Geothermal Steam Quality Testing

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Abstract

Geothermal steam quality and purity have a significant effect on the operational efficiency and life of geothermal steam turbines and accessory equipment. Poor steam processing can result in scaled nozzles / blades, erosion, corrosion, reduced utilization efficiency, and early fatigue failures accelerated by stress corrosion cracking (SCC). Upsets formed by undetected slugs of liquid entering the turbine can cause catastrophic failure.

The accurate monitoring and determination of geothermal steam quality / purity is intrinsically complex which often results in substantial errors. This paper will review steam quality and purity relationships, address some of the errors, complexities, calibration and focus on: thermodynamic techniques for evaluating and monitoring steam quality by use of the modified throttling calorimeters.

Introduction

Steam quality and purity entering geothermal plants are inferior to fuel fired systems. This processed steam contains gasses, solids and dissolved solids in varying quantities. As a result, geothermal steam turbines, etc., require higher maintenance and incur higher premature failure rates than conventional fuel fired steam plants.

Unlike conventional steam plants that continuously monitor fluid chemistry, geothermal plants take occasional grab samples, perhaps once per shift, and sample at individual site processing stations less frequently. Sampling and analytical errors are common and even if a process upset is detected, many hours to days can pass before a moderate upset can be confirmed and corrective measures taken. Damage can often occur during this window period.

Accurate geothermal steam quality and purity measurements are intrinsically complex. First a representative sample must be taken, which in itself is difficult, then that sample must be processed into meaningful results either by trace chemistry or thermodynamic means. It is not uncommon to incur errors in excess of 10x if conditions and techniques are not proper. In the measurement of effective steam qualities, values of 99.9999% can, in fact, be less than 99% because of complexities or improper technique. This false sense of security can lead to serious problems.

This paper will address some of the complexities inherent in the measurement of geothermal steam quality and purity. The review will include basic relationships between quality and purity; isokinetic sampling, probe effects and multi-phase flow regimes; trace chemistry, conductivity, and thermodynamic analytical tools; and calibration.

Although trace chemistry techniques can provide better precision, the bulk of this paper will address the throttling calorimeter for the determination of steam quality. This rather old and inexpensive tool, if properly utilized can provide fast and accurate results without chemicals or expensive and delicate laboratory equipment. This is an instrument that can be used in the field. As with any analytical tool, good judgment and cross calibration with other techniques is prudent.

Steam Quality

Steam quality is the percentage by weight of dry steam in a mixture of saturated steam and suspended liquid droplets of water at the same temperature. Thus 99.90% steam quality contains 0.10% moisture. Steam quality is determined by thermodynamic means via use of the throttling calorimeter on saturated steam samples. In geothermal applications, heat loss, Joule-Thomson effects, barometric pressure, static/stagnation state, and other effects must be corrected for meaningful results. Many of these concerns are not addressed in conventional pure steam measurements. A rule of thumb for turbine effect is, for every one percent inlet moisture, the turbine stage efficiency drops by effectively one percent (Kearton).

Steam Purity

Steam purity is the solids/dissolved solid content in a sample of condensed steam. Thus a 500 ppm TDS would constitute steam condensate contains 500 part by weight solids contamination per million total parts. Steam purity can be determined by evaporation, conductivity, flame photometry or by trace chemistry means. In geothermal service, trace chemistry is used to detect dissolved solids in small amounts in the condensate.

Conductivity measurements are highly affected by dissolved gasses (NH_3, CO_2, H_2S, etc.) in the liquid fraction and as such is not used for low TDS analysis. The major impurity concerns are for silica, iron, chlorides, and arsenic. These elements are prime indicators of scaling, corrosion and SCC potential. Tracer ions for sodium or chlorides can provide a general ratio of the overall total dissolved solids (TDS) entering the system once a baseline is established.

