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**MICROWAVE DETECTION OF MOISTURE
IN REACTOR COOLANT GAS
INTERIM REPORT**

D. P. BROWN and T. R. BILLETER

MAY 1967

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By

D. P. Brown and T. R. Billeter

Instrumentation Section
Applied Physics and Electronics Department

May 1967

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INTRODUCTION

Helium, because of its many suitable characteristics, can be employed as the heat absorbing medium in gas-cooled nuclear reactors. Because moisture in the gas is deleterious to proper system operation, it is necessary to monitor the coolant for water vapor. Quick response and reliable indication of moisture content are important considerations. The need for rapid monitoring response implies a detector capable of operating at the high temperature of the coolant so as to materially reduce the holdup time of a gas sampling system. Microwave measurement techniques hold strong promise for successful application to the problem.

Three basic approaches appear to be feasible for determining the moisture content of a gas with microwaves:

(1) measuring the frequency shift of a resonant cavity--this frequency shift is caused by the changing dielectric constant of the gas mixture--(2) measuring the phase shift of the signal in a section of waveguide--this phase shift is caused by the change in dielectric constant--and (3) determining the attenuation of the signal in a section of waveguide--this attenuation is caused by water molecules absorbing microwave energy. Of these methods, the first two are sensitive enough to allow measurements of small amounts of water vapor. The third method would require excessive lengths of waveguide to secure the required attenuation for sensitive measurements, as the values of absorption at about 22 GHz are about 0.1 dB km^{-1} . Thus, it was decided to investigate in detail the first two methods. The phase shift method has promise for use as a

truly in-line monitor, as the piping, or a section thereof, could conceivably act as a "waveguide" as well as a coolant pipe. However, this interim report is primarily concerned with the investigations for detecting moisture by the frequency shift method.

SUMMARY

The use of microwaves to detect and measure the moisture content of gases used for cooling reactors is being investigated. The detection sensitivity is limited by the stability of the microwave generator, its associated references, and the ability to measure frequency changes. At room temperature, the change in the dielectric constant of the gas mixture is measured by the change in the resonant frequency of a microwave cavity through which the gas flows. Detection sensitivity is 85 ppm change at concentrations of 400 ppm water vapor in helium. Because the dielectric constant is a function of temperature, an increase in temperature will decrease the dielectric constant and will reduce detection sensitivity. At 436 °C, the detection sensitivity was 875 ppm of water vapor in helium.

DISCUSSION

RESONANT CAVITY METHOD

The resonant frequency of a microwave cavity is a function of the dielectric constant of the material contained within the cavity. This is expressed in the following equation:

$$f^2 = \frac{k}{\epsilon} \quad , \quad (1)$$

where ϵ is the dielectric constant of the medium filling the cavity, k is a constant, and f is the resonant frequency.

From this, an expression can be derived expressing the resonant frequency change of the cavity as a function of the dielectric constant change.

$$\Delta f = \frac{f_1}{2} \Delta \epsilon \quad , \quad (2)$$

where

$$\begin{aligned} \Delta f &= f_1 - f_2 \\ \Delta \epsilon &= \epsilon_2 - \epsilon_1 \end{aligned} \quad .$$

These equations were derived by assuming that $\epsilon_1 \approx \epsilon_2 \approx 1$ and $f_1 \approx f_2$. These assumptions are reasonable inasmuch as the total frequency shift expected is about one MHz at a frequency of 30 GHz.

The dielectric constant of a gas is given by Debye as:

$$\frac{\epsilon - 1}{\epsilon + 2} V = \frac{4 \pi N}{3} \alpha \quad , \quad (3)$$

which leads to

$$\epsilon - 1 = 4 \pi N_1 \alpha \quad ,$$

where $N_1 = 2.68 \times 10^{19}$ molecules/cm³ and α is the polarizability.

