

Advancements in Tracer Flow Testing; Development of Real-Time Technology for Flow and Enthalpy Measurements

Matthew Broaddus, J. Ivan Katz, Paul Hirtz, Russ Kunzman

Thermochem, Inc. 3414 Regional Parkway, Suite A, Santa Rosa, CA, 95403, USA

matt@thermochem.com

Keywords: Tracer Flow Testing, MicroMod, Continuous Brine Monitor

ABSTRACT

The Tracer Flow Testing (TFT) method for dual-phase flowrate and enthalpy measurements has become a standard diagnostic tool for geothermal reservoir engineering and power plant optimization. The need for lower tracer injection volumes, faster analysis, and smaller equipment has driven development of a modular, field-portable, flow measurement system. Now, discovery of a new fluorescent liquid-phase tracer and development of an automated analysis method for the existing vapor-phase tracer has made possible the delivery of enthalpy data on a real-time basis. The new liquid-phase tracer has the analytical sensitivity needed for direct-fluorescence measurements, a key component of the real-time process. A sample conditioning system for vapor-phase tracer analysis has eliminated the need to collect individual gas samples, and can now provide continuous analysis of vapor tracer during flow testing. The integration of these developments into existing tracer flow test methodologies has made it possible to acquire mass flow and enthalpy data on a real-time basis.

1. INTRODUCTION

Production fluid enthalpy is an important performance indicator for two-phase geothermal resources. Consequently, accurate and up-to-date enthalpy determinations are critically important in resource development and exploitation. Changes in enthalpy are often the first sign of changes in reservoir conditions, so enthalpy monitoring is a basic function of any reservoir management program.

Although periodic measurements of production fluid enthalpy provide useful data for reservoir engineering applications, they do not always provide sufficient information to detect well-to-well interference, or to interpret more complex reservoir processes. Another limitation of periodic measurements is their inability to adequately characterize the output of wells which exhibit surging production behavior, a process which can severely impact generation at the power plant. Accordingly, the technological innovations in enthalpy measurements are driven by the need for a cost-effective means of providing real-time enthalpy data at multiple points in a geothermal field.

Various methods for real-time enthalpy measurements exist, but for geothermal applications, two methods are most common: direct physical measurement of the respective phases, and tracer-based measurement using phase-specific tracer chemicals.

Direct physical measurements are usually accomplished with production separators or James-Tube atmospheric separators, and are best suited for single, large-scale

applications such as combined wellpad stations, or power plant inlets. For this application, production separators provide adequate measurements of the combined enthalpy of several production sites, and a gross estimate of overall field output. However, in most geothermal fields, the large number of production wells makes this type of system too costly to be a practical solution for enthalpy determinations on a per-well basis. And in some cases, direct measurements require diversion of production fluid from the power plant, impacting generation and revenue (Hirtz, 2001).

Tracer-based enthalpy measurement systems were developed in part to address these limitations. In a typical application, phase-specific tracers are injected under steady-state conditions at precisely known rates into two-phase flow. Samples of the two phases are collected downstream during tracer injection. The concentration of each tracer in its respective phase is inversely proportional to the flow rate of that phase. These operations do not require the interruption or diversion of flow, and are capable of covering over a wide range of flows from measurements at individual wells up to the larger combined flows found at power plant inlets.

Although tracer-based systems provide high-precision data over a wide range of applications, their primary limitation has always been their inability to provide flow and enthalpy data on a real-time basis. However, recent developments in tracer chemicals and tracer analysis equipment have now brought real-time capability to these systems. The Continuous Tracer Flow Testing (CTFT) system is an example.

2. TRACER-BASED ENTHALPY MEASUREMENTS

A detailed explanation of TFT theory is given by Hirtz (1995). Briefly, the mass flow rate of either liquid or vapor ($Q_{L,V}$) is given by:

$$Q_{L,V} = \frac{Q_T}{(C_T - C_B)} \quad (1)$$

Where Q_T , C_T , and C_B are the tracer injection mass rate, tracer concentration by weight, and background tracer concentration, respectively. Correction for background tracer concentration is usually unnecessary for vapor.

The total enthalpy (H_T) of the two-phase fluid is given by:

$$H_T = \frac{(Q_V \times H_V) + (Q_L \times H_L)}{(Q_V + Q_L)} \quad (2)$$

where H_V and H_L are the known enthalpies of pure liquid and pure steam. Correction for high levels of non-condensable gas (NCG) in steam and dissolved solids in high-salinity brines can be applied if necessary.