Typical fuel fired plants keep the silica content of the steam below 25 ppb (Babcock & Wilcox). In geothermal applications, the limit on silica concentration is restricted to 1.0 ppm. Scale build-up can constitute reduced nozzle efficiency approximately 0.5% per 1/1000 inch of build-up (Kearton).

$$x = \frac{h_{g2} + c_p (t_c - t_2) - h_{f1}}{h_{fg1}} \quad (5)$$

Quality vs. Purity

If the moisture in the steam is separated brine of a known concentration, the following equality exists between steam quality and purity:

$$Steam\ Quality = \left(1 - \frac{ppm\ impurity}{ppm\ separated\ brine}\right) x\ 100 \quad (1)$$

$$ppm\ impurity = \frac{\%\ moisture\ x\ ppm\ in\ sep.\ brine}{100} \quad (2)$$

Steam quality can be a prime indication of steam purity under a certain state. However, this equality requires correction when conditions change. Friction-loss, heat-loss, stagnation state, precipitation, dissolved solids in the vapor phase are prime factors that influence this relationship. These corrections must be addressed if precision of state is desired.

Representative Sampling

Representative steam sampling is not as simple as drawing a slip-stream from a side port and having it analyzed. For even if the sample was analyzed accurately, the results would be highly in error because a representative sample was not taken.

Unlike blended gas or liquid sampling that can be representatively taken off side ports, multi-phase sampling of liquids, solids, gasses and steam is not evenly distributed within a conduit. They do not behave as a homogeneous mixture. An understanding of the flow regimes, thermodynamics and sampling probe designs are important for acquiring a representative sample for analysis.

Flow Regime

If a mixture of liquid and vapor was homogeneously blended, with the liquid dispersed in sub micron particles, representative sampling would be simple. Unfortunately, this is not the case in steam quality and purity sampling where at low rates the denser liquid fraction wants to settle out on the bottom of the pipe (Stratified - Figure 1); at higher rates the liquid concentrates onto the side of the pipe wall

(Annular - Figure 2); and at even higher rates the liquid droplets are sheared into small droplets and distributed throughout the conduit (Annular-Mist / Disperse - Figure 3). It is within this Annular Mist / Disperse flow regime that representative sampling via the use of insertion sample probes can be the most effective (Flow Regime Map - Figure 4).
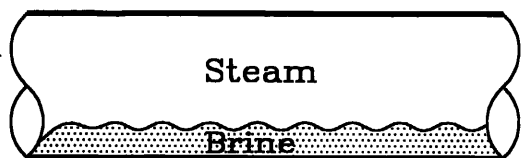

