# Tracer Flow Testing for Determination of Mass Flow Rates and Enthalpies, Case Study for KenGen-Olkaria Production Wells

Felix Kirui

Kenya Electricity Generating Company Ltd - Kenya

fkirui@kengen.co.ke

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**ABSTRACT**

Tracer flow testing is the routine measurement of well output in terms of mass flow and enthalpy in two phase pipelines and is of utmost importance in understanding reservoir performance. This is carried out by injection of exclusively non-radioactive and non-toxic tracers of high chemical and thermal stability- >330$^{\circ}$C with a lifetime of years. High precision multi-phase tracer metering systems with rapid-pulse tracer injection is used as the injection equipment to maximize concentrations at high flow and pressure. Multi-phase separators are used for steam, water and gas sampling. Analysis of samples is carried out by use of new ultra-specific and sensitive methods which include SPE clean-up, high performance liquid chromatography, UPLC separation, UV/fluorescence and triple-quad MS detection. Interpretation of data is carried out by numerical reservoir simulation services and not just qualitative and quantitative interpretation of results. This kind of tracer is injected in the flow line and sampling is downstream of the injection point. Liquid tracers injected must be conservative- cannot partition significantly to the vapor phase, adsorb onto rock, clays or sands decay chemically or thermally while in the reservoir for up to several years. They must also be very detectable at ultra low concentrations without interference from high concentrations of dissolved minerals in the produced water. Naphthalene sulphonates (NSA) are used for brine phase and Sulphur Hexafluoride (SF$_6$) for gas phase. Interpretation of tracer flow test data is only used qualitatively, to identify a connection between injector and producers to determine tracer breakthrough time (relative tracer flow).

## 1. INTRODUCTION

Tracer test data contains a wealth of information if the test is conducted and interpreted properly. It is possible to extract more useful, quantitative information from tracer testing, based on temporal behaviors of tracers. The interpretation methods have a rigorous mathematical basis and offer additional information about the sub surface. Data can also be used to constrain and calibrate numerical models by defining injection well volume and flow geometry. Interpretation methods are all based on analysis of tracer Residence Time Distributions (RTD).

In two-phase geothermal fields, monitoring the enthalpy of produced fluids is important in understanding the reservoir performance. Decreasing enthalpy can indicate breakthrough of injection water or invasion of cooler groundwater, while increasing enthalpy can indicate reservoir boiling and the formation of a steam cap.

Enthalpy is essential for the interpretation of geochemical data because it determines the steam fraction at sampling conditions and allows the correction of chemical concentrations back to reservoir conditions. Enthalpy and mass flow rate govern the amount of steam available from each well and ultimately the energy output of the powerplant.Mass flow rate of steam and water phases and total enthalpy of the flow can be measured directly for individual geothermal wells that produce to dedicated separators. However, due to the high capital cost of production separators, most geothermal fluid gathering systems are designed with satellite separation stations in which several wells produce to a single separator. In many cases all of the two-phase fluids produced from a field are combined by the gathering system and separated in a large vessel at the power plant. Without dedicated production separators for each well, the steam and water mass flow rates and total enthalpy of individual wells cannot be measured during production. (Hirtz et al, 2001)

Well testing with an atmospheric separator, James Tube and weir box can provide reasonably accurate enthalpy and mass flow rate values (James, 1970). However, this method requires diversion of flow from the power plant, with subsequent revenue losses. In some fields atmospheric venting of steam may not be allowed due to environmental regulations for hydrogen sulfide emissions and brine carry-over.

## 2. TRACER FLOW TESTING METHODOLOGY

To measure total mass flow and enthalpy in two-phase pipelines, it is necessary to measure the flow of the individual phases, steam and liquid-water (brine) separately. Tracer flow testing involves the quantitative injection and dilution of small quantities of chemical tracers, one for steam and one for liquid, in a pipeline. The tracers mix completely inside the pipeline, and at downstream sampling points separated water and steam are collected at the pipeline pressure.

