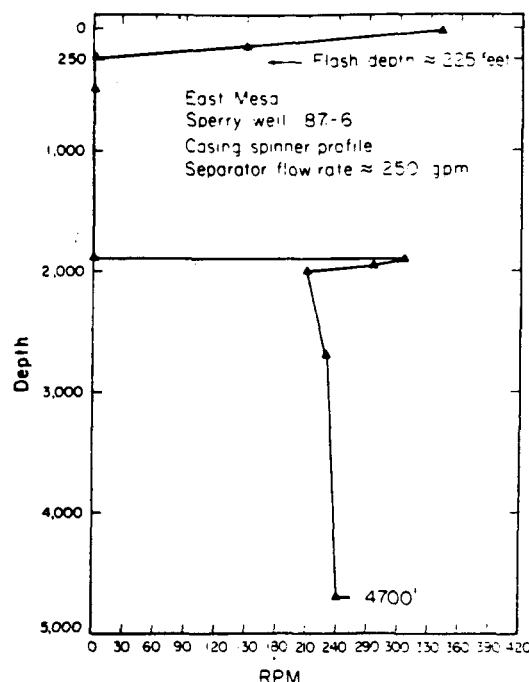
Imperial Valley, California: Well 1

Wells completed in sandstone formations may have an even permeability distribution over the bore length or it may be concentrated in discrete intervals. Wells in the Imperial Valley may have open intervals up to several thousand feet. Detailed reservoir engineering studies and well workovers require knowledge of the permeability distribution in the formation(s) penetrated. Correlation of geophysical borehole logs can be used for this purpose but rarely with sufficient confidence. Spinner surveys provide a direct method of determining the distribution of well productivity over the borehole length. Comparison of the productivity distribution to cuttings and borehole log analyses can be used to infer both the formation permeability and near-bore permeability damage.

A typical spinner survey from such a well is shown in Figures 3 and 4. The well completion is shown in Figure 5. In Figure 3, the casing profile is shown. At the very top of the well the

fluid velocity is relatively high (reflected by the rotation rate of over 300 RPM). At 225 feet, the fluid velocity drops to zero. This reflects the transition from the flashed to the unflashed brine in the wellbore (the flash depth). From 225 feet to 1750 feet the fluid velocity is below the starting velocity of the spinner. Therefore no fluid velocity is registered. From 1750 feet to the bottom of the casing (4700 feet), the fluid velocity remains nearly constant (with the exception of the higher velocities at the casing shoe).

Data from the spinner survey in the slotted liner is shown in Figure 4. Analysis of the data indicates that two intervals produce at least 73% of the fluid. The upper zone located between 4700 feet and 4720 feet produces approximately 18% of the total flow. Between 4720 feet and 4980 feet only 7% of the total flow is produced. The second major productive interval lies between 4980 feet and 5100 feet. At least 55% of the flow is produced from this interval. Because of the low fluid velocity below 5100 feet, it is not possible to determine if any fluid is being produced. Approximately 20% of the total fluid may be produced from below this depth.



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Figure 3. Casing spinner survey from well 87-6, Imperial Valley, Calif.

This is a good example of a conventional spinner log interpretation, and several key points are illustrated. First, the spinner easily detects the flash depth in the well. Second, the low flowrate (250 gpm) at which the survey was conducted created a relatively large uncertainty in the quantity of flow that was coming from below 5100 feet (20% uncertainty). Therefore, it would seem desirable to conduct the survey at a higher flowrate. However, there is a disadvantage to this, in that the flow regime in the vicinity of the perforations may become erratic at higher production rates. This results in a further ambiguity in the interpretation of the survey.

Imperial Valley, California: Well 2

The depth of the flash point in a well is typically inferred from abrupt changes in the slopes of flowing temperature and pressure profiles. In wells producing from gas rich reservoirs with highly saline brine, the slope of the pressure and temperature profiles change gradually, creating uncertainty in the true depth of the flashpoint. The spinner profile obtained from the upper portion of such a well is shown in Figure 6. Near the top of the well the fluid velocity is very high, reflecting a high steam content in the fluid. With increasing depth the fluid velocity gradually decreases (due to lower steam quality). Below 3000 feet the fluid velocity stabilizes, indicating that only a liquid phase is present. The spinner survey precisely locates the flash depth.

Wendel, California

The velocity of the fluid as it travels up the well is inversely proportional to the square of the bore radius. Therefore, even small changes in the radius can result in large changes in the fluid velocity. In openhole completions the bore diameter is often highly variable resulting in erratic fluid velocities. These changes are often so large that interpretation of the spinner data is very difficult. However, if a caliper survey is available, careful correlation of the two logs can result in quantitative evaluation of the spinner survey. This is demonstrated by the following example which was obtained from a geothermal well completed in a naturally fractured granitic rock. The spinner and caliper surveys from this well are shown in Figure 7. From the caliper survey (right side of Figure 7) it can be seen that the bore diameter is highly

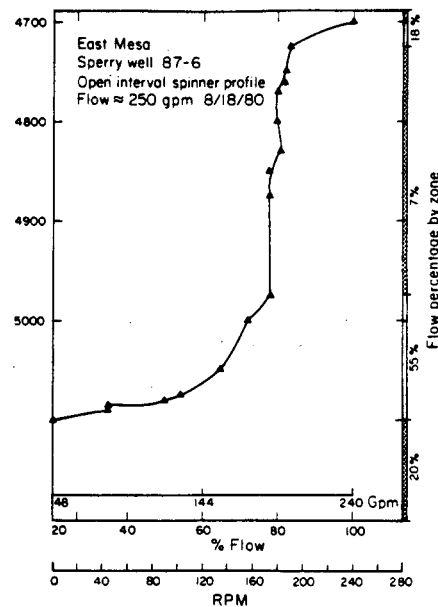


Figure 4. Open interval spinner survey from well 87-6, Imperial Valley, Calif.