Fig. 2   Annular
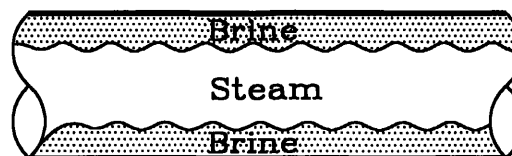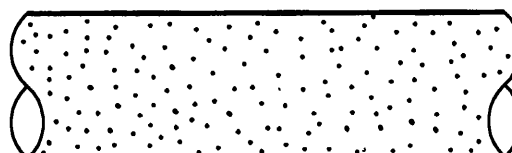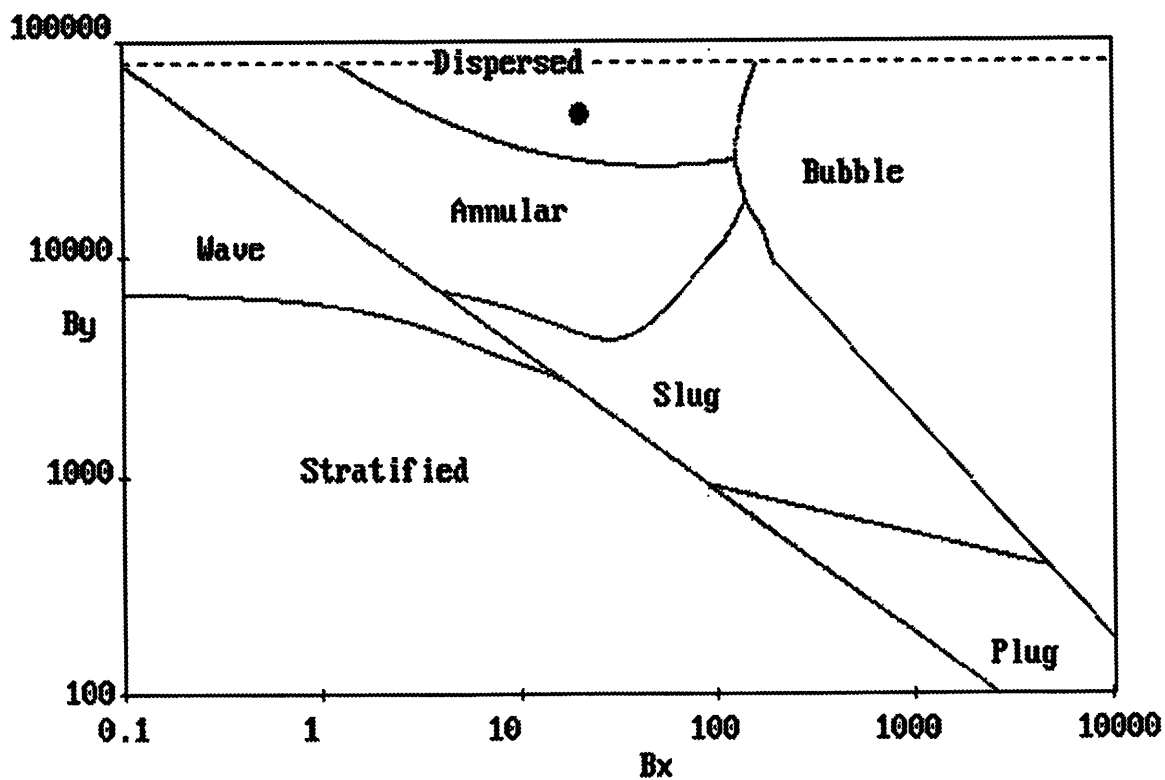

Fig. 1   Stratified

Fig. 3   Mist/Disperse

Fig. 4   Baker Map

There are many obstacles that can alter the flow regime affecting sampling accuracy. These might include: elbows, tees, valves, flow meters, separators, thermowells, upflow, downflow, incline pipe positions,. etc. Downflow sampling is perferred if possible, followed by upflow, with horizontal lines being the more difficult to accurately sample. As a general rule of thumb, a lower limit for sampling in horizontal lines is somewhere between 60'/s to 100'/s with vertical mounted probes top and bottom preferred (Jung, 12). The lower the line pressure, the higher the required velocity to obtain mist flow. The higher the vapor velocity, the better the liquid/vapor dispersion and the ability to sample representatively.

Steam Sampling Nozzles

There are two basic types of steam sampling probes: the single point transversing, and the multiport stationary type. The transversing type can be more accurate in undeveloped or complex profiles. Here the probe transverse across the pipe, much like a pitot tube, sampling in equal area segments. The greater the number of samples, the better the theoretical accuracy. In calorimeter use, a variable extension tube is a source for heat-loss which is difficult to calibrate. The transversing technique is best suited for chemical grab sample analysis. Its use has an important feature in that wall fluid can be monitored outlining impurity gradients.

The multiport sample probe is an impurity averaging stationary design. Here a probe inserted into the pipeline samples uniformly at equal area segments of the pipe. It is important for structural stability that the natural frequency of the probe does not match the forcing frequency (probe shedding vortex) of the steam flow or failure will occur. Some multiport steam sampler probes are designed to operate between the 1st and 2nd harmonic to reduce the probe diameter and interfering stagnation boundary layer that can effect sampling accuracy (Jung, 14).

