A Microwave Sensor for Steam Quality

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Abstract—A microwave-based in-line sensor for steam quality is described and test results are reported. The sensor employs a novel high-pressure process seal that minimizes mismatch effects when water condenses on its inner surface.

Index Terms—Dielectric measurement, microwave measurements, interferometer, process monitoring, steam quality.

I. INTRODUCTION

Steam quality is the parameter that quantifies the amount of condensed water present in steam. Although quality is an important process variable, it is not one that is easily measured in real time. A standard method for measuring steam quality involves expensive and complicated calorimeter devices, as well as considerable time and effort [1]. As a result, timely measurements of quality are often not available. This is an undesirable situation that leads to less-efficient and less-economical operation of a given process.

In response to this problem, a novel microwave probe-type sensor that can be permanently inserted into process piping has been developed to provide real-time, in-line measurement of steam quality [2].

Among the difficulties in designing such a probe for steam quality measurement is the hostile environment in which the sensor must operate. In particular, the problem of coupling microwave energy into and out of a steam pipe or vessel is not trivial. The probe reported here employs a coaxial feed-thru structure that can withstand the high temperatures and pressures of a steam line, as well as tolerate significant condensation of water on its dielectric surfaces.

II. INSTRUMENT FEATURES

A. Measurement Principle

The dielectric properties of water continue to be of considerable interest, both for pure water as well as for water mixed with and bound in other materials [3]. At 100°C the real part of the static relative permittivity of water changes from about 56 for the liquid phase to approximately 1.012 as a gas [4]. This large difference in permittivity between liquid water and steam provides the basis for measuring quality with a microwave sensor.

The formula for steam quality, denoted by \( x \), is

\[
x = \frac{m_s}{(m_s + m_w)}.
\]

Here, \( m_s \) is the mass of the dry steam and \( m_w \) is the mass of the liquid water [5]. The mass quantities can equivalently be expressed in terms of corresponding mass flow rates. Quality is often expressed as a percentage.

Whereas there is a large difference in the permittivities of liquid and vapor, the typical range in the permittivity values seen for a mixture of water and steam is much less. This reduction in sensitivity is due to the fact that the permittivity of a mixture of molecules depends upon the relative volume occupied by each constituent [6]. As a consequence, the permittivity of steam varies only from about 1.012 for dry steam to about 1.08 for 50% \( (x = 0.5) \) quality steam at 100°C. As temperature increases, the permittivities of both dry steam and water decrease.

Fig. 1 shows the predicted change according to an index of refraction mixing equation in the static value of the relative permittivity of steam at a pressure of 1034.2 kPa and temperature of 171°C, as the quality varies from 50 to 100%. The common index of refraction mixing equation may be written as

\[
\varepsilon_{\text{mixture}} = \left[ \phi_1 \cdot \varepsilon_1 + \phi_2 \cdot \varepsilon_2 \right]^2,
\]

where \( \varepsilon_{\text{mixture}} \) is the permittivity of the mixture of two homogeneous materials, \( \phi_1, \phi_2 \) are the volume ratios of the two materials, and \( \varepsilon_1, \varepsilon_2 \) are their electrical permittivities.

To express the mixing equation in a form that shows the permittivity in terms of steam quality, \( \varepsilon(x) \), it is necessary to write the volume fraction of each component in terms of the quality variable \( x \) and the densities of water in its two phases. If \( \rho_s \) is the density of steam and \( \rho_w \) is the density of liquid water, then the mixing equation for the static value of the permittivity as a function of steam quality \( x \) is found to be

\[
\varepsilon(x) = \left[ \frac{x \cdot \left( \rho_w / \rho_s \right)}{1 + \left( \rho_w / \rho_s - 1 \right) \cdot x} \cdot \varepsilon_w^\gamma + \frac{1 - x}{1 + \left( \rho_w / \rho_s - 1 \right) \cdot x} \cdot \varepsilon_s^\gamma \right]^2,
\]

where \( \gamma \) is a parameter that depends on the temperature and pressure of the system.
where $\varepsilon_B$, $\varepsilon_w$ are the permittivity values for pure steam and liquid water, respectively, at the appropriate temperature and pressure.

