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SUMMARY

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A continuous-reading humidity sensor was developed for transient studies of a hydrogen-oxygen fuel-cell system in which the water produced is removed from the cells in vapor form by a recirculating hydrogen stream. The basis of the sensor is a fluidic oscillator that has an oscillation frequency sensitive to molecular weight and, hence, humidity of the hydrogen-steam mixture. A test program was conducted on the instrument to define its steady-state and transient performance. The test program also resulted in a determination of the failure modes and accuracy limitations of the instrument. An analog computer program that serves as a data analyzer and results in the conversion of the humidity sensor from an indirect- to a direct-reading instrument was also developed.

The steady-state performance tests resulted in calibration curves that relate humidity to oscillation frequency of the sensor at various pressure and temperature conditions of the hydrogen-steam mixture. The calibration accuracy was approximately ±2 percent. Analysis of frequency-response data indicated that the frequency response of the sensor was flat, at least to the 3-cycle-per-second limit of the test apparatus.

Author

INTRODUCTION

A test program was undertaken at the Lewis Research Center to investigate the dynamics of hydrogen-oxygen fuel-cell systems. In the type of system presently being studied, the water produced in the cells is removed in vapor form by a recirculating stream of hydrogen. This type of fuel cell is discussed in reference 1. A portion of the test program planned for this system consists of introducing controlled disturbances into the humid-hydrogen stream that enters the fuel cell and studying the effects of these disturbances on its operating parameters. In order to study the effects on the fuel-cell water-removal processes, it is necessary to know, on a continuous basis, the humidity (steam-to-hydrogen mass ratio) of the hydrogen stream leaving the fuel cell. Because of the nature of the planned tests, the instrument to be used for measuring the recirculating stream humidity, in addition to being a continuous-reading device, has to have a certain speed of response. Since a measurement technique or a humidity transducer with the required speed of response could not be found, the Research Laboratories Division of The Bendix Corporation was contracted by NASA Lewis to design and develop an instrument based on a fluidic-oscillator concept. This concept utilizes the fact that the frequency of oscillation of a fluidic oscillator is dependent on the molecular weight of the fluid medium. In a two-component mixture, such as hydrogen-steam, the molecular weight, in turn, depends on the mass ratio of the components.

In order to define the steady-state and transient performance of this instrument prior to beginning work on the fuel-cell test program, an experimental investigation was conducted on the humidity sensor at Lewis. The results obtained from this investigation are discussed herein. The fuel-cell-dynamics test apparatus was used to set a range of stream conditions that resulted in steady-state calibration curves in which the frequency of oscillation is a function of stream mass ratio (humidity), temperature, and pressure. Also, the calibration work resulted in the determination of the accuracy limitations and failure modes of the instrument. The speed of response was verified by running a frequency-response analysis, the range of which was limited by the periodic mass-ratio variation capable of being produced by the test apparatus.

A discussion is included of the development of an analog computer program that converts the humidity sensor from an indirect- to a direct-reading instrument. The program converts the normal instrument output of frequency of oscillation at a given temperature and pressure directly to a steam-to-hydrogen mass-ratio reading.

APPARATUS

Humidity Sensor

A schematic diagram of the fluidic-oscillator element is shown in figure 1. The oscillator is designed so that the stream flowing through the nozzle locks itself to one of the two stream attachment walls. A pressure pulse is produced that traverses the delay line of the side to which the stream is attached. The pulse forces the stream over to the other attachment wall where the same process is repeated. It is in this way that an oscillation is established. The frequency of the oscillation is a function of the pressure propagation time through the delay line and any time lag involved in the stream switching from one attachment wall to the other. For a given length of delay line,