Using a steam-phase tracer that travels entirely in the steam the steam flow is calculated as:

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Equation 1;

$$Steam\ flow\ \left(\frac{t}{h}\right) = \frac{steam\ tracer\ injection\ rate\,(g/h)}{steam\ tracer\ concentration\ in\ steam\ (g/t)}$$

The calculation is analogous for water flow, where the liquid-phase tracer (e.g., benzoate or bromide) is totally dissolved in the brine.

Equation 2;

$$Ht = \frac{SFh_g + WFh_f}{SF + WF}$$

where Ht, SF, $h_g$, WF, $h_f$ are total discharge enthalpy, measured steam flows, enthalpy of water at pipeline temperature, measured water flows and enthalpy of steam at pipeline temperature respectively.

The above expressions do not include non condensable gases ($CO_2$, $H_2S$, etc) which may constitute several percent of the total mass flow from a well. These must be determined separately.

Tracer flow testing is currently the only viable on-line method for measurement of two-phase flow in pipelines. The failure of other methods (e.g., Doppler-based systems) is due to that fact that the two phases are present in varying proportions, and may not be uniformly distributed across the pipeline. This is not an issue with tracer flow testing where the two phases are measured independently. On-line, non-invasive testing has a number of major advantages over traditional methods (atmospheric testing or total flow separators):

• power station operations are not interrupted

• generation load losses associated with taking wells out of service are avoided

• stable flow conditions are more likely (since production is not disturbed)

• there is no need for permanent wellhead test equipment, aside from sampling ports

• atmospheric discharge of wastewater is avoided

• there is greater flexibility in scheduling testing

Tracer flow testing can provide the greatest benefits when implemented at the steam field design stage, rather than by retro-fitting. With new geothermal developments, it is common to do away with dedicated wellhead test equipment in favour of tracer flow testing methods. In addition to well testing, tracer flow testing procedures can be used for power plant steam audits (e.g., as a check on annular measurements) and for measurement of combined flow from several wells.( Lovelock, 2001)
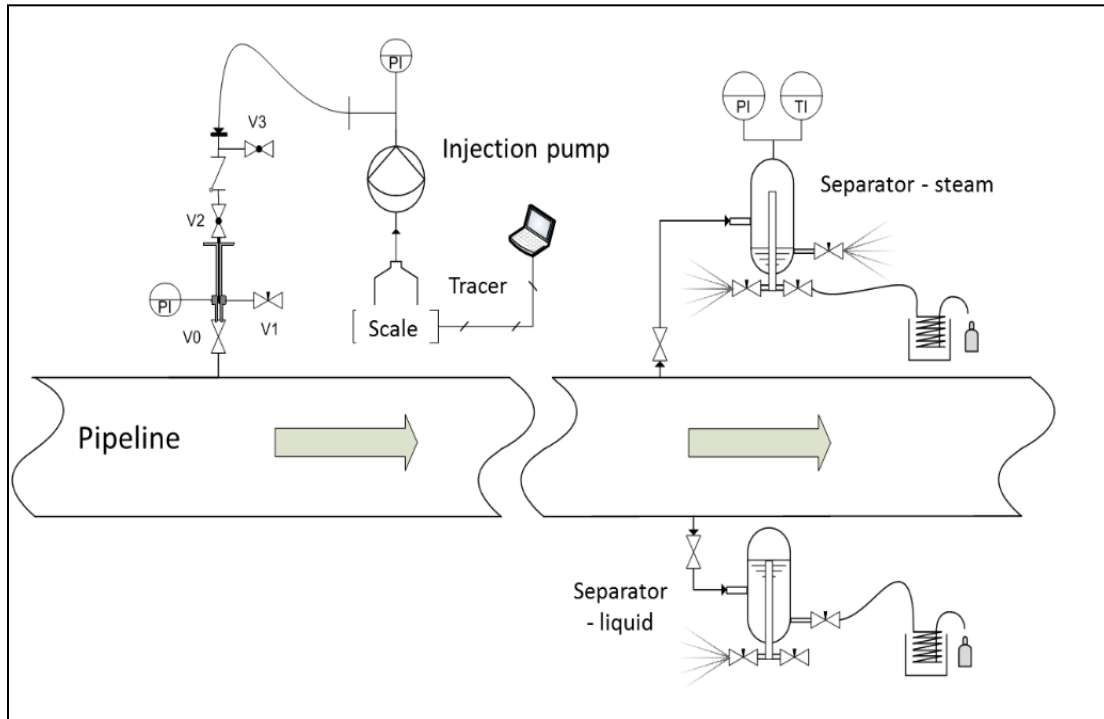
**2.1 Tracer Injection System Overview**