![Graph showing the predicted permittivity value as a function of steam quality.](image1)

**Fig. 1.** Permittivity of 1034.2 kPa steam as a function of steam quality.

### B. Sensor Configuration

The instrument described here uses an interferometer technique based upon differential path lengths to sense the changing permittivity of steam as its quality varies. The sensor consists of two parallel transmission lines exposed to the steam. These lines of different length and are terminated in short circuits. This differential-length ($\Delta L$) design provides several advantages for the steam environment. Because each line is exposed to the same temperature and each penetrates a process seal into the steam line, there are minimal errors caused by differential heating of the lines. Likewise, both signal paths include process seals that are exposed to the same coating and condensing conditions. With suitable averaging, any errors associated with these effects are minimized. The photo of Fig. 2 shows the portion of the probe that is inserted into the steam line.

![Photograph of the probe portion of the $\Delta L$ sensor.](image2)

**Fig. 2.** Photograph of the probe portion of the $\Delta L$ sensor.

For the sensor implemented here, a waveguide hybrid tee is used to present balanced swept-frequency signals to the parallel transmission lines. The input signals are of equal phase when applied to the H-plane (narrow wall) arm of the tee. The reflected waves that are produced on each of the transmission lines by the short circuit terminations are subtracted by the tee to produce a resultant signal in the tee’s E-plane arm.

The electrical lengths of the exposed portions of the two lines vary according to the electrical properties of the steam. When the frequency of the source is adjusted such that the wavelength in the steam-exposed lines is equal to $2\Delta L$, a null condition is observed at the output. Fig. 3 shows the prototype unit as installed in a steam line for testing and calibration.

To minimize the number of components in the assembly and to provide a high integrity pressure seal design, the main body of the waveguide hybrid tee, comprising the co-linear and H-plane arms, is machined into the outer face of the mounting flange of the sensor. Small holes in each of the co-linear arms of the tee allow the center conductors of the parallel coaxial transmission lines to be inserted to form a waveguide to coax adapter. The outer conductors for the coaxial transmission lines that connect the signal to the exposed sensing portion of the assembly, seen in Fig. 2, are also machined as integral parts of the mounting flange. The center conductors of the coaxial lines penetrate ceramic process seals and connect to the exposed transmission lines that make the $\Delta L$-sensor. The ceramic seals are laser welded to the inner and outer conductors, which are also made of stainless steel.
Fig. 3. Photograph of the complete sensor assembly installed in the steam test loop.

Fig 4 is a cutaway of view of the transmission line assembly. The center conductors projecting from the right side in the figure are those that penetrate the co-linear arms of the hybrid tee and couple energy between the waveguide arms and the coaxial lines. Ceramic spacers, which also form the dielectrics for the coaxial lines, are placed between the inside wall of the waveguide and the process seals that allow the microwave energy to enter the steam pipe.

The ΔL length for the sensor is about 14.4 mm (0.56 inches). The choice of length was based upon providing a proper insertion depth and sampling area cross-section for the chosen pipe size. The insertion depth for the sensor is approximately 13.98 mm (0.55 inches) and was chosen to position the center of the ΔL portion of the transmission lines at the same recommended depth as that of a sampling nozzle used in a calorimetric steam quality measurement as specified in the ASTM standard for sampling steam. The recommended depth is 0.2R, where R is the radius of the pipe [1].

The frequency of operation is set by the ΔL value. For this ΔL, the null frequency is computed to vary from about 10.346 GHz for dry steam (100% quality) to about 10.275 GHz for 50% quality steam.

The design of the process seals required dealing with the situation in which the inner surfaces of the seals are coated with a thin film of water. Although the water will be reasonably pure, and therefore have a fairly low conductivity, the reflection from the water film could be substantial. To minimize the effects of the discontinuity between the transmission line and the steam in the pipe, the inner face of the ceramic dielectric of the seal is tapered as shown in Fig. 5. The drawing shows both the outer stainless steal portion and the inner dielectric material. The ceramic has a relative dielectric constant of about 4.5. The large diameter of the ceramic portion of the seal is about 22 mm and it tapers to a diameter of 6.45 mm over a length of about 9.85 mm. The center conductor diameter is about 1.3 mm.