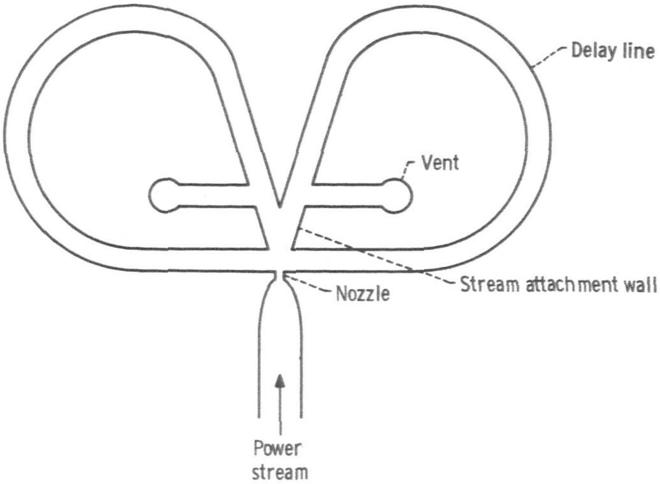


Figure 1. - Schematic diagram of fluidic oscillator.

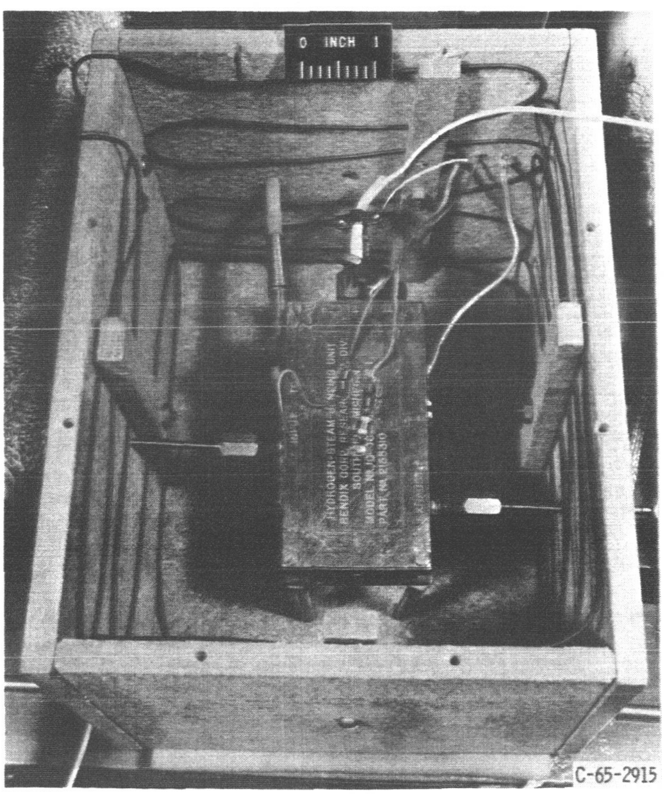


Figure 2. - Oscillator mounted in oven.

the pressure-propagation time is a function of the temperature and molecular weight of the stream in question, and the molecular weight is related to the mass ratio (humidity) by a constant. The switching time, once the pressure pulse has reached the attachment wall, may be a function of the stream pressure. A more detailed description of the principles involved in fluidic oscillators is presented in reference 2.

The oscillator unit is constructed of noncorrosive stainless steel, is small ($1\frac{1}{16}$ by 2 by 4 inch) and is an in-line device. The oscillator is shown in figure 2 mounted in the oven. The oven is used to prevent steam from condensing out of the mixture as it passes through the oscillator. Also, for this particular application, the temperature-regulated oven makes it possible to control the stream temperature in the oscillator delay lines by controlling the temperature of the oscillator body. The fact that the stream temperature can be controlled in this manner was found as the result of some preliminary testing in which stream temperature excursions representative of those expected in the fuel-cell test program were introduced in the sensor input lines. In each case, the temperature change was completely attenuated before the stream entered the oscillator element, and the mixture flowing through the element merely assumed the temperature of the oscillator body. Thus, during the fuel-cell tests, the oven will be used to main-