Isokinetic Sampling

Isokinetic sampling means the flow velocity entering each sample port must match the flow velocity within the pipeline. This technique is important in acquiring a representative sample. If we consider a control

volume, traveling at a fixed rate, with a sample port intercepting the path of all mass equal to this port size, that is isokinetic sampling (Isokinetic Sampling - Figure 5). If the sample rate is too fast, the port will suck more steam from the surrounding area diluting the sample (Fast Sampling - Figure 6). If the sampling rate is too slow, the heavier liquid mass will penetrate the port concentrating the sample (Slow Sampling - Figure 7). And if the sampling rate is very slow, a stagnation boundary layer can develop in front of the probe deflecting a portion of the liquid fraction, causing a sample dilution (Stagnation Effect - Figure 8)(Jung, 14). The isokinetic sampling rate is determined by the following relationship:

$$f = (a/A) F \qquad (3)$$

where:

f = *sample flow rate.*

F = *total flow rate in pipe.*

a/A = *ratio of total port area to pipe area.*

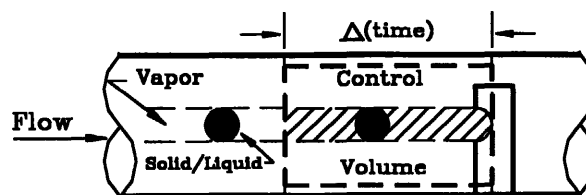Care must be taken to insure equal sampling from all ports by internal design.

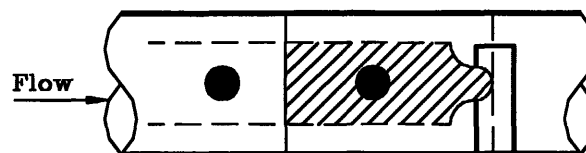Fig. 5   Isokinetic Sampling
(Sample Velocity=Line Velocity)

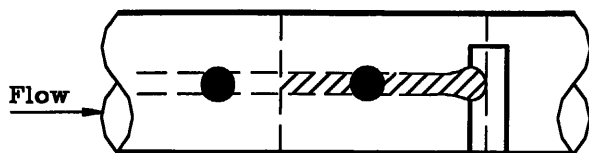Fig. 6   Sampling Too Fast
(Dilute Sample)
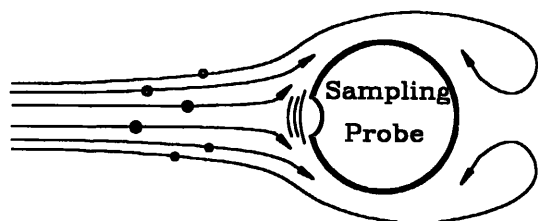
Fig. 7 **Sampling Too Slow (Concentrated Sample)**

Fig. 8 **Stagnation Effect (Very Slow Sampling— Dilute)**

Throttling Calorimeter

The basic throttling calorimeter has been in use for over 100 years. It is a rather simple and old technology used for the determination of steam quality. The process functions by expanding steam adiabatically across a nozzle. The initial and final enthalpy will remain the same assuming there is no heat-loss and kinetic energy changes. When wet saturated steam is throttled across a small control orifice, the liquid fraction is atomized and vaporized into super-heat with the pressure drop from high-pressure to low-pressure. By measuring the amount of super-heat existing within the calorimeter, the amount of moisture can be determined.