Development of the tracer-based enthalpy measurements into a system capable of delivering real-time data has required significant improvements in liquid tracer detection limits, as well as in vapor tracer analytical technique. Several different types of vapor-phase and liquid phase tracers have been evaluated, as shown in Figure 1.

Tracers Evaluated for TFT and CTFT Application	
Liquid Phase Tracers	Vapor Phase Tracers
Fluoride (as KF)	Propane
Bromide (as NaBr)	Sulfur hexafluoride (SF ₆)
Fluorescein dye	Freon-12
Sodium benzoate	Helium
Rhodamine WT dye	Isopropanol
1,5-naphthalene disulfonate	
2,7-naphthalene disulfonate	
Proprietary TT	

Figure 1: Tracers which have been evaluated for TFT and CTFT applications. SF₆ and the proprietary TT have emerged as the best tracers for CTFT applications.

Of the liquid tracers shown, all but two are fluorescent tracers. The fluorescence detection method is well suited to the real-time analytical requirements of the CTFT process. Several fluorescent tracers are in use for standard TFT applications, but so far, the proprietary TT is the only tracer with the fluorescence efficiency and thermal stability required to support the CTFT process.

Sulfur hexafluoride (SF₆) has been shown to have the best balance of chemical and thermal stability, vapor-phase specificity and analytical detectability. Other vapor-phase tracers such as the low-boiling alcohols have also been investigated, but have been found to lack the phase-specificity (Lovelock, 2000) needed for CTFT applications.

3. LIQUID-PHASE MASS FLOW MEASUREMENTS IN REAL-TIME

The primary challenge in the development of real-time liquid-phase mass flow measurements has been the lack of a tracers and tracer detection systems with the necessary sensitivity and speed. Fluorescent tracers and detection systems have been in use since 2001 (Hirtz, et al.) but the photosensitivity and reactivity of these compounds, combined with the requirement for HPLC analysis has, up to now, prevented these tracers from developing into a viable liquid tracers for real-time measurements. However, a proprietary fluorescent compound in the family of polyaromatic sulfonates (PAS), termed TT, has demonstrated the chemical and thermal stability, as well as analytical detectability, to enable measurements by direct fluorescence. This means HPLC separation of the tracer from its liquid matrix is no longer required. A continuous brine monitor (CBM) system makes use of this simplified analytical process to provide real-time measurements of the TT concentration in the liquid phase.

3.1 Instrumentation

High-sensitivity detection of the TT liquid tracer by direct fluorescence has made possible the development of the CBM system. Utilizing a dosing pump to draw tracer into

the detector, and a flow-through detector cell (25 mm diameter), the CBM is able to provide real-time TT concentration data at a detection limit of 5 parts per billion (ppb).

Tracer concentration data from the CBM is stored in an onboard data logging computer, and is also simultaneously transmitted through a serial connection to an external computer system for processing.

The excitation light source in the CBM is a dedicated light emitting diode (LED) which offers much higher wave length specificity in the emitted light, and therefore requires less filtration than a conventional incandescent excitation system. The low power consumption, long operational life, and minimal heat output of the LED excitation source make it suitable for extended use in an online monitoring system.

3.2 Field Application

The CBM has been used to measure liquid-phase flow in dual-phase flow systems, as well as in single-phase liquid flow systems in all stages of geothermal energy production from individual production wells to power plant liquid re-injection systems.

In a typical field application, the CBM is first set to the appropriate sensitivity range, and calibrated with a series of TT standard solutions. The CBM is then connected to a continuous stream of cooled sample liquid which has been separated from the two-phase production source using ASTM method e1675. With an onboard metering pump, the CBM draws in a side stream of this liquid and passes it through the detector cell to measure any background fluorescence signal which may be present in the produced liquid.

Tracer injection upstream of the sampling point then begins and the CBM continues to analyze the tracer concentration in the incoming sample liquid. In applications where the two-phase flow is stable, this tracer concentration rises to a stable concentration, and holds at this concentration for the duration of the test. When tracer concentration is converted to a flow rate, it indicates stable flow, as shown in Figure 2.