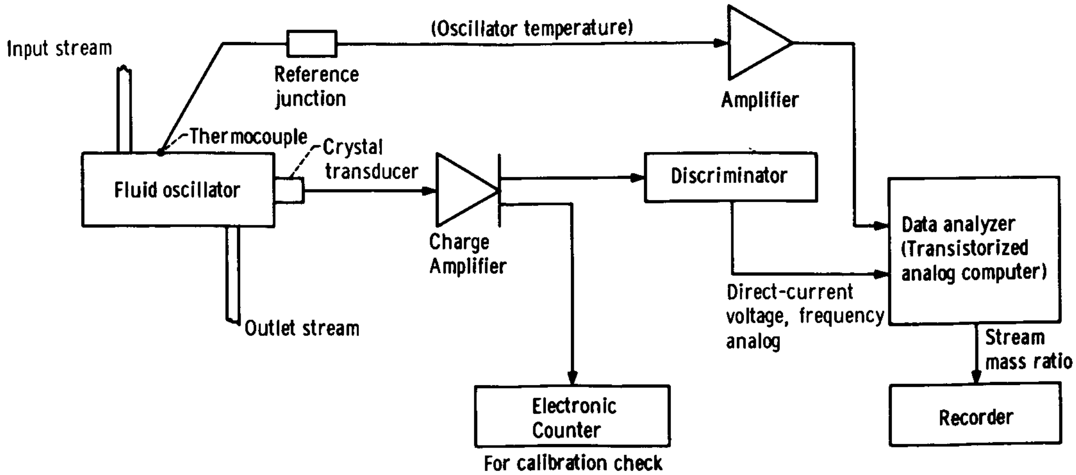


Figure 3. - Block diagram of complete humidity sensor.

tain the oscillator at one of the temperatures at which the sensor is calibrated. A small temperature effect, however, may still be present in the output frequency of the sensor due to inaccuracies of the oven temperature control.

The other components that make up the instrument are illustrated in figure 3 by a block diagram. The crystal transducer, mounted on one of the oscillator delay lines, measures the frequency of oscillation by measuring the pressure pulsations set up by the oscillating stream. The output of the crystal transducer is a high-impedance-charge signal that is not suitable as an input to the recording devices. A charge amplifier, therefore, is used to convert the output to a recordable low-impedance periodic voltage. This voltage then serves as the input to a discriminator that converts the periodic voltage to a direct-current voltage, which is the analog of the oscillator frequency. The output of the charge amplifier is also read by an electronic counter for quick checks of the calibration. The measurement for the temperature compensation discussed previously is obtained, as indicated in figure 3, by a thermocouple attached to the outside of the oscillator body. Input stream pressure is not indicated as a recorded transient parameter of the sensor since, in the intended application of the sensor in the fuel-cell test program and in the present test program, this pressure is controlled to a constant value during a given humidity transient. The instrument, however, was calibrated at several input stream pressures.

Data Analyzer

It can be seen from figure 3 that, without the analog computer (data analyzer), the data taken from the humidity sensor would be in the form of two recordings: the