The basic relationship can be demonstrated by the following equation:

$$x = \frac{h_2 - h_f}{h_{fg}} \times 100 \qquad (4)$$

or a more practical version:

$$x = h_{g2} + \frac{c_p \, (t_c - t_2) - h_{fl}}{h_{fgl}} \qquad (5)$$

where:

x = initial steam quality, percent.

h_2 = enthalpy of super-heated steam at calorimeter (btu/lb).

h_{g2} = enthalpy of saturated steam @ calorimeter pressure.

h_{fl} = enthalpy of saturated liquid in mixture prior to throttling.

h_{fgl} = enthalpy of vaporization corresponding to pressure or temperature of steam entering calorimeter.

t_c = superheated temperature in calorimeter

t_2 = saturation temperature ($^\circ F$) @ calorimeter pressure

c_p = specific heat of saturated steam. Assume 0.463 for approximate atmospheric pressure in calorimeter.

An alternative way to determine steam quality is by means of the Mollier Diagram (Figure 9). Here point A corresponds to the calorimeter superheat temperature at saturation pressure; and point B correspond to a straight line to the initial line pressure. This technique is a quick way to determine steam quality for moisture levels greater than 0.25%.

Design Styles

There are many different calorimeter types such as throttling, separating, throttling/separating and separating/throttling. Our discussion will focus on the throttling of which there are many designs. The two units that will be addressed will be the Ellison U Path (Figure 10) and the ASME Pipe Fitting (Figure 11). The U Path design is compact and incorporates a thermo-barrier using the discharge steam and a quick orifice change-out mechanism. The ASME is very simple with several variations and can be inexpensively fabricated with mostly off-the-shelf-fittings. Regardless of the calorimeter used,

calibrating to mitigate various interferences that will affect the steam quality determination is critical if high precision is desired. A precision, calibrated system can measure steam quality to 99.95% (Jung,14).

Heat Loss

Since the determination of steam quality is a function of temperature, any heat transfer to the outside control volume constitutes an error. Cold, wind and rain all add to increase error. Insulation is critical on the pipe, sampling apparatus and calorimeter. Even with insulation, the small amount of heat loss is not negligible for precision measurements above 99.5%. Stationary and online calibration techniques can mitigate this effect.
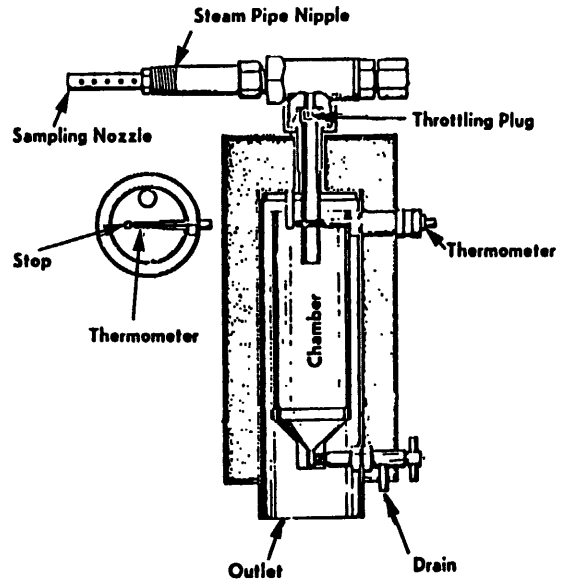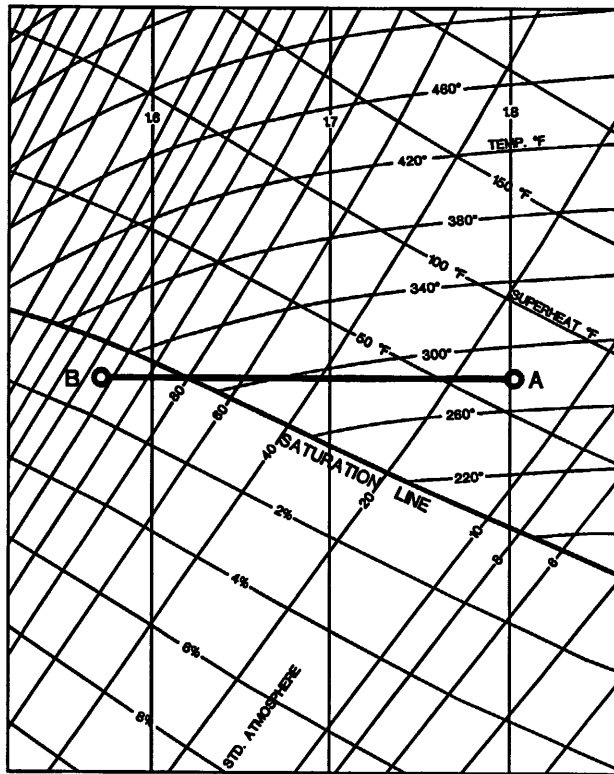