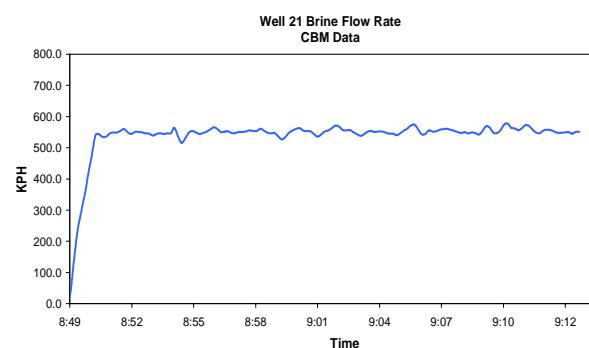


Figure 2: CBM data recorded for Well 21, under stable brine flow rate conditions. Only 1 minute elapsed from the start of tracer injection at 08:49 to final equilibration of the tracer at the steady-state concentration.

If the production source is exhibiting surging or otherwise unstable flow, the observed tracer concentrations will fluctuate over a range directly proportional to the ranges of flow. Conversion of tracer concentrations to flow rate demonstrates the unstable flow, as shown in Figure 3.

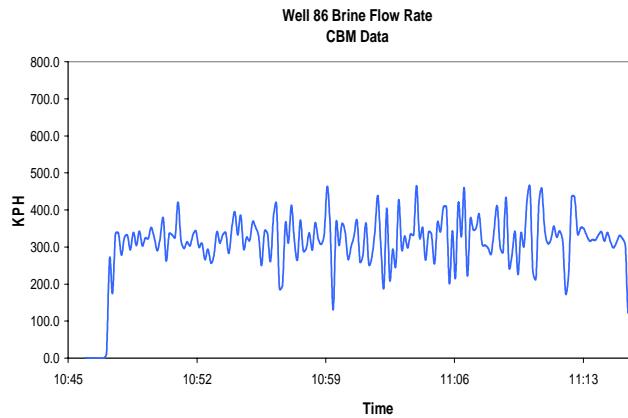


Figure 3: CBM data for unstable brine flow rate.

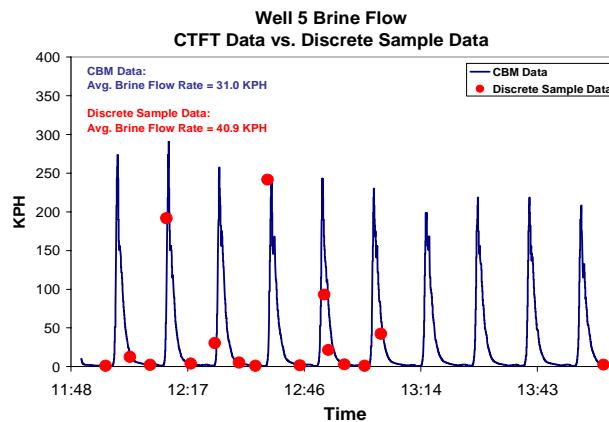


Figure 4: Comparison of CBM data to discrete sample data on a well with unstable brine flow rate.

The increased resolution of CBM data can also help explain apparently erroneous results calculated from discrete samples. In Figure 4, CBM data is compared directly to data from discrete samples collected at the same time.

Without the benefit of the CTFT data, the large variation in tracer concentration among the discrete samples would provide little information on brine flow behavior outside of a qualitative indication of unstable flow. At Well 5, the wellhead pressure remained stable through the duration of the test, so unstable liquid flow was not immediately suspected. Until CTFT was performed at this well, sampler error or instrument malfunction were considered the most likely explanation for the wildly fluctuating results in liquid tracer concentration.

The high resolution of the continuous data from the CBM easily explains the variance in discrete sample tracer concentrations. Information for the peak and minimum liquid-phase flows, and an accurate estimate of the time interval between flow excursions helped reservoir engineers identify the source of the flow anomaly. Due to the uneven distribution of the discrete sample points in the overall flow pattern, the standard TFT method over-estimates the liquid flow by almost 25%. The more accurate average flow rate provided by the CTFT process provided parameters on hardware changes needed to accommodate the unstable liquid flow rate.

4. VAPOR-PHASE MASS FLOW MEASUREMENTS IN REAL-TIME

In many geothermal applications, variations in steam flow rates have a much greater effect on the overall enthalpy of production fluids, and so great importance is placed on accurate analyses of steam flowrates in two-phase systems. However, analysis of the gas tracer in steam is not as straightforward as the liquid-phase tracer analysis, and development of a real-time vapor tracer analysis system has long been a missing component of the CTFT process.

The analysis of the vapor-phase tracer poses a different set of challenges than that found with the liquid-phase tracer analyses. Whereas liquid-phase analyses are constrained by limitations in instrument sensitivity, no such limitations exist in the current analytical method for gas tracer analysis. In fact, in most applications the sensor is adjusted so that sensitivity is *decreased* by several orders of magnitude to accommodate the gas tracer concentrations normally encountered in the steam during TFT.