Fig. 5. Inner face of ceramic dielectric process seal.

With this configuration, the transition can tolerate even a highly conductive film of water on its inner surface. If the water becomes conductive, the film behaves as the outer conductor of the transmission line. The characteristic impedance of the line varies according to the changing diameter of the line, but a sharp discontinuity, with corresponding large reflection, is avoided. At the very tip of the seal, a conductive film will behave as part of the center conductor and the line voltage is established between the narrow tip and the outer diameter sleeve of the seal.
An important consideration for any steam quality sensor is that of measuring a truly representative sample of the steam/water mixture. To minimize sampling errors, a slotted orifice mixing plate was placed in the line upstream of the steam quality instrument for the purpose of achieving a homogeneous flow profile [7].

III. EXPERIMENTAL PROCEDURE

An experiment was run at the Turbomachinery Laboratory at Texas A&M University in which the raw output of the sensor was calibrated to steam quality measurements as determined from independent measurements. The A&M steam system provided for carefully controlled injection of water to vary the steam quality value over the desired testing range and instrumentation for temperature, pressure and flow to assure uniform and accurate quality set points.

Details of the steam generation and measurement system are documented by Flores [7]. The limiting factors for the accuracy of the steam quality value used in calibrating the microwave instrument were the accuracy of the mass flow rate sensors for both water and steam. The error in quality obtained via the reference instrumentation, as determined from data supplied by Flores, varied from about ±0.4% to ±1%, depending upon the quality value. The error varied over the span of quality values due to the differing accuracies of the mass flow meters that were needed to cover the full span. To achieve the wide span in quality values it was necessary to employ two flow meters for measuring the injected water. A small-capacity higher-accuracy flow meter was used to measure the injected water for quality values greater than about 85%. For quality values between about 60 and 85%, a larger capacity meter was needed. The larger capacity meter was operating near the bottom end of its range and exhibited higher standard deviations in reported readings.

Fig. 6 shows the forward scattering parameter waveforms, $S_{21}$, for the $\Delta L$ steam sensor as measured by a vector network analyzer (VNA). The waveforms shown are near the opposite ends of the test measurement range, which varied from about 60 to 100% quality. A minimum of three independent readings, each the result of averaging 16 waveforms, were taken with the VNA at each quality set point. The frequency at the minimum point in the waveform was determined using the VNA instrument’s signal-minimum tracking feature.

The VNA used in this test is configured with a high accuracy reference oscillator, which is reported by the manufacturer to provide a frequency accuracy of ±1Hz. The absolute accuracy of the frequency measurement, however, is not of primary important in the calibration of the microwave sensor since the actual permittivity values of the steam-water mixture are not necessary, nor were they computed. Rather, the sensor is calibrated directly against the independently determined quality value, as is typically done in the calibration of microwave sensors [3]. The frequency span of the VNA for the experiment was set to be from 10.2 GHz to 10.4 GHz in 1601 steps, giving a frequency step size of 125 kHz. This frequency step size corresponds to a quality range of approximately 0.0825%. Fig. 7 shows the measured average minimum frequency readings for each of the quality data points.

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**Fig. 6.** Captured instrument screen shot for two steam quality set points.

**Fig. 7.** Sensor output frequency versus reported steam quality value.
Fig. 8. Calibration performance for the microwave steam quality sensor.

IV. CONCLUSION

The calibration results are shown in Fig. 8. These data were produced with an Excel spreadsheet linear regression tool using output frequency, square root of frequency, and frequency squared as the independent variables and the lab measured steam quality as the dependent variable. The data exhibit an adjusted R-squared of 0.945 and a standard error of 0.028 (2.8% quality).

The prototype sensor performed well and provided a solid demonstration of the measurement method for steam quality. The measurement span was quite large in comparison to normally desired operating conditions. The wider spread in center portion of the data shown in Fig. 7 can, in some degree, be attributed to the flow meter inaccuracies rather than the quality sensor being tested. The data point showing a quality value greater than 100% (x>1) represents a superheated steam situation.

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REFERENCES

[4] NIST/ASME STEAM PROPERTIES DATA BASE: VERSION 2.21, NIST Standard Data Base 10, From International Association for the Properties of Water and Steam (IAPWS), 1995