For a mixture of two gases, in which a gas of molecules n_2 are added to a gas of molecules n_1 ,

$$\epsilon - 1 = 4 \pi n_1 \alpha_1 + 4 \pi n_2 \alpha_2 \quad ;$$

and since $n_1 + n_2 = N_1$,

$$\Delta \epsilon = 4 \pi n_2 (\alpha_2 - \alpha_1) \quad . \quad (4)$$

Thus the change in dielectric constant is related to the number density of molecules of gas n_2 and to the difference in the polarizabilities of the two gases.

Substitution of $\Delta\epsilon$ from Equation (4) into Equation (2) gives an expression for the change in frequency as a function of the number of water molecules (gas n_2):

$$\Delta f = 2 \pi f_1 (\alpha_2 - \alpha_1) n_2 ,$$

or

$$n_2 = \frac{1}{\omega (\alpha_2 - \alpha_1)} \Delta f$$

$$n_2 = 1.84 \times 10^{11} \Delta f \text{ molecules/cm}^3 . \quad (5)$$

This number is the theoretical sensitivity of the cavity. Actual sensitivity depends on system ability to resolve a frequency difference. The method used, to be described in a later section, can resolve 9.5 kHz on a short term basis. This is approximately equivalent to 65 ppm of water vapor in the gas.

METHOD OF MEASUREMENT

Measurement of a frequency change of 9.5 kHz at a base frequency of 30 GHz requires a stable oscillator. For this reason, the system oscillator was frequency-locked to a reference cavity tuned to the same frequency as the sample cavity containing dry helium. Deviation of the sample cavity resonant frequency was then measured with respect to the reference cavity. The method of doing this is explained in detail in the appendix.

A variable pressure saturator⁽¹⁾ was used to provide controlled amounts of water vapor content, and the actual amount was measured by a "dewpointer".* Figure 1 is a schematic of the measuring system. The dry helium gas is introduced into the variable pressure saturator at 100 psig, where a pressure

* Dewpointer, an instrument for determining the dew point of gas mixtures.

reducing valve can vary the pressure from 0 to 100 psig. A second pressure reducing valve keeps the output pressure constant at one psig across the cavity. The water content in parts per million is a function of the water vapor pressure and of the total pressure on the high pressure side of the second pressure reducing valve and can be expressed as follows:

$$H_2O_{\text{ppm}} = K \frac{P_{H_2O}}{P_T},$$

where P_{H_2O} is the vapor pressure of the water, and P_T is the total system pressure. Thus the water content can be varied over a wide range by varying the system's total pressure. The gas then passes through the dewpointer before entering the detection cavity. This cavity, shown in Figure 2(d), is a cylindrical microwave cavity operating in the TE_{011} mode. It is 0.55 in. in diameter and 0.35 in. deep, with 0.106 in. diam coupling holes in the cylinder walls. The gas is introduced through a small hole in one end and exits through a small hole in the opposite end.

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FIGURE 1. Microwave System

(a) Microwave Apparatus

(b) Variable Pressure Saturator

(c) Microwave Circuit Showing Placement of Sample Cavity

(d) Sample Cavity

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FIGURE 2. Test Apparatus

The microwave generator is frequency-locked to the reference cavity that is tuned to the resonant frequency of the sample cavity containing dry helium. The reference signal of the phase-lock amplifier serves to modulate slightly the frequency of the generator about the reference cavity resonant frequency. If the generator frequency is matched to the cavity resonant frequency, the detected signal at the reference cavity output will contain only the second harmonic of the modulation frequency. If the generator frequency is not matched to the cavity resonant frequency, there will be a component of the

modulation-frequency fundamental which can be amplified and averaged by the phase-lock amplifier and which can be used to bring the generator frequency back to the cavity resonant frequency. By this method the microwave generator is kept tuned to the reference cavity. This modulation of the generator frequency is also used in the detection system. A more complete discussion of how the modulating frequency is used in both the stabilization loop and the detection system is presented in the appendix. Shown in Figure 2 are pictures of the actual test apparatus.