The primary challenge of the current analytical method is its dependence on gas chromatography (GC) to separate SF₆ from other non-condensable gases (NCG) in the steam prior to analysis. Those gases are primarily carbon dioxide, hydrogen sulfide, ammonia, and oxygen (atmospheric contaminant). Laboratory methods for sequestering these

gases in discrete samples are common practice in the industry (ASTM e1675), but adapting them to a CTFT application has, up to now, been unsuccessful.

Real-time SF₆ analysis has now been demonstrated with a continuous steam monitor (CSM). The system has an integrated sample conditioning system which removes most of the interfering NCG. Although still dependent on a GC separation step, the CSM's automated analysis system provides tracer concentration readings at approximately 60 seconds intervals on a continuous basis throughout the flow test.

4.1 Instrumentation

The CSM pre-treats the incoming sample stream, separates the SF₆ from interfering gases, and measures the concentration of SF₆ tracer in the steam. In the pre-treatment step, live steam from the sample source enters an insulated calorimeter, where it is quenched by a precisely metered flow of cooling water. The change in temperature of the cooling water from inlet to outlet, and the enthalpy of the incoming steam (based on temperature) is used to calculate the steam flowrate through the calorimeter.

As the steam is quenched, the SF₆ and remaining non-condensable gas (NCG) flow into a stripping chamber where they mix with a solution of sodium hydroxide (NaOH). The NaOH absorbs the remaining carbon dioxide, hydrogen sulfide, and ammonia, leaving behind the SF₆, oxygen, and trace levels of other non-condensable gases.

The headspace of the stripping chamber is swept by a constant metered flow of nitrogen (N₂) gas, which carries the sample gas mixture through a refrigerated water trap and into the injection system. An automated gas sampling syringe periodically withdraws an aliquot of the sample gas mixture and injects it into the analytical column of the GC. The gases separate in the column, and the ECD sensor records the concentration of SF₆ in the sample gas stream. The concentration of gas tracer in the steam is the quotient of the SF₆ mass flow rate through the CSM and the

measured flow rate of steam condensate through the calorimeter. Tracer concentration data from the CSM, as well as temperatures of incoming steam, cooling water inlet and outlet, and injection pressure are transmitted to an external computer for processing.

4.2 Field Application

Given the sensitivity of its detector system, the CSM can be used to quantify and characterize steam flow behavior in a wide range of settings from individual production wells to main steam pipelines. With minor alterations, it can also be used to monitor sour gas flowrates at the power plant.

In cases where well flow is relatively stable, the CTFT data compares well with data from conventional TFT. A comparison of average steam flow, brine flow, and total fluid enthalpy for a TFT/CTFT comparison test is shown in Figure 5.

Comparison of TFT and C-TFT Enthalpy Results, Well 2

Flow Test Method	Average Steam Flow (KPH)	Average Brine Flow (KPH)	Average Total Fluid Enthalpy (btu/lb)
TFT	166.9	518.2	558.5
C-TFT	169.8	520.7	560.4
%RSD	1.20%	0.35%	0.24%

Figure 5: Data comparison of TFT and CTFT results for well 2. Flow and enthalpy results from both methods agree well, indicating the high accuracy of the CTFT method.

The data from the CSM is easily integrated with CBM data to provide total fluid enthalpy results in real time. The real-time printout from the comparison test at Well 2 is shown in Figures 6. During this test, individual samples of the steam