FIGURE 10. Ellison U Path
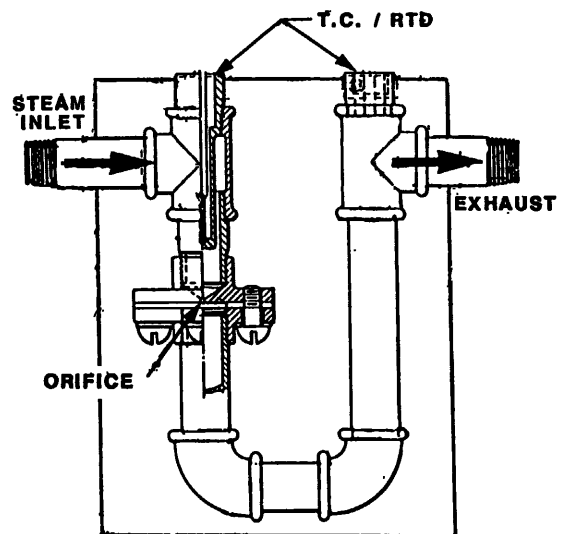

FIGURE 9

FIGURE 11. A.S.M.E. Pipe Fitting

Joule-Thomson Effects

Although some gasses will increase in temperature when throttled, most gasses will experience a substantial decrease in temperature. The change in temperature over the change in pressure is known as the Joule-Thomson Coefficient. That is:

$$Joule\text{-}Thomson\ Coefficient = dT/dp \qquad (7)$$

Different gasses and vapors have different coefficients when throttled. A mixture of gasses will not behave like a pure vapor altering the final temperature. Geothermal steam contains gasses that when throttled do not follow the same temperature / pressure curve as pure steam. The greater the amount of gasses entrained in the steam, the more effect this will have on the throttling calorimeter readings. This effect can be mitigated by calibration.

Boiling Point Rise

This is generally a minor point except in areas where the brine has a high TDS such as in the Salton Sea Geothermal Fields in California. Here the brine carry-over entrained in the steam has a high dissolved solid concentration that alters the boiling point of the fluid. As such, vaporizing this fluid is more difficult, and correcting for the solid content and scaling potential of the fluid presents other problems.

Gradients

In undersaturated liquids and superheated vapor temperature gradients are common. That is to say, if one were to transverse a conduit or piece of equipment, such as a calorimeter, there will exist a temperature difference where a homogeneous average temperature might be desired. This effect can be corrected by way of calibration.

Barometric Pressure

As the barometric pressure changes, the temperature reading of the calorimeter can vary according to the saturation temperature / pressure curve. Since steam quality calculations are based on the discharge calorimeter pressure, this correction is important. Online calibration can correct for this effect.

Stagnation/Static State

A common misunderstanding in flow kinetics is the relationship between static and stagnation state. As an example, a dry saturated steam in a stagnation (low velocity) state enters a nozzle. The steam accelerating in a nozzle will not only experience a drop in static pressure but will become wet (i.e., Wilson Line) and not super-heated (Moore, 10). This is because some internal energy must be converted into kinetic energy and as a result, condensation or supersaturation exists.