Figure 3 shows the response of the detector over a range of <50 ppm to $>15,000$ ppm. It is thought that the nonlinearity at the low values of moisture concentration is due to the difficulty of reading the dewpointer, as this device relies upon human ability to observe the formation of water droplets in a pressure chamber into which a sample of the gas has been compressed and suddenly decompressed. The point in the pressure ratio at which no droplets are formed is the dewpoint. The usual error would be in failing to see droplets when they are present. This would result in reading too low a pressure ratio. Higher pressure ratios would move the points to the right on the graph of Figure 3.

The speed of response of the experimental system is limited only by the transport time of the gas to the cavity and by the time constant of the synchronous demodulator used in the detection circuit. This time is about 10 seconds for full indication of a step increase, or a time constant of about two seconds. The time constant of the synchronous demodulator was set at one second. Figure 4 is a section of chart from a recorder showing the response to step changes in moisture content.

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FIGURE 3. System Response

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FIGURE 4. Output Versus Time for Step Changes in Water Vapor Content

PHASE SHIFT METHOD

The phase constant of a waveguide is

$$\beta = \frac{2\pi f}{c} \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \sqrt{\epsilon} \quad , \quad (6)$$

where β = phase shift in degrees per centimeter and

f = frequency

f_c = waveguide cutoff frequency

ϵ = dielectric constant.

From this equation the expression can be derived for the change in phase for a corresponding change in dielectric constant as follows:

$$\Delta\beta \approx \frac{\pi f}{c} \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \Delta\epsilon \quad . \quad (7)$$

Substituting into Equation (7) the values of the various parameters gives for the change in phase,

$$\Delta\beta = 4.63 \times 10^{-20} n_2 \text{ deg cm}^{-1}$$

or

$$\Delta\beta = 12.4 \times 10^{-7} \text{ deg cm}^{-1} \text{ ppm}^{-1} \quad . \quad (8)$$

It is evident from Equation (7) that the phase shift is a function of frequency, and from Equation (8) a function of waveguide length. Choosing an appropriate length would result in phase shifts that are readily measureable. For example, with a 10-meter long waveguide at 30 GHz and 1,000 ppm, the total phase shift would be

$$\Delta\beta = 1.05 \text{ degrees} \quad .$$

The actual sensitivity and other limiting factors will be determined by future planned experimentation. Because this measurement technique has the possibility of using the waveguide within the process tubing or as part of the process tubing, it can become a truly-in-line measurement technique.

Figure 5 illustrates a proposed system for measuring the phase shift. The moisture-laden helium is passed through a section of waveguide where phase shifting of the microwave energy takes place. This signal is then fed into one end, Arm 2, of a magic TEE.* A directional coupler is used to obtain a reference signal which is fed into the opposite end, Arm 1, of the magic TEE. The detector is placed in the third, or E-Arm, where the difference between the two signals is produced. The detector will have an output when the phase of the two signals is different, as shown in the following equation:

$$\begin{aligned} E_3 &= E \sin \omega t - E \sin (\omega t + \phi) \\ &= (-E \cos \omega t)\phi \text{ for } \phi \text{ small} \quad ; \end{aligned}$$

therefore

$$E_{\text{det}} = K \phi \quad ,$$

and, for small phase shifts, E_3 is a function of ϕ . The attenuator and phase shifter allow the system to be balanced when dry helium is in the test section.

APPLICATION TO HIGH TEMPERATURES

To provide more direct and rapid measurements of moisture in coolant gas, it will become necessary to make the measurement at high temperatures. Through the use of appropriate materials and measuring techniques, such measurements can be

* A combination of an E-plane TEE and a H-plane TEE. If energy enters the two opposite arms of the TEE, the difference appears in the E-Arm while the sum appears in the H-Arm.

accomplished. The sensitivity is expected to be lower at high temperatures since the polarizability is a function of temperature as follows:

$$\alpha = \alpha_o + \frac{\mu^2}{3kT} = \alpha_o + \alpha_d \quad , \quad (9)$$

where

α_o = Optical polarizability

α_d = Polarizability due to dipole moment

μ = Dipole moment.

