Deployment of an Optical Steam Quality Monitor in a Steam Turbine Inlet Line

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ABSTRACT

The deployment and evaluation of an optical monitor for the real-time monitoring of steam quality in geothermal process streams is reported. The monitor is based upon the selective absorption of infrared radiation by moisture and uses optical components developed for the telecommunications industry in the design of a robust instrument capable of performing in harsh environments. The monitor was installed in a steam turbine inlet line at the Brady Geothermal Power Plant near Fallon, NV and operated for 150 days. During the deployment, the instrument was able to successfully track small changes (~0.25%) in moisture content that occurred during scheduled operations, such as turbine water washing, and also demonstrated the ability to alert operators to off-normal conditions.

Introduction

Geothermal plants contain gaseous, liquid, and particulate species in process streams that require abatement to minimize equipment damage, maximize performance and/or meet regulatory requirements. These abatement processes involve the use of costly chemicals and/or the consumption of energy; and in addition, are conservatively applied, in part, because the targeted species are only measured periodically. Consequently, engineers at the Idaho National Engineer-ing and Environmental Laboratory (INEEL) are investigating the application of devices that have been developed for the telecommunications industry for the design of robust instrumenta-tion for monitoring various process parameters (Partin and Jeffery, 1998, Partin and Davidson, 2002). The goal is to develop new, user-friendly technologies for the real-time control of abatement processes in geothermal plants to make them more efficient and less costly to operate.

The measurement of steam quality is important because of the impact that excessive moisture can have on turbine performance and maintenance costs. Moisture can be introduced into the steam line by either inadequate phase separation processes or during steam "washing" employed to reduce particulate, chlorides, and other chemicals to levels that are not as damaging to equip-ment. If too much water is added, the washing process may actually make the damage problem worse. Droplets entrained in the steam can erode turbine internals, while particulate and other contaminates dissolved or entrained in the moisture can deposit on and scale turbine compon-ents. Both scaling and erosion adversely impact turbine efficiency, which also decreases as the amount of moisture in the steam increases. Decreases in turbine efficiency reduce the power output and lower revenue streams. For a 50 MW plant the revenue losses due to a 1% loss in efficiency can be as high as $175,000 per year, depending upon the cost of electricity.

Eventually, the turbines must be removed from service for cleaning, resulting in additional lost revenues and maintenance costs. In some cases, very expensive turbine components have to be replaced.

Calorimeters are most commonly used for the measurement of steam quality, but difficulties with sensitivity, accuracy, and range limit their suitability for use in many applications. A number of factors can impact the sensitivity and accuracy of calorimeter data (Jung, 1995). The measurement of quality with this instrument is based upon the assumption of a constant enthalpy expansion from the process pressure to atmospheric pressure. Any heat loss from the measure-ment volume results in a deviation from this assumption and introduces error. The gases found in geothermal streams may also have different Joule-Thompson (dT/dP) coefficients; and conse-quently, a mixture of these gases and steam may not accurately correlate with the pressure and temperature curves used to interpret the data. In addition, because the calorimeter uses a side- stream flow it is difficult to obtain a representative sampling of the stream, even when multi-port probes are used. The calorimeter range is also restricted by its ability to produce a measurable superheat for determining steam quality. (For a 50 psig process stream expanded to one atmosphere, this minimum limit on the inlet steam quality is on the order of 97%.)

In order to address some of these measurement limitations, a new instrument has been developed for the real-time, *in-situ* monitoring of steam quality. The measurement is based upon the selective absorption of infrared radiation for determining the water content of moist air and takes advantage of the strong rotational and vibrational absorption bands produced by water vapor (steam) and liquid water in near-infrared ranges of the electromagnetic spectrum. Two wavelengths are typically used in the measurements: a wavelength that is strongly absorbed by liquid water and a reference wavelength that is minimally influenced by water and steam; and thereby, serves as the reference to correct for particulate or droplet scattering. The two wave-lengths are chosen to be as close as possible in order to more effectively correct for scattering effects.

