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Short Papers

A Probe for Measuring Temperature in Radio-Frequency-Heated Material

RONALD R. BOWMAN

***Abstract*—Measuring temperature in material being heated by radio-frequency (RF) fields is difficult because of field perturbations and direct heating caused by any conventional leads connected to the temperature sensor. A temperature probe consisting simply of a thermistor and plastic high-resistance leads appears to practically eliminate these problems. The design goals are described, and the performance of an initial test model of this type of probe is discussed.**

INTRODUCTION

For bioeffects research and the control of potentially hazardous electromagnetic fields, a need exists to measure temperature in subjects and models during exposure to intense fields [1]–[7]. This problem would be trivial except for the fact that conventional thermocouples and thermistors use leads that grossly distort the internal field structure and also produce intense heating directly due to the induced radio-frequency (RF) currents [1]–[7]. One solution to this problem utilizes fiber optics coupled to a liquid-crystal temperature transducer [6]. Another approach uses a prepositioned, electrically nonconductive well that allows rapid insertion of the temperature sensor after the field source is turned off [2], [4]. Others have developed a probe consisting of a Wheatstone bridge circuit, extremely fine electrodes connected to a thermistor, and high-resistance plastic leads [5]. The temperature probe described here also uses a thermistor but is simpler in design (see the next section) and should produce considerably less heating (due to the use of higher resistance leads). As of this writing, parts are being obtained and fabricated to construct a probe with a 1-mm-OD tube, a thermistor with dimensions less than 0.5 mm, and high-resistance plastic leads with resistances of about 160 kΩ/cm.[1] This short paper describes the test results for a probe that was made from parts that were immediately available. Since this initial model of this type of probe has much greater sensitivity, stability, and dynamic range than the probe described in [6], it is believed that these early test results are of interest.

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[1] *Note Added During Review:* This probe has been fabricated. It has a response-time constant of less than 0.2 s, short-term stability better than 0.01°C, and a high-resistance-line heating error (see section on experimental tests) of less than 0.005°C for a heating rate of 1°C/min.

PROBE DESIGN AND CONSTRUCTION

As shown in Fig. 1, the probe consists simply of two pairs of very-high-resistance leads connected to a small high-resistance thermistor (about 750 kΩ at 25°C and a coefficient $\simeq -0.04/°C$). The thermistor resistance is sensed by injecting a constant current through one pair of leads and measuring the voltage developed across the thermistor by means of a high-impedance amplifier connected to the other pair. If the current generator and amplifier have high impedances compared to the leads, the thermistor can be measured accurately despite the large and unstable lead resistances. This technique is commonly used when the lead resistance is significant, but in the present application the lead resistances will typically be 10 MΩ rather than the usual lead resistances that are of the order of 10 mΩ. The main difficulties in realizing good probes of this type are fabricating high-resistance lines with lineal resistances of 100 or more kilohms per centimeter and attaching these leads reliably to the thermistor.

Leads with the required high resistance can be made by either thick- or thin-film processes, but it may be difficult to make long leads using these processes. The present probe design uses plastic high-resistance leads developed earlier for use with electromagnetic hazard meters [8], [9]. For the initial test model, the cross section of the leads is about 0.25 by 0.25 mm and their lineal resistance is about 40 kΩ/cm. The leads are bonded to the thermistor with silver-loaded epoxy.

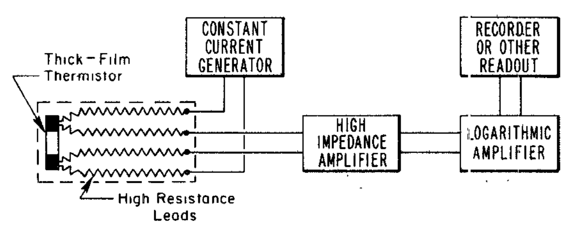

Fig. 1. Schematic of probe and associated electronics.

EXPERIMENTAL TESTS

For the following tests, the current generator was set to provide about 0.35 μA, which generates less than 0.1 μW of heating in the thermistor and about 0.2 μW of heating along the high-resistance leads. At 25°C this current causes about a 0.25-V drop across the thermistor. The signal from the voltage amplifier was passed through a logarithmic amplifier to provide a signal that is nearly linear with temperature change. After calibration, the probe was placed in a constant-temperature bath. The noise and drift on the signal to the recorder corresponded to less than ± 0.01°C. When dipped into a beaker of water, the probe displayed a 90-percent response time of about 10 s. This rather slow response is due in part to the use of an unneccessarily large (3-mm-OD) probe-tube and in part to the fact that the thermistor was not potted into the tube.

