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Humidity Measurement in Fuel Cells and Gas Turbines: Practical Application of Warmed Probe Sensor Technology

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Abstract: This paper describes the practical application of humidity instrumentation for water management in fuel cells and inlet air monitoring of gas turbines. A description of the instrumentation is provided. Measurement challenges in each application are identified and successful solutions are described in detail.

Keywords: humidity, fuel cell, turbine.

1. INTRODUCTION

Much work has been done in the laboratory to devise and refine standards for precise water vapor metrology. Beyond the scientific merit of this work, the ostensible purpose is to enable the development of new or improved measurement technologies, which in turn are used by various industries to improve process capability or performance.

This paper bridges the gap between the laboratory and the practical application of humidity measurement technology for industrial purposes. It demonstrates the real-world value of measurements that were difficult or impossible just ten years ago.

We will begin by describing a humidity measurement innovation and its theory of operation. Two separate applications for this innovation will then be described in detail. The first is the measurement of water vapor in hydrogen in the high temperature, high humidity conditions found within proton exchange membrane (PEM) fuel cells. The second is the measurement of humidity in the inlet air of combustion turbines used for power generation.

2. HUMIDITY MEASUREMENT USING THE WARMED SENSOR HEAD METHOD

Polymer based humidity sensors are commonly used to measure humidity over a wide range of conditions. Condensing conditions sometimes compromise accurate and responsive environmental humidity measurements. These conditions are detected by a polymer sensor, but the wet sensor may not respond to subsequent drier conditions in a timely fashion, as it is necessary for water on the sensor to completely evaporate before accurate measurement can resume. Vaisala developed and patented the warmed sensor head method to expand the capability of polymer sensors [1]. In this method, the polymer humidity sensor is warmed a few degrees above ambient temperature to prevent condensation. The temperature of the humidity sensor is measured by a platinum resistance temperature detector, which is bonded to it. With measured temperature and relative humidity values, it is possible to calculate the partial pressure of water vapor and other humidity parameters using well-known formulas (available from many sources, e.g., P. Wiederhold's text on water vapor measurement [2]).

The warmed sensor head technique also improves speed of response when the temperature around the sensor is changing. With a conventional relative humidity measurement, the sensor must come to thermal equilibrium with the environment before a reliable measurement can be obtained. This is a dominant factor in response time [3]. The warmed sensor technique does not require thermal equilibrium with the environment; speed of response depends primarily on the diffusion rate of water vapor molecules to the sensor's polymer dielectric material.

An evolution of the warmed sensor head technique now includes the automatic, short-term application of extra heat to the humidity sensor when it is exposed to very high humidity or liquid water. When extra heat is called for, the measurement is interrupted while the temperature of the humidity sensing element is rapidly increased to evaporate any liquid water. Measurement resumes when the sensor cools and temperature and humidity are within acceptable limits. This recovery function is designed to address rapidly changing conditions (e.g., entrained water droplets in an airstream, or process pressure variations that may result in the formation of condensation) that cannot be addressed by sensor head warming.

The warmed sensor technique has been applied to environmental measurements with good success. More recently, the technique has been used to address industrial applications with similar challenges.

3. PEM FUEL CELLS

PEM fuel cells use hydrogen as a fuel to create electricity. Hydrogen flows through the cell and comes into contact with a polymer membrane. The membrane is typically hydrated by humidifying the hydrogen. Hydration is critical to the performance of the membrane; too much or too little water reduces the performance of the membrane.

3.1. Measurement conditions

Humidity measurements are made in PEM fuels cells to assure that hydrogen is humidified to an optimum level. Specific conditions vary among cell manufacturers, but the temperature of the hydrogen is often in the range of 75 to 90 °C. Relative humidity is typically 80% or higher. Measurements may be made at atmospheric pressure, or at pressures up to 350kPa.

3.2. Measurement experience

Initial measurement attempts of the conditions described above provided mixed results. Although several end users were working on similar applications, none were willing to divulge the exact measurement conditions. Commercial fuel cell development was often performed with a degree of secrecy in 1998, when Vaisala first became aware of this application. As a result, the users specified their own instruments. In a typical instance, a cylindrical steel probe was specified by the user to seal into a positive pressure environment. Only the tip of the probe was installed into the process, leaving approximately 150mm of steel probe outside of the process in ambient room conditions. When the fuel cell system was run at target conditions, the sensor output became erratic. Subsequent examination of the sensor indicated that condensation had been present on the sensing element, even though saturation conditions were not thought to be present. Author Santoro and colleagues, upon learning the details of the measurement conditions, concluded that the exposed steel probe was sinking heat from the process. The probe tip inside of the process was equilibrating at a temperature lower than the process dewpoint, resulting in the formation of condensation on the sensor.