**Figure 1: The figure above is a schematic impression showing injection equipment, tracer injection point, steam pipe, sampling point and sampling equipment**

2.1.1 Sampling

Whenever possible, individual separators should be used to collect the brine and steam samples. This will help prevent problems from brine and steam carryover. One possible exception to this rule is sample collection from the brine and steam outlet of production separators. A typical sample suite for brine is 10 liquid samples in 125ml plastic bottles, collected at 3 minute intervals over a period of 30 minutes. Brine tracer samples should be diluted five times in distilled water. Each brine sample should be collected in an "integration bottle" first. That is, all brine that flows from the brine cooler during the 3 minute interval should be collected in a single large bottle or jug. At the end of each 3 minute "integration interval", the jug should be capped and shaken to thoroughly mix the contents. A sample bottle should be filled from the jug, and then the jug should be emptied and reused for the next integration interval. All 10 samples should be collected in this manner.

For gas, six (6) bottles should be collected, spaced approximately 5-10 minutes apart. It is important during gas sampling that the condenser be allowed to flush thoroughly before sampling, so it is best to let the condenser flow non-stop throughout the test. This is a typical sample suite for reliable data. For higher precision tests, additional gas and liquid samples should be collected, and the test length should be extended.

2.1.2 Analysis of Gas and Brine (liquid) Samples

Like other steam-phase tracers (e.g., SF6), alcohols must be analyzed by GC techniques. (Lovelock, 2001). For tracer flow testing carried out in Olkaria, samples are analyzed by head-space Gas Chromatography in the Geochemistry laboratory. Brine samples were analyzed by a portable custom made ultra violet visible analyzer made specifically to detect Naphthalene sulphonates. Analysis of brine was carried out both in the field and in the laboratory for all the wells tested.

**3. OLKARIA FLOW TEST RESULTS COMPARED TO JAMES MEASUREMENT**
Flow measurements have been done in the Olkaria geothermal field traditionally by employing the James Tube method. It was until 2017 that KenGen decided to adopt the modern Tracer Flow Test method acquired from Thermochem Inc. from the USA.

The new TFT method has been carried in about sixty (60) Olkaria production wells repeatedly and consistent results were achieved. Below is a table showing results of three wells sampled and analyzed during this period.

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| WELL | WHP | Enthalpy(KJ/Kg) | Steam (t/hr) | Brine((t/hr) | Total Mass flow rate (t/hr) |
|---|---|---|---|---|---|
| **OW-44A** | | | | | |
| **TFT** | 10.04 | 2644 | 53.1 | 0.8 | 55.9 |
| **JAMES** | 11.71 | 2620 | 50.5 | 4.5 | 55 |
| | | | | | |
| **OW-44B** | | | | | |
| **TFT** | 11.1 | 1945 | 66.7 | 34.9 | 107.8 |
| **JAMES** | 12.23 | 1950 | 62.3 | 44.7 | 107 |
| | | | | | |
| **OW-14** | | | | | |
| **TFT** | 10.5 | 2682 | 18.2 | 1.0 | 19.2 |
| **JAMES** | 11.14 | 2591 | 20.3 | 0.81 | 21.1 |

**Figure 2: The figure above is a chart showing comparison of flow measurement results for various Olkaria wells; 44A, 44B and 14 by use of TFT and James method.**