While these techniques have been known for decades, they have not been widely used due to the cost and complexity of the instrumentation required. In general, large-scale, Nerst glowers were needed to provide sufficient infrared radiation for the measurements, which were typically performed in regions of the electromagnetic spectrum that were not compatible with remote sensing over optical fibers or the use of room temperature detectors (Wexler, 1963). The INEEL is investigating the re-engineering of these types of systems to incorporate semiconductor emitter and detector technologies that are compact, relatively inexpensive, and compatible with standard low-loss optical fiber technology. All of these components operate at room temperature and may be packaged as devices that can be directly interfaced to steam lines and used to collect and transmit data from locations throughout the plant.

The deployment and evaluation of the new optical steam quality monitor is presented. The monitor was installed in a turbine inlet line at the Brady Geothermal Power Plant located near Fallon, NV on August 20, 2003 and operated for 150 days. In addition to demonstrating that the device could be successfully installed and used to make high sensitivity measurements in an operating steam line, the goal of the extended deployment was to determine the long-term reliability and to identify any potential maintenance issues associated with the instrumentation.

Optical Steam Quality Monitor

The optical steam quality monitor records changes in signal intensities that are governed by Beer's Law. This law states that if a beam of parallel light rays of wavelength, λ, passes through an absorbing media, the original intensity, I_0, of this radiation will decrease by an amount that is dependent upon the number of molecules present, or the concentration of the absorbing medium, as follows

$$I = I_0 \exp[-\varepsilon(\lambda)\rho L] \quad (1)$$

In this expression, I is the intensity of the light measured at a distance L. I_0 is the initial light intensity. ε is an absorption constant for the medium that is dependent upon material compos-ition and wavelength λ of the light. ρ is the density of the medium and L is the absorption path.

In addition to signal loss, or attenuation, that is caused by absorption, the light may also be attenuated by scattering and through reflection from surfaces. The impact of these effects tends to reduce the value of Equation 1 by a constant amount or

$$I_1 = \beta I_{01} \exp[-\varepsilon(\lambda)_1 \rho L] \quad (2)$$

In this expression, I_{01} is the initial intensity of a probe beam of wavelength, λ_1, and β is a factor, approximately independent of wavelength that accounts for scattering and reflective losses, as well as for geometric losses as the beam propagates through the measurement volume. If a wavelength, λ_2, of light is not absorbed by the medium, its intensity is:

$$I_2 = \beta I_{02} \quad (3)$$

With a two-wavelength technique, a wavelength, λ_1, is selected that is absorbed by liquid water, but not by steam (vapor), and another wavelength, λ_2, that is not absorbed by either steam or water, and therefore, serves as a reference. Equations (2) and (3) can then be combined to give

$$\ln [I_1 / I_{01}] - \ln [I_2 / I_{02}] = -\varepsilon(\lambda)_1 \rho_{water} L_{water} \quad (4)$$

I_1 is the intensity of the water-absorbing wavelength, λ_1, and I_2 is the intensity of the reference wavelength, λ_2, after passing through the test section. I_{01} and I_{02} are the intensities of λ_1 and λ_2, respectively, with no water present. It should be noted that non-absorptive losses have been cancelled in this process and are no longer a factor. The constant, $\varepsilon(\lambda)_1$, generally must be established through calibration. The wavelength, λ_1, could be also chosen to be a wavelength that is more strongly absorbed by steam than liquid water, allowing for an independent determination of vapor concentration. Making this selection may give more sensitive results for some process conditions.

The optical steam quality instrumentation is shown in Figure 1. The monitor consists of an electronics package, containing laser diodes, beam combiners/separators, detectors and a data logger, that is fiberoptically-coupled to a pair of specially designed optical probes. The probes are aligned across the process stream of interest. This allows data to be collected in a volumetric cross section extending across the entire process stream, resulting in the collection of more repre-sentative data for higher accuracy measurements that are applicable to all flow regimes. The optical signals are collimated into a beam of radiation that is transmitted through a sapphire window and across the process stream where it is collected by an identical probe assembly and transmitted back to the electronics box for analyses. (Sapphire windows have a combination of physical, chemical, and optical properties that allow them to operate in high pressure, high temperature, and chemically caustic environments.) The probes can be located at distances up to 1 kilometer from the electronics package.