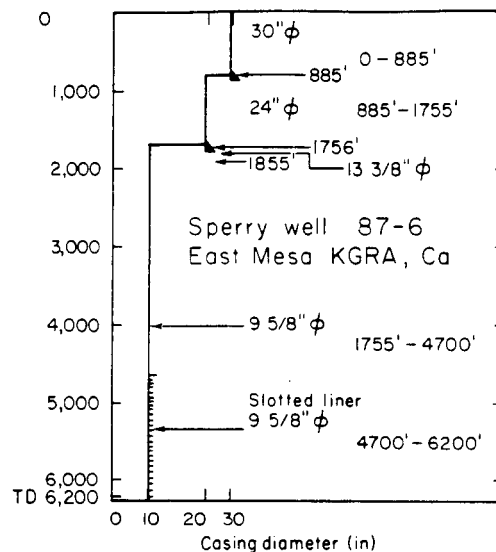


Figure 5. Casing schedule, well 87-6, Imperial Valley, Calif.

erratic. This is reflected in the variations in the fluid velocity shown in the spinner survey (left side of Figure 7). By comparing the flow velocity to the caliper survey at the depths at which the bore diameter is that of the originally drilled hole (13 inches to 5300 feet) the distribution of production intervals can be determined. The survey showed that 7% of the flow was entering the bore between 5120 feet to 5180 feet, 13% between 5190 feet and 5260 feet, and the remaining 80% between 5280 feet and

5320 feet. Below 5320 feet the impeller stopped rotating, indicating that the fluid velocity had dropped below the running velocity. Because the survey was conducted at a relatively high flowrate (680 gpm) it can be determined that less than 6% of the flow (40 gpm) was entering the well below 5320 feet.

This example demonstrates the extreme sensitivity of the flowmeter results to changes in the bore diameter. Whereas for conventional applications this may be a drawback, it can be very useful for detecting scale buildup or casing collapse in a wellbore. Because the spinner can be run while the well is under production, the spinner can be used as a production mode borehole caliper. This has the advantage in that scale buildup or casing problems can be diagnosed without shutting in the well.

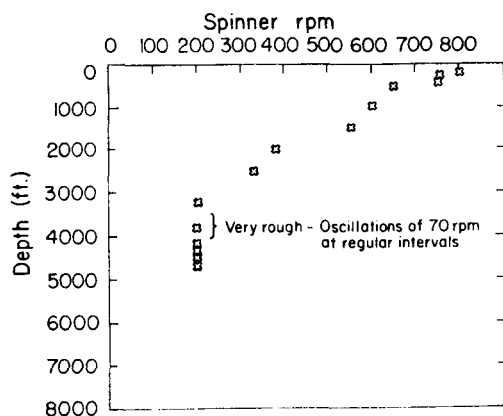


Figure 6. Spinner survey through the flash zone.

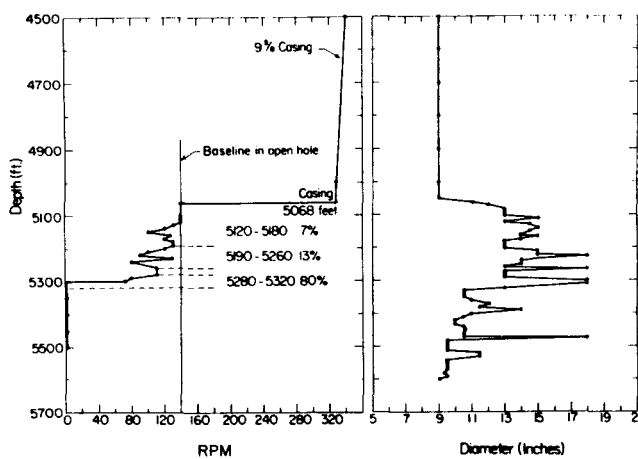


Figure 7. Spinner and caliper surveys from a well with an open hole completion.

CONCLUSION

By using existing technology a high temperature (300°C) downhole flowmeter can be constructed. In addition to the conventional uses, downhole flowmeters can be used for 1) locating the flash point in a well, and 2) as a very sensitive production mode borehole caliper. Careful analysis is required to avoid erroneous interpretation of the data and to extract the maximum amount of information from the survey. If a caliper survey is available, a spinner survey can be used successfully in an openhole completion.

There are several practical guidelines to follow in order to obtain the best quality spinner data.

- 1) Ensure that the instrument is adequately centralized during the survey.
- 2) A combination of logging at a constant line speed with regular stops throughout the regions of interest will provide the most accurate record.
- 3) Conduct the survey at the maximum flowrate possible without developing a highly erratic flow regime around the perforations. This flowrate must be determined empirically.
- 4) Expect to spend a fair amount of time on the analysis of the data.

ACKNOWLEDGEMENTS

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