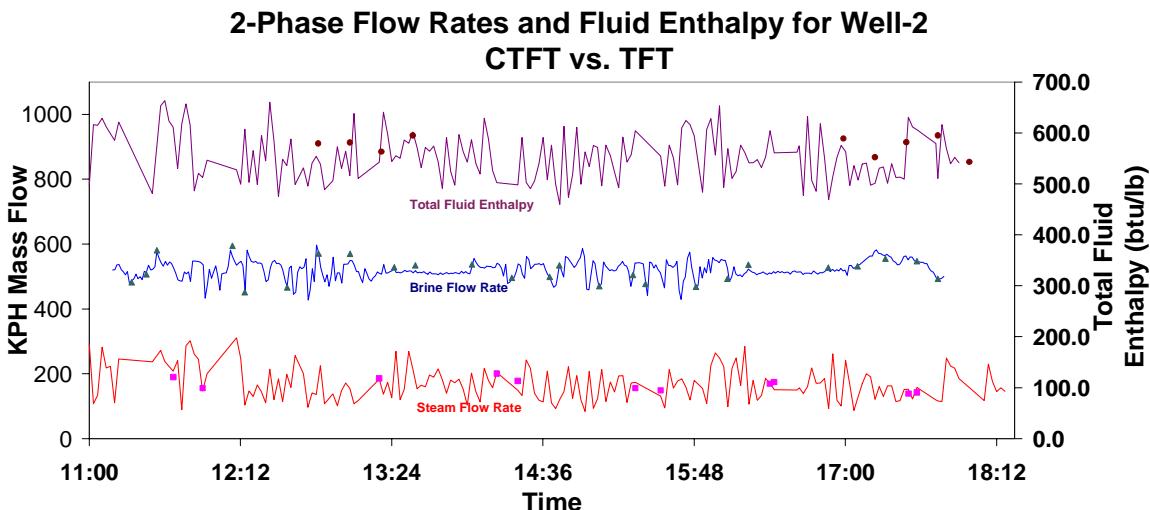


Figure 6: Composite graph of TFT and CTFT data. Although overall agreement between the two methods is shown to be quite good, the CTFT results reveal a periodic brine flow anomaly which would have gone unnoticed with conventional TFT.

were also collected and analyzed separately for comparison of the two methods. While the averages flows and enthalpies closely agree, the increased resolution of the CTFT system reveals a periodic brine flow anomaly which may have gone unnoticed with the benefit of continuous data.

5. CONCLUSIONS AND FUTURE WORK

Advances in liquid and vapor phase tracer technologies have led to a continuous tracer flow testing system capable of delivering real-time enthalpy measurements. Development of a thermally stable fluorescent liquid tracer with sufficient analytical sensitivity to support direct fluorescence measurements has eliminated the need for HPLC analysis in brine flow determinations. Although gas chromatography is still required for vapor tracer analysis, a new sample pre-treatment and auto-injection system has streamlined this process, and real-time gas tracer analysis is now available.

Future work on the components of the CTFT system will focus on two key areas: further reductions in the detection limit of liquid tracer analysis by direct fluorescence, and development of a true flow-through ECD for gas analysis.

The sensitivity of any fluorescence analysis is directly related to the intensity of the excitation light source, as well as the efficiency of light transmission throughout the system. Attenuation of the excitation or emission light sources will decrease signal intensity and raise detection limits. While the LED excitation light source currently used by the CBM does have higher specificity than conventional incandescent light sources, a laser source of the same wavelength would significantly improve instrument sensitivity and reduce response time. Fluorescent signal detection by use of a charged coupled device (CCD) will greatly enhance instrument sensitivity by allowing the integration of the fluorescence signal over the entire emission spectrum rather than just the peak emission wavelength. This has been demonstrated for the napthalene sulfonate tracers by Rose,

et al. (2002), and preliminary work on enhanced excitation strategies for TT have been undertaken by various other laboratories. Taken together, these changes could increase sensitivity of the liquid tracer analysis by as much as 2-3 orders of magnitude, thus drastically reducing the required tracer injection rates, with according reductions in operating cost of liquid-phase CTFT.

Significant steps have been made in recent years in the development of the CTFT method into an efficient and practical tool for geothermal applications. The ultimate goal of improvements in continuous tracer flow testing is the creation of a high-precision, cost effective system designed for permanent installation at geothermal facilities, conventional power plants, and any other applications where dual-phase flow metering is required.

REFERENCES

- Hirtz, P., Kunzman, R., Broaddus, M., and Barbitta, J.: Developments in Tracer Flow Testing for Geothermal Production Engineering, *Geothermics*, **30**, (2001), 727-745.
- Hirtz, P., and Lovekin, J.: Tracer Dilution Measurements for Two-Phase Geothermal Production: Comparative Testing and Operating Experience, *Proceedings of the World Geothermal Congress*, vol. 3, International Geothermal Association, Florence, Italy (1995).
- Lovelock, B., Stowell, A.: Mass Flow Measurement by Alcohol Tracer Dilution, *Proceedings of the World Geothermal Congress*, International Geothermal Association, Kyushu, Japan (2000).
- Rose, P., Harris, J., Kilbourn, P., Kleimeyer, J., Carter, T.: Greatly Enhanced Detectability of Geothermal Tracers Through Laser-Induced Fluorescence, *DOE project DE-FG07-98ID13619*, (2002)