The stainless steel probes are designed for "hot tap" insertion into the process stream using a ball valve installation, as

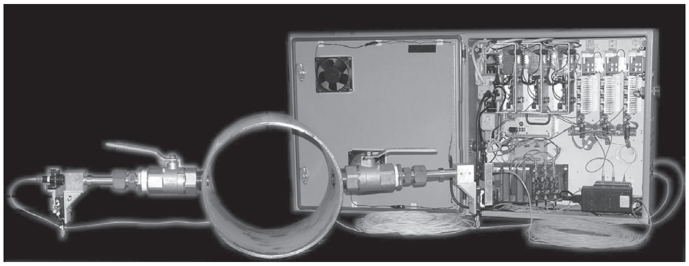

Figure 1. Monitor Instrumentation and *In-situ* Probes.

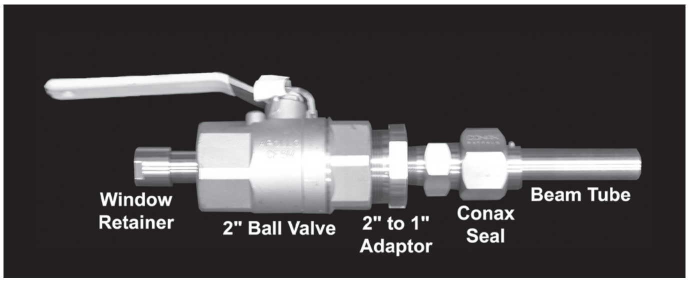

Figure 2. Ball Valve and Window Assembly.

illustrated in Figure 2. The process flow across the windows minimizes the formation of condensate and particulate deposition without the use of active heating or gas purging. The probes can also be easily removed for cleaning or replacement without shutdown of the process stream.

The 0-2.5 volt analog signals, collected from the monitor, are acquired using a National Instruments Fieldpoint data logging system, which also enables the data to be downloaded for display and processing on a user computer through a built-in ethernet connection. FTP and WEB-based access is also available. The data is archived on a 512 megabyte flash card with a new file generated every 24 hours. If a power failure occurs the system will reboot and auto-matically generate a new data file.

For the extended deployment and evaluation, the optical steam quality monitor was installed at the Brady Geothermal Power Plant, operated by ORMAT, Inc., near Fallon, NV. The plant was well-suited for the *in-situ* evaluation, since turbine water washing is periodically used in the operation to reduce scale, providing known changes in steam quality for the monitor to track. The optical probes were inserted into a turbine inlet line using aligned ball valve installations located immediately upstream of the turbine and downstream from a series of throttling valves, as shown in Figure 3. The optical signals, used for the determination of steam quality, were fiber-optically-coupled from the probes to the instrumentation box installed in the control room.

Experimental Results

The monitor was installed at the plant on August 20, 2003 and operated until January 17, 2004. The signals recorded were correlated with known changes in the plant operation, such as water washing, changes in the chemical treatments used for particulate inhibition, or other changes in plant operations which could impact steam quality. An example of the instrument's response during a washing cycle is presented in Figure 4. The graph shows a reduction in the monitor signal amplitude due to absorption and scattering as small quantities of water, 1.0-1.5 gallons per minute, were metered into the nominally 120,000 lb/hr steam flow.