**3.1 Results of Tracer Flow Testing in Olkaria Presentation Format**

| | | | | Saturation | | | |
|---|---|---|---|---|---|---|---|

### Tracer Flow Test
### Olk Feb 2018 TFT
### Well OW44   2/8/2018

| Cleanup  for Report |
|---|
| Restore Hidden |

| Lab Number | Sample Time Interval | | Separator Temp, °C | Saturation Pressure Barg | 5.00 % SF6 Inj. Rate, SCCM | ppm, Tracer in Steam | Steam Flow Rate, Tonne/hr |
|---|---|---|---|---|---|---|---|
| k889 | 14:11 | 14:14 | 186.3 | 10.75 | 96.0 | 3.59E-02 | 54.5 |
| k910 | 14:19 | 14:22 | 186.7 | 10.86 | 96.0 | 3.63E-02 | 62.7 |
| k870 | 14:27 | 14:30 | 187.0 | 10.93 | 96.0 | 3.60E-02 | 52.5 |
| k954 | 14:53 | 14:56 | 186.7 | 10.86 | 196.8 | 6.90E-02 | 56.3 |
| k942 | 15:01 | 15:03 | 186.1 | 10.70 | 196.8 | 7.18E-02 | 54.1 |
| k917 | 15:08 | 15:11 | 188.3 | 11.28 | 196.8 | 6.97E-02 | 55.6 |
| | Averages | | 186.9 | 10.90 | | | 54.3 |

**Steam Port Location**          TPUSCV

| Lab Number | Sample Time Interval | | Separator Temp, °C | Saturation Pressure Barg | 2.0 % ThermoTrace Inj. Rate, g/min | ppb, Tracer in Brine | Brine Flow Rate, Tonne/hr |
|---|---|---|---|---|---|---|---|
| 3 | 14:19 | 14:22 | 186.3 | 10.75 | 15.2 | 957.1 | 32.2 |
| 4 | 14:23 | 14:26 | 186.5 | 10.80 | 14.8 | 987.3 | 35.1 |
| 5 | 14:27 | 14:30 | 186.8 | 10.88 | 15.5 | 942.6 | 34.1 |
| 6 | 14:53 | 14:56 | 187.3 | 11.01 | 25.3 | 920.6 | 32.9 |
| 7 | 14:57 | 15:00 | 187.2 | 10.99 | 25.2 | 887.5 | 34.0 |
| 8 | 15:01 | 15:03 | 187.6 | 11.09 | 25.1 | 923.6 | 32.6 |
| 9 | 15:04 | 15:07 | 187.4 | 11.04 | 25.1 | 896.3 | 33.4 |
| 10 | 15:08 | 15:11 | 189.1 | 11.49 | 25.1 | 887.9 | 33.9 |
| | Averages | | 187.0 | 10.94 | | | 33.5 |

**Brine Port Location**          45DUSCV

| | | | |
|---|---|---|---|
| | | Average Test Enthalpy, KJ/Kg : | 2025.0 |
| WHP, barg | 10.6 | Average Total Flow, Tonne/hr : | 87.8 |
| Control Valve (%) | 100.0 | Enthalpy Temperature, °C : | Out of Range |
| | | Steam Fraction @ 10.9 barg (Average) | 0.0183 |

**Table 1: The figure above is analyzed data report for Olkaria well 44 Tracer Flow Testing done in 8th February, 2018.**

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**Tracer Flow Test**
**Olk Oct 2017 TFT**
**Well OW 44   10/20/2017**

[ Cleanup for Report ]
[ Restore Hidden ]

| Lab Number | Sample Time Interval | | Separator Temp, °C | Saturation Pressure Barg | 5.00 % SF6 Inj. Rate, SCCM | ppm, Tracer in Steam | Steam Flow Rate, Tonne/hr |
|---|---|---|---|---|---|---|---|
| k855 | 11:36 | 11:37 | 186.9 | 10.90 | 199.8 | 6.66E-02 | 56.7 |
| k862 | 11:45 | 11:46 | 186.8 | 10.88 | 199.8 | 6.63E-02 | 57.1 |
| k856 | 11:52 | 11:53 | 186.9 | 10.90 | 199.8 | 6.63E-02 | 57.2 |
| k913 | 12:15 | 12:16 | 185.2 | 10.47 | 96.1 | 3.43E-02 | 56.7 |
| k914 | 12:21 | 12:22 | 187.0 | 10.93 | 96.1 | 3.36E-02 | 57.0 |
| k864 | 12:26 | 12:27 | 187.3 | 11.01 | 96.1 | 3.49E-02 | 55.5 |
| Averages | | | 186.7 | 10.85 | | | 56.5 |