In geothermal systems because of seeding effects from impurities, the Wilson Line might not be reached before condensation occurs. If a sample is theoretically taken in this high velocity wet zone, the results could be tainted as dry steam instead of wet. The throttling calorimeter is basically a stagnation device. As a rule of thumb, if sampling is taken at velocities greater than 150'/s, kinetic energy effects must be taken into consideration.

Calorimeter Range

The moisture range of the throttling calorimeter is restricted to its ability to produce a measurable super-heat (SH). This limit is approximately 3.15% @ 50 psig, 4.3% @ 100 psig, 5.6% @ 200 psig and 7% @ 400 psig. As a general rule of thumb, a minimum of 6°F SH to 10°F SH is required to adequately vaporize all incoming moisture. This limit can be confirmed visually by observing if the discharge calorimeter is wet or entrained droplets with the steam are being emitted. If a higher moisture content is encountered (you could have serious problems), a separating calorimeter can extend this range.

Instrumentation

Conventional throttling calorimeters depend on pressure and temperature measurements. Pressure gauge and transmitter accuracy are affected by temperature (Benedict). For every 10°F change over calibration, the error can be affected up to 0.5%. Pressure gauges are generally psig and not psia calibrated, this effects accuracy with changing atmospheric conditions. Since geothermal systems

incur variations in pressure, these variations must be tracked to corresponding temperatures.

High precision temperature measurements are preferred to pressure measurements for several reasons. Pressure fluctuations will be dampened by the mass of the temperature probe and correspond more readily with other temperature elements. Partial pressure of gasses will not have the same interfering effect on these elements. Having the same elements of uniform calibration and response characteristics enable more uniform readings. Platinum RTD's of the 100 ohm, 3 or 4 wire shielded elements are preferred for accuracy and stability. However, for differential temperature measurement, thermocouple (T - Copper Constantan or J - Iron-Constantan) cut from the same wire spool is more precise. Cold reference junctions are required for thermocouples.

For temperature measurements, static and stagnation conditions should be considered. It is important for quick response to keep the mass of the temperature element as small as practical. No thermowells should be used as the extra mass causes significant time delays for heat-up, slows response time, and acts as an interfering heat sink. Element diameters of 1/4" to 1/8" stainless shielded stems are preferred.

Calibration

The calibration of a throttling calorimeter for geothermal service requires establishing a control baseline. Two measurements are required at any given temperature, pressure and flow rate: the temperature of the calorimeter (super-heat) with 100% saturated steam entering; and the saturation temperature of the calorimeter at atmospheric conditions. This establishes the base reference point where all saturated steam entering the calorimeter must fall. Outside of this range and the moisture content exceed the limitations of the calorimeter or super-heat conditions exist.

A 100.00% steam quality reference source must be established to calibrate the calorimeter. This requires the same source steam that will be exposed to the calorimeter, at the same pressure, at the same steam flow rate (control orifice), an ultra high efficiency polishing separator, with uniform dimensions and insulation on the external connections.

For high precision measurements, a dual calorimeter system is required to compensate for fluctuations in line pressure, barometric pressure, ambient temperature, gas variations, etc. One calorimeter will provide the 100% steam quality reference, while the other tracks the moisture in the steam. Everything must be as uniform as possible. The control orifice must be calibrated to ensure isokinetic flow. Calculations to size the orifice can be made using Napier's Formula:

$$w = \frac{ap_1^{.97}}{60} \quad \text{when } p_2 \text{ is less than } 0.58p_1 \quad (8)$$

where:

w = *dry steam in pounds per second*

p_1 = *upstream pressure psia*

p_2 = *downstream pressure psia*

a = *smallest section of nozzle or orifice in square inches*

A mass flow calibration can be established by flowing steam at choke flow through an orifice through a condensing coil (3/8" or 1/2") and measuring the condensate / NCG's (Jung,11). As long as the down stream pressure of the orifice is somewhere between 58% to 0% of the upstream line pressure, choke flow will be established and no additional flow will can pass though the orifice, even though a higher differential pressure is applied across the choke element.