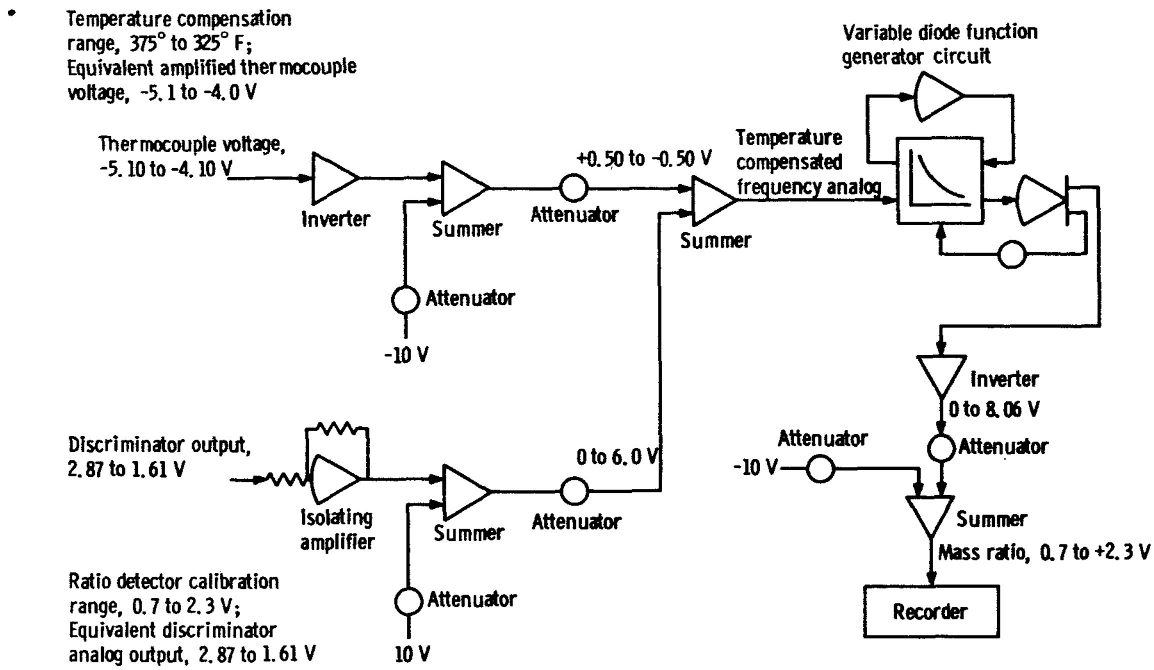


Figure 4. - Data analyzer computing circuit.

oscillator temperature and the analog of the frequency of oscillation. To correct the frequency for any drift that might occur in the oscillator temperature and to transform the corrected value to a plot of mass ratio with respect to time would require a rather tedious point-by-point conversion. Therefore, a data analyzing program was developed for an analog computer that accepts the temperature and the frequency analog as inputs and gives as an output a directly recordable mass-ratio analog.

A circuit diagram of the computer program is shown in figure 4. The main component of the circuit is the variable diode function generator. When used in conjunction with two of the computer direct-current amplifiers, this element can be set up to produce a segmented straight-line approximation to an arbitrary function so that a voltage x into the function generator circuit produces a voltage $y = f(x)$ at the output. For the data analyzer, the function incorporated in the function generator is the sensor calibration curve at a given temperature and pressure (350° F and 8 psig); the curve relates the analog of the oscillator frequency x and the corresponding mass ratio analog y. Since, in the range of interest, the temperature effect on the oscillator frequency is linear, the effect of the deviation from 350° F is merely subtracted from the frequency analog before it is used as the input to the function generator circuit.

If the temperature effects were not linear, a three-variable map-reading technique would be employed. A diagram of the function generator circuit that would be required for this technique is shown in figure 5. In this method, a family of constant temperature curves (all at a given pressure) is simulated by translating the x- and y-axes of a

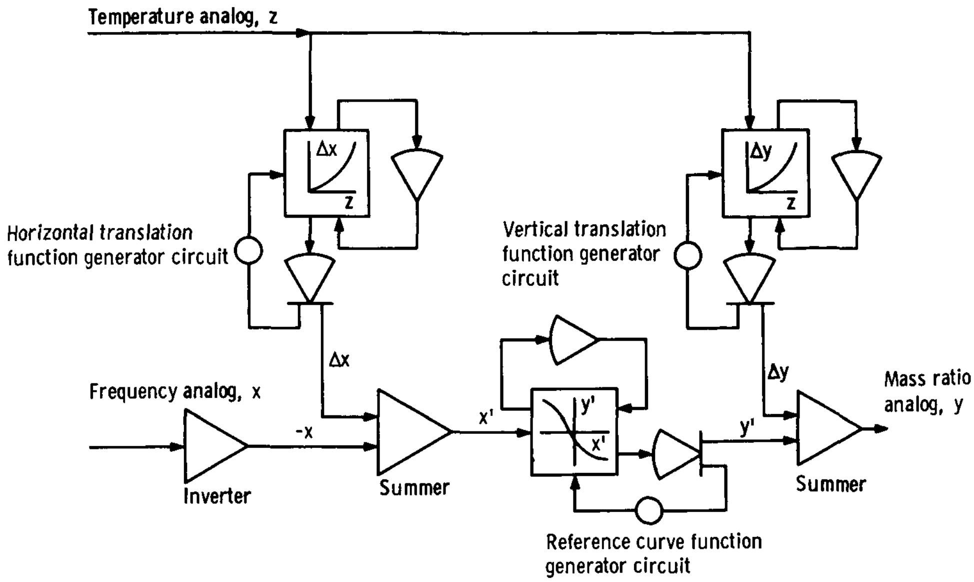


Figure 5. - Computer circuit for three-variable map reading.

function generator plot of a reference curve. The translations necessary are determined from the deviations of temperature from that of the reference curve.