**Steam Port Location**        TPU SCV

| Lab Number | Sample Time Interval | | Separator Temp, °C | Saturation Pressure Barg | 2.0 % ThermoTrace Inj. Rate, g/min | ppb, Tracer in Brine | Brine Flow Rate, Tonne/hr |
|---|---|---|---|---|---|---|---|
| 26 | 11:30 | 11:33 | 185.8 | 10.62 | 15.0 | 962.7 | 31.9 |
| 41 | 11:37 | 11:40 | 186.1 | 10.70 | 15.0 | 953.1 | 32.1 |
| 31 | 11:42 | 11:45 | 186.5 | 10.80 | 15.0 | 964.6 | 31.8 |
| 30 | 11:46 | 11:49 | 186.9 | 10.80 | 15.0 | 953.6 | 32.2 |
| 46 | 11:50 | 11:53 | 186.7 | 10.85 | 15.0 | 957.1 | 31.8 |
| 22 | 12:13 | 12:15 | 188.2 | 11.25 | 25.2 | 1045.6 | 29.8 |
| 21 | 12:16 | 12:19 | 188.4 | 11.30 | 25.2 | 1065.3 | 30.1 |
| 67 | 12:20 | 12:23 | 187.7 | 11.11 | 25.3 | 1041.4 | 30.0 |
| 48 | 12:22 | 12:25 | 187.6 | 11.09 | 25.2 | 996.3 | 30.2 |
| 56 | 12:24 | 12:27 | 187.2 | 10.88 | 25.3 | 996.9 | 30.4 |
| Averages | | | 187.1 | 10.96 | | | 31.0 |

**Brine Port Location**        45DU SCV

| | | | |
|---|---|---|---|
| WHP, barg | 10.6 | Average Test Enthalpy, Kj/Kg : | 2079.6 |
| Control Valve (%) | 100.0 | Average Total Flow, Tonne/hr : | 87.5 |
| | | Enthalpy Temperature, °C : | Out of Range |
| | | Steam Fraction @ 10.8 barg (Steam) | 0.6469 |
| | | Steam Fraction @ 11.0 barg (Brine) | 0.6455 |

**Table 2: The figure above is analyzed data report for Olkaria well 44 Tracer Flow Testing done in 10th October, 2017.**

## 3. CONCLUSION AND RECOMMENDATIONS

The TFT technique for two-phase mass flow rate measurement is accurate and robust if implemented based on the original development criteria, emphasizing specific properties for the liquid- and vapour-phase tracers and high-accuracy mass injection techniques. Evaluations of numerous tracers for this application over almost 10 years indicate that sulphur hexafluoride and sodium benzoate are ideal vapour- and liquid-phase tracers, respectively. Alcohol vapour-phase tracers such as isopropanol are not suitable for general TFT use. They suffer from significant liquid-phase solubility, require long mixing runs compared to the gas tracers, and exhibit losses when used on fluids with high brine fractions, resulting in erroneously high steam flow rates. The losses of alcohol may be due to chemical reactions in the liquid phase between alcohol and boron or silica. These reactions are expected to be enhanced by high brine fractions and long mixing runs. (Hirtz et al, 2001)

Results of flow rates tests previously done in Olkaria compared to TFT shows low variance as results are comparable. KenGen Olkaria geothermal project has since adopted TFT method as it is robust, accurate and there is no downtime on electricity generation when this method is used.

## 4. ACKNOWLEDGEMENTS

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