Application

The throttling calorimeter is a valuable tool when used properly. Its application complements precision trace chemistry testing especially in areas where moderate cost, fast response time, and continuous monitoring are desired. This tool can be applied to monitor relatively dry production wells, separator performance, scrubber performance, steam wash and turbine wash. The reaction time, for detecting a serious separator upset can be fast (in a matter of seconds), offering additional protection against turbine and facility damage from geothermal fluids.

Summary

1. Poor geothermal steam quality & purity will cause premature equipment damage, reduce power plant efficiency, and result in lost revenue.

2. Virtually all fuel fired steam power plants continuously monitor steam quality / purity or fluid chemistry as a means to detect and prevent scaling, corrosion, loss of efficiency and premature damage to the steam turbine & components.

3. Representative steam quality and purity sampling and analysis is intrinsically complex. Isokinetic sampling, proper probe design, and understanding flow regimes are critical. Analytical techniques require special calibration to compensate for interference of various contaminates and conditions unique to geothermal applications.

4. Thermodynamic & trace chemistry techniques are two ways to analyze geothermal steam quality & purity. Both techniques can provide good accuracy and valuable information if properly installed and calibrated.

5. Trace chemistry techniques, although inherently of greater accuracy than thermodynamic methods, if properly implemented, have long time lags between sampling and analysis. The accuracy is highly susceptible to sampling error and contamination if improperly implemented.

6. Geothermal facilities perform periodical grab samples, with lag times between sampling/analysis/results spanning hours to days. The results can give a false impression of high steam quality and purity. Turbine scaling / erosion / corrosion is common in geothermal service.

7. Conventional calorimeter measurements in geothermal applications can be highly erroneous. Errors >> +/- 0.50% mass rates are common. This level of accuracy cannot protect the turbine and components from damage. Calibration techniques described in this paper can significantly improve accuracy in the determination of geothermal steam quality.

8. Throttling calorimeters incur errors from Joule-Thomson effects, heat loss, boiling point rise, static / stagnation effects, atomization, barometric pressure, gradients, etc., & sampling inaccuracy.

9. Geothermal steam quality can be measured to 99.95% with effective calibration and sampling.

10. Throttling Calorimeters can provide an inexpensive, fast response, continuous monitoring instrument for the detection of process upsets resulting in poor steam quality and purity.

References

1. ASME / ANSI PTC 19.11 Water & Steam in the Power Cycle.

2. ASME / ANSI PTC 19.3 Temperature Measurement.

3. ANSI/ASTM D1192 Equipment For Sampling Water & Steam.

4. Benedict, R .P., Fundamentals of Temperature, Pressure, and Flow Measurements, Second Edition, 1977, John Wiley & Sons.

5. Moyer, J.A., Power Plant Testing, 4th Edition, 1934, McGraw Hill.

6. Kearton, W.J., Steam Turbine Theory and Practice, 7th Edition, 1958.

7. Babcock & Wilcox, Steam, 39th Edition, 1978.

8. Baumeister & Mark, Standard Handbook For Mechanical Engineers, 7th Edition, 1967, McGraw Hill.

9. John, J.E.A., Gas Dynamics, 1969, Allyn & Bacon.

10. Moore, M.J., Two-Phase Steam Flow In Turbines and Separators, 1976, Hemisphere Publishing Corp.

11. Jung, D.B., Steam Quality & Purity Test Loop Calibration & Apparatus, 11-15-80, Internal Report.

12. Jung, D.B., Steam Wash Pilot Test, 2-25-81, Internal Report.

13. Jung, D.B., Sample Probe Design & Analysis, 5-7-81, Internal Report.

14. Jung, D.B., Continuous Monitoring of Steam Quality & Purity - Steam Wash, 10-16-81, Internal Report.

15. Jung, D.B., BPP Turbine Scaling - Steam Purification, 10-13-94, Internal Report.