Test Apparatus

The calibrating stream was supplied to the humidity sensor by the fuel-cell-dynamics test apparatus that has the capability of producing a humidified stream of hydrogen at a controlled temperature, pressure, and mass ratio. A schematic diagram of the test apparatus with the humidity sensor installed for calibration is shown in figure 6. As can be seen in this figure, the test apparatus is made up of four closed-loop control systems. The amount of each constituent in the mixture is set by controlling the upstream pressure of a sonic-flow orifice. Control of the temperature of the mixture is achieved by manipulating the hydrogen flow that by-passes the heater, and the pressure at the inlet of the component being tested is controlled by positioning a valve in the vent line parallel with the component. (A series arrangement is used when the mixture flow rate into the component is of interest.)

Speed of response and control accuracy were the parameters given primary consideration in the design of the test apparatus. The various components shown in figure 6 were chosen on this basis. Each of the four electrohydraulically actuated control valves has a frequency response that is flat to 10 cycles per second. The feedback pressure transducers are the strain gage type, display a natural frequency of 6000 cycles per second, and are mounted with a minimum of tubing volume from the flow stream to the

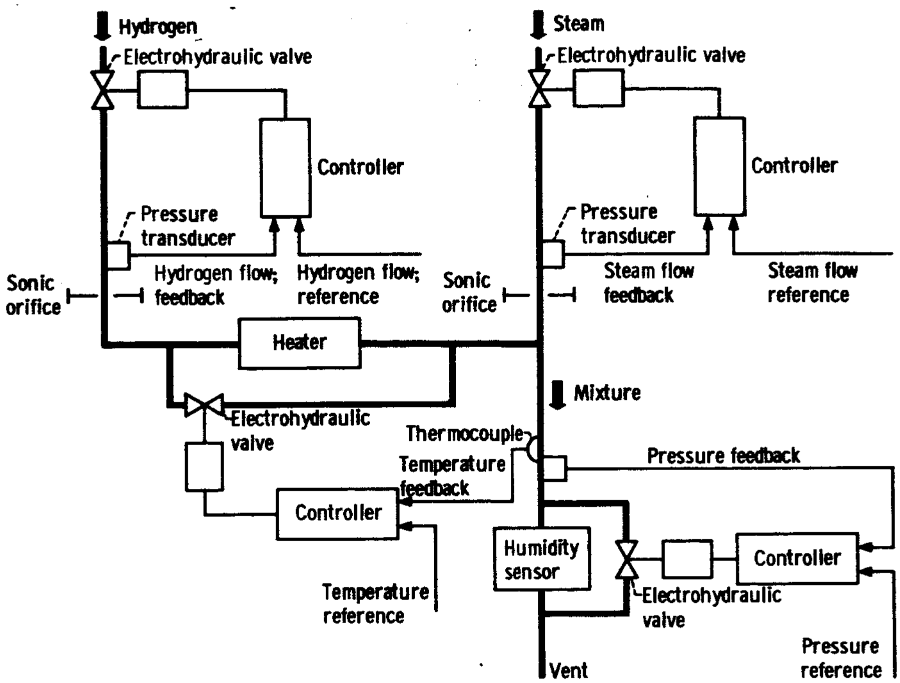


Figure 6. - Schematic diagram of fuel-cell-dynamics test apparatus.

diaphragm. The hydrogen heater is a specially designed, low volume, fast responding unit. The entire apparatus is laid out so that the flow volumes and the resulting time lags are kept to a minimum.