The user was able to gain some satisfaction by wrapping the exposed metal probe with heating apparatus and maintaining the exposed probe body at a temperature near the process temperature. This increased system complexity, which was acceptable for process development but undesirable for production equipment.

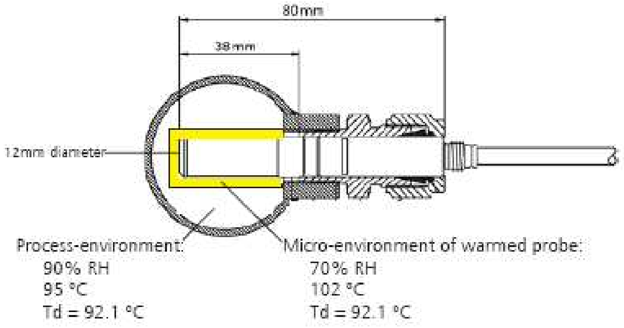

Fig. 1. Diagram of typical probe installation showing process conditions and the and the micro-environment created by probe warming.

3.3. Measurement solution

Vaisala technical staff reasoned that warmed probe technology developed for environmental measurements might be a good fit for the fuel cell measurement. The probe assembly of the HMP247 warmed sensor head instrument is made of steel and is pressure tight, but only 69mm in overall length, with more than half of this inserted into the process. The instrument maintains the temperature of the probe above the process temperature at all times, effectively eliminating the possibility of condensation.

Initial field testing of the warmed sensor head gave excellent results. An off-the-shelf instrument was able to provide valid and reliable measurements without modification. Since then, over one hundred warmed head instruments of various types have been installed in fuel cell applications.

4. INLET AIR MONITORING OF COMBUSTION TURBINES

Combustion turbines are used to generate electricity in many parts of the world and must be capable of operating over a wide range of environmental conditions. Monitoring of the humidity of the turbine's inlet air is done to improve the operating efficiency of the turbine, and in some cases, to protect the turbine ice formation.

4.1. Measurement conditions

Hygrometers used for inlet air monitoring in combustion turbines must operate over the range of environmental conditions found at the location of the turbine. Ice formation within the turbine inlet assembly is undesirable, as pieces of ice may break free and be ingested into the high-speed compressor vanes, opening the possibility of substantial damage. Instruments used for detection of icing conditions must function reliably when temperatures are at or just above 0 °C and relative humidity is high.

Water vapor measurements may also be made downstream from water injection apparatus. Water is injected into the inlet air to manage the efficiency of the turbine on hot days.

4.2. Measurement experience

Several years ago, Vaisala was asked by a manufacturer of power turbines to submit an instrument for testing in the inlet air duct of a combustion turbine used for power generation. A standard relative humidity instrument worked well and even recovered from saturated conditions. The user desired faster recovery from saturation, so a warmed sensor head device was also tested. This instrument provided measurements with high reliability and little or no downtime due to saturation.

The warmed sensor head was also tested in the more demanding post-water-injection application. In this case, even the warmed sensor head saturated and would not recover. Water injection is accomplished by atomizing water directly in the inlet duct, resulting in small water droplets directly impinging on the humidity sensor.

4.3. Measurement solution

Recognizing that physical impingement cannot be overcome even with a warmed probe, author Santoro improvised a solution during field trials on a combustion turbine in Florida, USA. A section of PVC pipe was purchased from a local building supply store, and a makeshift baffle was constructed by drilling a line of holes in the pipe to facilitate airflow. The baffle was installed over the probe with the holes facing away from the direction of airflow. This arrangement protected the sensor from impingement, enabling continuous measurement during water injection.

Ultimate design of the baffle was determined by testing several configurations of hole patterns. The final design greatly reduces impingement on the sensor and allows any collected water to drain from the baffle. The steel baffle assembly fits closely over the humidity probe, providing a mechanism to keep the probe's screw-on sintered metal filter captive in the event that it loosens during service. This is extremely important, as any loose parts from this section of the inlet duct would be ingested by the turbine.

The turbine manufacturer referenced above has standardized on Vaisala warmed probe devices and has since ordered many instruments. At least one utility company has installed warmed probe devices on existing turbines and reported positive results [4].

Fig. 2. Photograph of warmed probe and a "field expedient" baffle fabricated on site from PVC pipe. The baffle protects the humidity sensor from direct impingement of entrained water droplets.

5. CONCLUSIONS

Humidity instruments using warmed sensor head technology can provide reliable measurements in saturated or near saturated conditions over a wide range of temperatures. This capability has practical industrial applications that provide real benefits to users. Combining a user's process expertise and an instrument maker's measurement expertise can successfully move technology from the laboratory to the industrial domain.

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