For water vapor, (2)

$$\alpha_o = 1.57 \times 10^{-24} \quad (10)$$

and

$$\alpha_d = \frac{\mu^2}{3kT} = \frac{8.25 \times 10^{-21}}{T} \quad (11)$$

when

$$T = 300 \text{ } ^\circ\text{K}, \alpha = 2.90 \times 10^{-23}, \text{ and when } T = 1,300 \text{ } ^\circ\text{K}, \\ \alpha = 0.78 \times 10^{-23} \quad .$$

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FIGURE 5. Schematic of Microwave System for Phase Shift Measurement

It is evident that as temperature increases, sensitivity decreases; and that it is reduced by approximately four times for a temperature rise from 27 °C to 1,000 °C. In addition, there will be a reduction in sensitivity caused by a reduced number of molecules in the cavity at the higher temperature.

To test these concepts, the cavity and gas were heated to 436 °C and measurements were made of frequency shift versus water vapor concentrations. The theoretical reduction in sensitivity due to both causes mentioned above is 5.2. The actual experimental reduction in sensitivity was about 7.88; thus, the detection sensitivity is 875 ppm of moisture in helium. The curve in Figure 3 illustrates this reduction in sensitivity. In a parallel experiment, the heated gas mixture was cooled before being introduced into the microwave cavity. The sensitivity remained the same as for the low temperature experiment, suggesting that for maximum sensitivity, the gas should be cooled before entering the cavity.

FUTURE EFFORT

The phase shift method will be fully explored and its characteristics and limitations defined. Propagation in normal waveguide modes and in larger pipes will be explored as a possible means of making the measurement truly-in-line. The cavity method will be extended to higher temperatures (>1,000 °C) and methods of detection to account for reduced sensitivity will be explored.

APPENDIX A

Frequency shift measurements are made by modulating the frequency of the generator approximately ± 10 MHz about the resonant frequency of the cavity, typically 30 GHz. This produces an output signal from the detector of a frequency twice that of the modulating frequency, as illustrated in Figure 6. As the resonant frequency of the cavity changes from the center frequency of the oscillator, a fundamental component of the modulating frequency appears. The magnitude of the fundamental component is a function of the amount of deviation from the center frequency. For very small frequency shifts, and for square law detection, the frequency shift versus output voltage can be expressed as follows:

$$E_1 = \frac{8 Q^2 \delta_o \Delta \delta}{1 + 8 Q^2 (\delta_o^2 + \Delta \delta^2) + 16 Q^4 (\delta_o^2 - \Delta \delta^2)^2}, \quad (1-A)$$

where

Q = cavity quality factor

$$\delta_o = \frac{f_1 - f_o}{f_o}$$

f_o = oscillator center frequency

f_1 = maximum (or minimum) frequency due to modulation

$$\Delta \delta = \frac{f - f_o}{f_o} = \frac{\Delta f}{f_o}$$

f = resonant frequency of cavity .

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FIGURE 6. *Detector Response for Small Frequency Modulating Signal (a) Center Frequency Equals Cavity Resonant Frequency (b) Center Frequency Displaced from Cavity Frequency*

If the frequency shift is small, this equation reduces to

$$E_1 = \frac{8 Q^2 \delta_o \Delta \delta}{(1 + 4 Q^2 \delta_o^2)^2} \quad (2-A)$$

For this work, the following constants were Used:

$$Q = 980$$

$$f_o = 30.310 \text{ GHz}$$

$$f_1 - f_o = 10 \text{ MHz} ,$$

which leads to

$$\Delta f = E(9.5 \times 10^9) \text{ Hz} . \quad (3-A)$$

Equation (1-A) was derived by using the expression for the universal resonance curve,

$$\left| \frac{k}{k_{\text{res}}} \right|^2 = \frac{1}{1 + (2\delta_o Q)^2} .$$

To relate Equation (2-A) to measured values of E in deriving Equation (3-A), the right hand side of Equation (2-A) has been multiplied by 3.6 millivolts, which is the value in volts of the height of the detected resonance curve.

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