By calibrating the pressure transducers with an accurate gage prior to each test run, the steam and hydrogen flow rates and stream pressure can be controlled to within 0.1 percent of their set points. The oven temperature controller will hold the oven to within 3° of the desired value, which is ± 0.4 percent based on a temperature of 300° F. Thus, the control accuracy of the apparatus is limited by the oven temperature control.

PROCEDURE

Steady-State Tests

The dynamics apparatus was used to set up the calibrating humidities and the conditions at which the steady-state calibration data were obtained. While holding a constant set point on the controlled stream and oven temperatures, data were taken at four discrete pressures for each humidity setting. By repeating this procedure at four different temperatures, data were obtained for 16 different conditions at each humidity setting over the calibration range of the instrument.

Dynamic Tests

By impressing a sinusoidal variation on the set point of the steam-flow controller, a corresponding periodic variation in steam flow was obtained through the sonic-flow orifice. The periodic steam flow was injected into a constant hydrogen flow, thus producing a sinusoidally varying stream humidity. Pressure pulsations at the inlet of the humidity sensor caused by the varying flow were automatically removed by the pressure control loop.

RESULTS AND DISCUSSION

Steady-State Performance

The humidity sensor steady-state calibration data are presented in figure 7 in the form of calibration curves faired through the data taken at each of the 16 calibration conditions. The oscillator frequency as a function of steam-to-hydrogen mass ratio is given at pressures of 5, 6, 7, and 8 pounds per square inch gage in figure 7. For each pressure, calibration curves are shown for sensor temperatures of 250°, 300°, 350°, and 400° F. The small amount of data-point scatter around the faired curves can be attributed to temperature control inaccuracies. As pointed out previously, the accuracy of the pressure and flow controls is ±0.1 percent, while the accuracy of the oven temperature control is ±0.4 percent. With these accuracies and the sensitivities indicated by the curves, it can be determined that the control errors in pressure and input mass ratio were negligible and that the error of the temperature control was the cause of the data scatter. The maximum point scatter was approximately ±6.0 cycles per second, which corresponds to a calibration accuracy of ±2.0 percent in mass ratio over the range shown. It appears that a more accurate calibration could be obtained by refining the oven-temperature controller.

Dynamic Performance

At frequencies higher than 0.3 cycle per second, a true sinusoidal variation in mass ratio could not be produced with the test apparatus. Though this was the case, the frequency-response test was carried to the limit of the apparatus (3.0 cps) on the basis of a periodic mass ratio input rather than on a pure sinusoid. An example of the form of the data taken in the frequency range of 0.3 to 3.0 cycles per second is shown in figure 8. Since the portion of the input mass ratio trace above the centerline approximates a half sine wave, only this portion of the data was used in determining the attenuation and