As indicated in Figure 4, the instrument was able to track small (0.25% or less) changes in steam quality that occurred during water washing cycles conducted during the deployment. This result is particularly encouraging since the data was collected in a turbulent flow regime which is the most challenging for maintaining optical alignment and provides the highest potential for measurement fluctuations. The monitor also demonstrated the ability to alert operators to various off-normal conditions. An example of one of these off-normal events is illustrated in Figure 5, where data trends

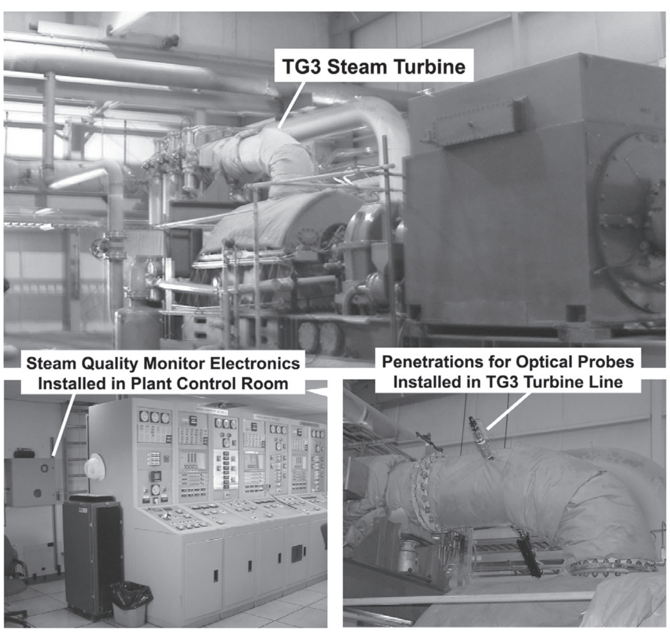

Figure 3. Optical Steam Quality Monitor Deployment at Brady Power Plant.

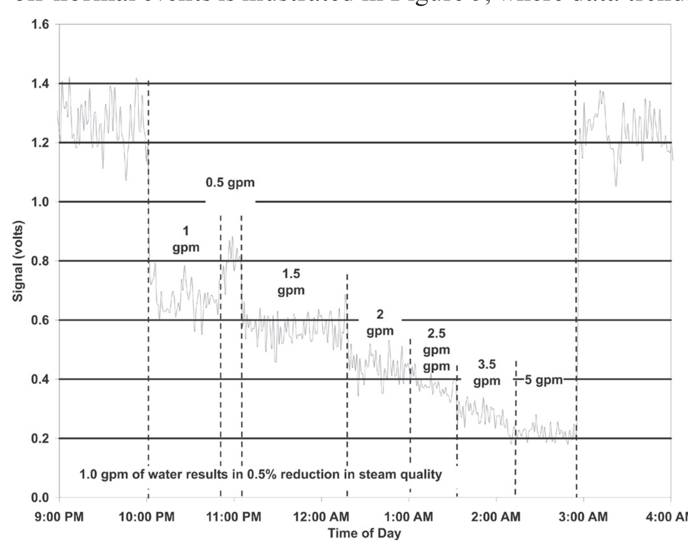

Figure 4. Steam Quality Data Collected During Water Washing Procedure.

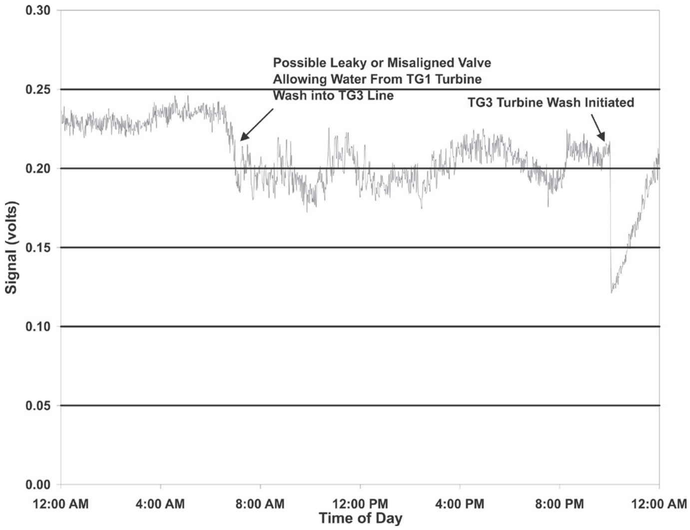

Figure 5. Steam Quality Monitor Detection of Valve Problem.

correlating with water washing helped locate a problem with valve seals on the water wash isolation systems. Referring to the figure, a loss in signal level, indicating a decrease in quality, is detected at the same time (around 7 AM) that a water wash is being performed on a different turbine system, TG1. From the data, it appeared that the water wash supply valve to the TG3 turbine might have misaligned or leaked, allowing moisture into the steam line to TG3.