The probe was placed as shown in Fig. 2 and exposed to 2.0-GHz fields. The high-resistance lines were parallel to the incident electric field to maximize the RF heating of these lines. With the water flow off, the RF power was adjusted to give approximately 1°C/min initial heating rate in the water at the probe tip when the RF power was turned on. (This heating rate requires about 70-mW/cm^3 power absorption and corresponds to a relatively high internal-field exposure for electromagnetic bioeffects experiments.) As will be seen, some thermistor heating due to heat generation in the high-resistance lines is apparent in the thermistor heating curve following a turn-on of the RF power.[2]

An approximate expression for the response of the thermistor without the high-resistance leads can be determined as follows. The heating rate in the water should be nearly constant until the water temperature rises enough to establish strong convection currents. Assuming a constant heating rate S in the water and that the thermistor heating rate is proportional to the difference between the thermistor temperature and the water temperature, it is easy to show that the thermistor temperature change T is given by

$$T = St - S\tau[1 - \exp(-t/\tau)] \qquad (1)$$

where the water heating begins at time $t = 0$ and τ is the time constant of the probe for still water. Since τ is about 4.3 s for this probe, a 1°C/min heating rate in the water will correspond to an eventual lag of about $S\tau = 0.07$°C in the thermistor response.

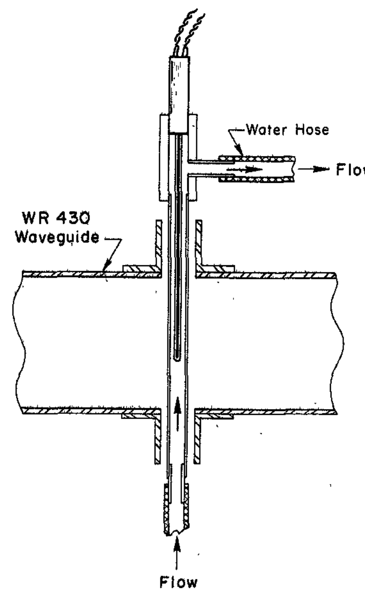

Fig. 2 Experimental arrangement for measuring the temperature error due to RF heating of the high-resistance leads. The probe is inserted into a thin-walled plastic tube filled with water and aligned parallel to the electric vector in a WR 430 waveguide.

Fig. 3 shows the thermistor response as predicted by (1) for 1 min of 1°C/min water heating. The actual response of the thermistor is shown by the "water-flow-off" curve of Fig. 4. Apparently, the inherent lag of the thermistor temperature is more than compensated by the RF-generated heat from the high-resistance lines. The excess temperature can be shown by establishing a rapid water flow rate through the tube. With the same RF power level and using a water velocity of more than 30 cm/s, the temperature rise of the flowing water is less than 0.01°C. Then the thermistor heating above the constant water temperature is shown by the water-flow-on curve of Fig. 4 and is about 0.12°C. This error is probably not important, and it will be much less for the fully developed probes.

PERTURBATION OF THE INTERNAL FIELD

In addition to the direct heating of the thermistor by the leads, significant errors can occur because the field structure in the material of interest will be different with the probe in place [2], [4]–[6]. Metallic leads are particularly troublesome because of their very high conductivity. Even Nichrome has a conductivity of about 10^6 S/m. For comparison, muscle tissue has a conductivity of about 1 S/m. An effective solution to the field-perturbation problem, as well as the direct-heating problem, is to use leads with a conductivity comparable to that of the subject or model material of interest; e.g., saline-filled glass tubes [2, p. 705]. The probes described here use leads with a conductivity of only 4 S/m,[3] and most of the bulk

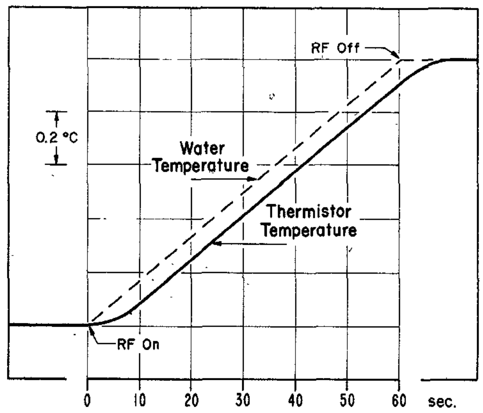

Fig. 3. Theoretical thermistor heating curve for the case of no RF heating of the high-resistance leads.

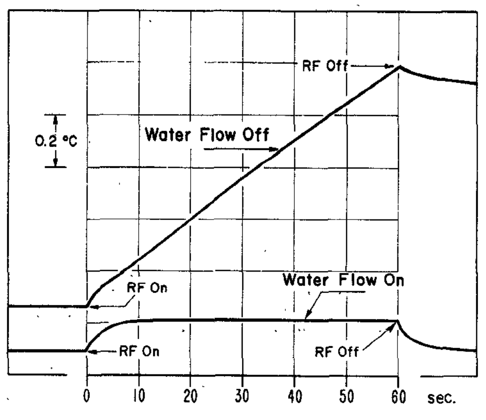

Fig. 4. Measured probe response with water flow off and on, with the RF power level constant. With the water flow on, the probe response of about 0.12°C is due to RF heating of the high-resistance lines.

[2] The induced RF currents in the thermistor will also cause the thermistor to heat; but, because the thermistor material has much lower electrical conductivity than the lead material, the heat generated directly in the thermistor is believed to be negligible.