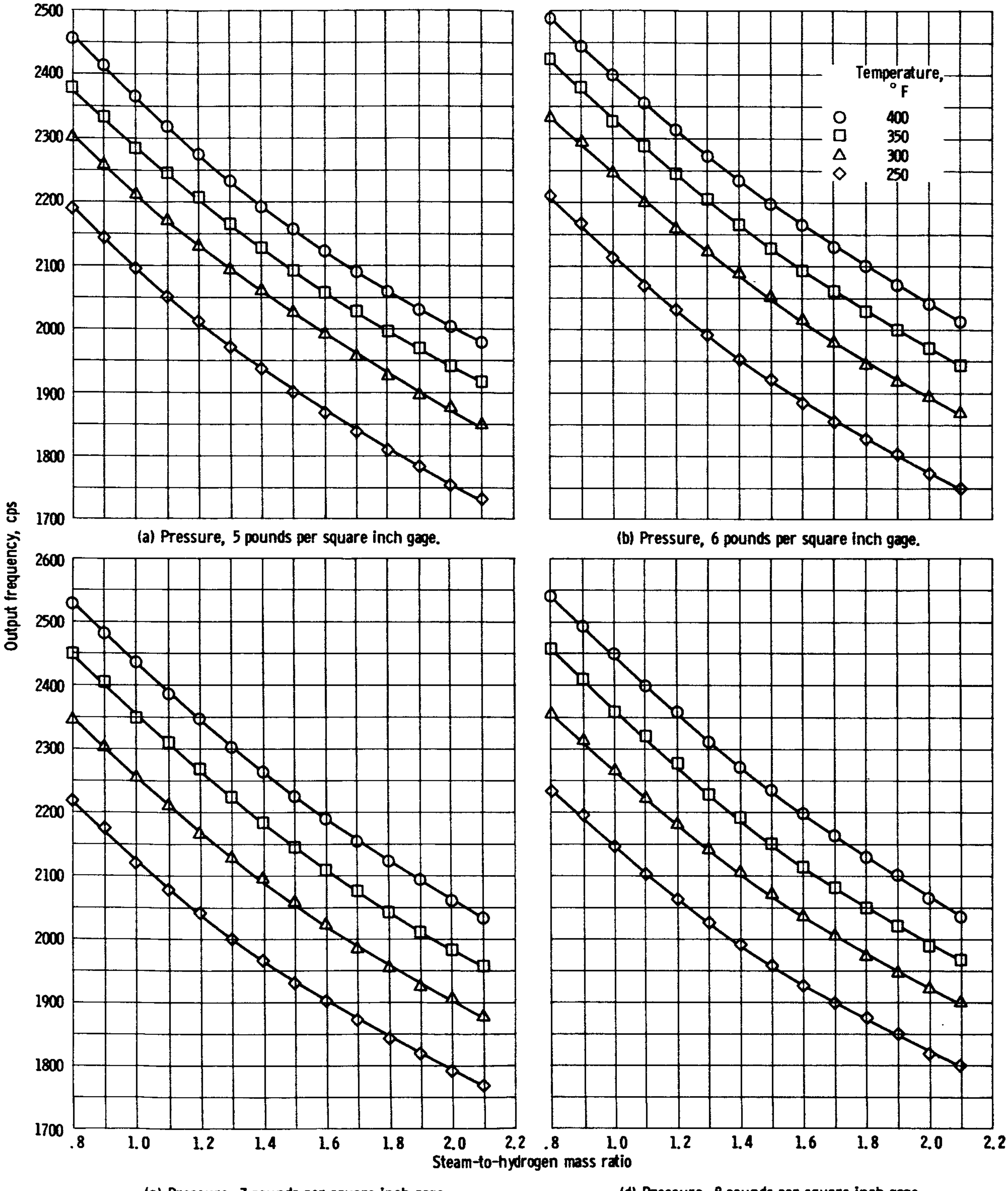
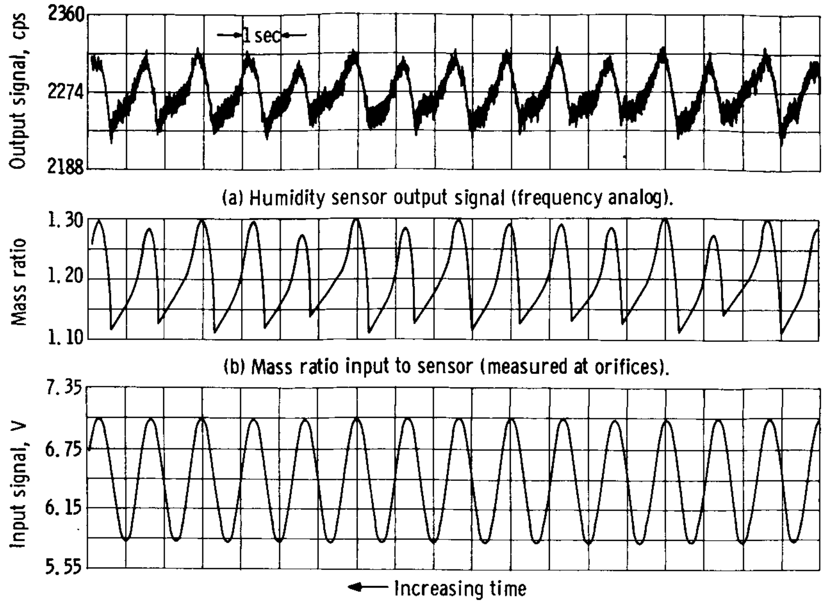


Figure 7. - Humidity sensor steady-state calibration.