Some fouling of the probe windows did occur during the deployment. In Figure 6, the value of the water sensitive diode signal collected by the monitor at 12 AM each day is plotted for a period of 60 days (October 12, 2004 - December 10, 2004). The signal is seen to decrease in amplitude at a rate of approximately 2.5% per day until day 34, when a water washing cycle was performed. The signal amplitude is seen to recover around 75% of the pre-wash value then continue to decrease at approximately the same rate.

The fouling, while not desirable, was easily corrected using the reference signal and generally was small enough on a per hour basis that it did not impact the monitor's ability to track off-normal events without correction. In fact, the fouling itself could be used as an indicator of when washing is merited and could also be used to determine when internal components are sufficiently clean that the process could be terminated.

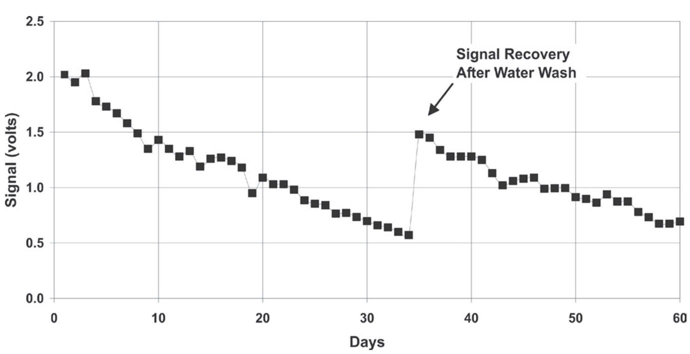

Figure 6. Change in Monitor Signal Output Due to Fouling.

Conclusions

A new optical steam quality monitor has been developed. The monitor offers several advantages over existing techniques. The measurement is based upon a direct, rather than inferred, indication of the presence of water using very sensitive spectroscopic techniques for improved sensitivity and accuracy. The instrumental configuration is simple, compact, and can be fiberoptically-coupled to locations of interest. Open path measurements are possible allowing real-time data to be collected within a volume that extends through a cross-section of the process stream. This results in a more representative sampling of the stream and avoids the errors intro-duced into the measurements with point sampling of complicated flow regimes. The data can be recorded continuously with analyses available within seconds. The instrumentation can also operate over a wide range of moisture conditions.

The monitor was installed in a steam turbine inlet line at the Brady Power Plant for testing and evaluation. The *in-situ* installation and alignment of the valve assemblies for the probes was performed in less than 10 hours. During the 150 day deployment, the device was able to successfully track small changes in moisture content that occurred during scheduled operations such as water washing to reduce scale. In addition, the monitor also demonstrated the ability to alert operators to off-normal conditions in the plant. The instrument operated with minimal impact to the plant operation. No serious maintenance issues were discovered during the operation. In fact, the optical probes were never removed for cleaning or repair during the entire deployment.

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References

Partin, J.K. and C. L. Jeffery, 1998. "Investigation of Near-Infrared Diode Laser Spectroscopy for H_2S Monitoring in Geothermal Plants," Geothermal Resources Council *Transactions*, v. 22, p. 435-439.

Partin, J. K. and J. D. Davidson, 2002. "Investigation of Optical Technologies for Measuring Geothermal Fluid Properties," Geothermal Resources Council *Transactions*, v. 26, p. 739-743.

Jung, D.B., 1995. "Geothermal Steam Quality Testing," Geothermal Resources Council *Transactions*, v. 19, p. 575-583.

Wexler, A., Ed., 1963. *Principles and Methods of Measuring Humidity in Gases*, Reynold Publishing Corporation, New York, New York.