[3] Carbon-loaded material with less conductivity can no doubt be made, but does not appear to be readily available.

of the probe consists of nonconducting material. The field-perturbation effects of the initial model were not determined; however, thermographic [2, p. 705] tests for these effects will be performed for the next model to quantify any errors associated with the leads or the small amounts of highly conducting material used to make contact with the thermistor.

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A Computer Program for the Direct Calibration of Two-Port Reflectometers for Automated Microwave Measurements

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Abstract—**A short computer program is developed to solve explicitly a very useful reflectometer error model currently receiving high utilization in microwave measurement systems. The program architecture is designed to enhance its utilization as a stand-alone subroutine operating in conjunction with a measurement program, or to replace iterative solution software in existing automated measurement systems.**

INTRODUCTION

The history of automated network analyzers is well documented and their contribution to accurate and high-speed microwave measurements is nothing short of phenomenal. However, because of heavy capital equipment investments required to purchase a fully automated system, many manual systems are still being utilized. Over the last few years, the introduction of inexpensive minicomputers such as the HP-9830 and the availability of programmable sources and measurement instruments have made it possible to build "homemade" automated network analyzers [1] at a substantially lower cost than the completed system purchase price. Utilizing the minicomputer as a controller (talker) and some standard data transfer/interface bus schemes, listening instruments such as sources may be set to the desired driving frequencies, and listening/talking devices such as scanning digital voltmeters may perform measurements. Software routines may be utilized to process the data thus acquired.

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PROGRAM DESCRIPTION

A very important attribute of these systems is that if the measurement system is properly modeled, measurements can be made upon sets of precision standards and the error model can be solved. Unknowns can then be measured and corrected for errors [2]. High degrees of accuracy are thus possible for measurements of unknown two-ports.

Since most minicomputers utilized for instrumentation purposes are limited in core size, program size and efficiency are of paramount importance. The currently available software for automatic network analyzer application [3] solves the error vectors of particular models by iterative methods because of quadratic coupling between a number of system equations derived from the normal calibration standards. Although the iterative algorithm converges quickly (2 or 3 tries), the process must be repeated at each frequency point. Therefore, it would be very desirable to utilize a direct solution for the system equations.

Recent work has shown [4], [5] that explicit solutions are possible for the commonly utilized error models. Rehnmark [5] solves explicitly the 10-error vector model called GPS3 in the Hewlett-Packard Software Manual [3], while [6] solves explicitly the 12-error model GPS2. The 10-error model, shown in signal flowgraph form in Fig. 1, is significant because it may be used to model a useful, commercially available, and remotely programmable reflectometer (HP8746). The explicit solution for the unknown scattering parameters imbedded in the signal flowgraph of Fig. 1 is as follows:

$$S_{11} = \frac{\left(\dfrac{M_O - e_{00}}{e_{01}e_{10}}\right)\left[1 + e_{22}\left(\dfrac{M_3 - e_{33}}{e_{32}e_{23}}\right)\right] - e_{22}\left(\dfrac{M_3 - e_{30}}{e_{32}e_{23}}\right)\left(\dfrac{M_O - e_{03}}{e_{01}e_{10}}\right)}{D} \tag{1}$$

$$S_{22} = \frac{\left(\dfrac{M_3' - e_{33}}{e_{23}e_{32}}\right)\left[1 + e_{11}\left(\dfrac{M_O - e_{00}}{e_{01}e_{10}}\right)\right] - e_{11}\left(\dfrac{M_3 - e_{30}}{e_{23}e_{32}}\right)\left(\dfrac{M_O' - e_{03}}{e_{01}e_{10}}\right)}{D} \tag{2}$$

$$S_{21} = \frac{\left(\dfrac{M_3 - e_{30}}{e_{32}e_{10}}\right)}{D} \tag{3}$$

$$S_{12} = \frac{\left(\dfrac{M'_O - e_{03}}{e_{01}e_{23}}\right)}{D} \tag{4}$$

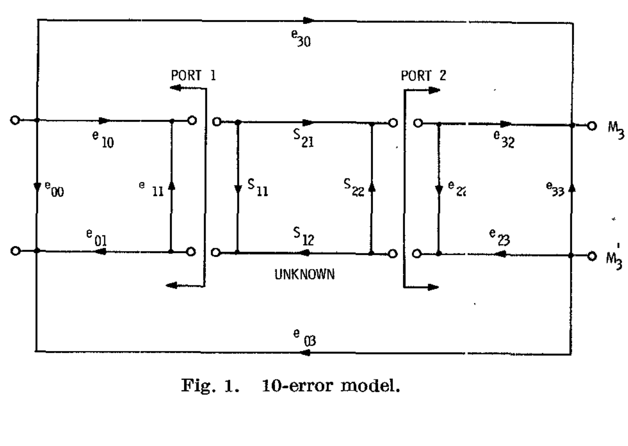

Fig. 1. 10-error model.