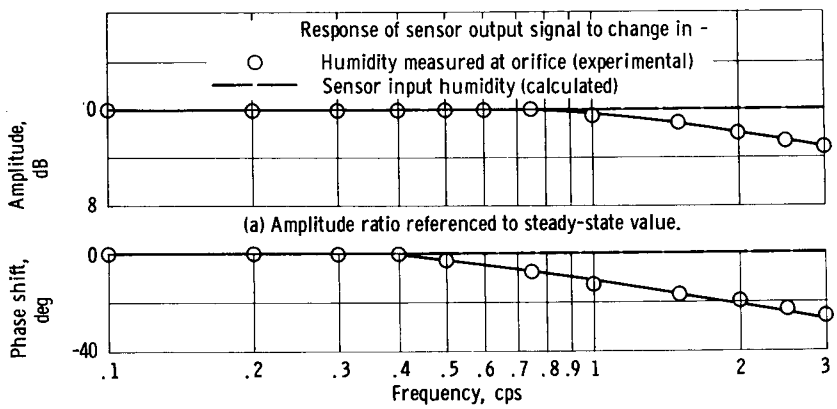


(a) Humidity sensor output signal (frequency analog).

(b) Mass ratio input to sensor (measured at orifices).

(c) Input signal-to-steam control loop.

Figure 8. - Example of waveforms obtained in frequency response testing in frequency range of 0.3 to 3.0 cycles per second.



(a) Amplitude ratio referenced to steady-state value.

(b) Phase shift.

Figure 9. - Humidity sensor frequency response.

phase shift. Also, because of the nonuniform amplitude of the mass-ratio input and the fairly high noise level of the sensor data, the attenuation at any one frequency was obtained by averaging the attenuations of 25 cycles at that frequency.

The frequency-response plots of amplitude and phase shift are given in figure 9. Calculations showed that the shift response indicated by the data was a result of the volume of the test-apparatus tubing between the orifice, where the change in steam flow was measured, and the input of the sensor. Since this is the case, the frequency response of the sensor itself is flat out to the 3.0-cycle-per-second limit of the test, as indicated in the figure by the calculated curves for amplitude and phase.

Failure Modes

During the 100 hours of operating time logged for the calibration and checkout tests, various sensor failures occurred. However, none were of a very serious nature, and all could be corrected in the laboratory. Thus, little "downtime" was incurred.

Until a fine-mesh filter was installed in the sensor input stream, oscillator-port blockage was a problem. Though the oscillator element could not be dismantled, it could be cleaned by being removed from the rest of the oscillator assembly and immersed in an ultrasonic cleaner. This, in turn, presented another problem, because each time the oscillator unit was disassembled, cleaned, and reassembled, a calibration shift occurred that necessitated a complete recalibration. This shift in the base frequency of oscillation of the unit could have been caused by a slight shift in the alinement of the components from the positions they were in before the unit was disassembled. If this is the case, some form of alinement guide would alleviate the problem.

Two crystal transducer failures occurred. One was a failure of the transducer mechanism that resulted in replacement of the whole unit. The other was caused by contamination of the electrical connectors of the transducer with moisture. This had the effect of lowering the insulation impedance which, in turn, caused the transducer output signal to be attenuated. The problem was solved by baking and potting the transducer connectors.

SUMMARY OF RESULTS

The fluidic humidity sensor was calibrated at various steady-state temperatures and pressures of a hydrogen-steam mixture. The calibration accuracy was ±2 percent. The accuracy limitation was a result, not of the sensor itself, but of the accuracy of maintaining its operating temperature.

The results of the frequency-response tests bore out the expectations that the sensor would display no attenuation or phase shift for the frequency range studied of 0 to 3 cycles per second.

Over the duration of the testing, the reliability of the instrument was good. Several failures occurred in the electronic components, but all were of a minor nature and could be repaired easily. The basic component, the fluidic oscillator, proved to be a reliable device. Initial oscillator-port blockage problems were corrected by the installation of a fine-mesh filter in the input stream.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 16, 1966,
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