A New Thermocouple Thermometer

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ABSTRACT

An accurate thermometer with fast response and high reliability has been designed and built by using a very fine copper–iron thermocouple coated with sputtered gold, and a newly available ultralow drift operational amplifier.

The newly designed thermometer has attained an accuracy of about 0.04°C (one standard deviation, with both the surroundings of the oven and the circuitry at room temperature) and is estimated to attain a time constant of 4 ms in a 20 m s^{-1} airflow. This thermometer was originally designed for airborne use to measure temperature in cloud, but the thermometer could be used for other applications, especially those which need high-accuracy, fast response time, and a small sensing element which does not change calibration if the sensing wires are stretched by the impaction of particles in a flowing fluid.

The most important use envisaged is to mount it on an aircraft to examine the entrainment process at the top surfaces of clouds. It is hoped to also develop a wet-bulb version for such use.

1. Introduction

This thermometer was originally designed to measure temperature in cloud, a major factor involved in the study of buoyancy driven atmospheric processes.

Measurement by aircraft is recognized as the best way to obtain useful data; however, it requires a fast response time if small space scales of importance are to be resolved (such as a time constant better than 100 ms with an aircraft speed of 100 m s^{-1}, to resolve phenomena of 10 m width). Direct in situ measurements allow accuracy and resolution in measurements far exceeding remote sensing techniques.

Although infrared thermometers, resistance thermometers, and thermistor thermometers are the most frequently used sensors, they all have important limitations.

Infrared thermometers currently have a range of about 0°–30°C with ±0.2°C accuracy (Tebo, 1969). However, cloud temperatures vary from about −30° to +30°C. Besides its restricted temperature range, its response time is also slow for an aircraft measurement; it integrates radiation over a considerable volume and is not easy to use. While improvements are in progress, this technology will always tend to depend on changes between clear air and cloud, and so will be difficult to interpret at the cloud top or edges where entrained dry air leaves very dilute patches. Such studies are one of the most important uses of an airborne thermometer. Furthermore, it is hard to imagine how an infrared thermometer could be applied to measure the wet-bulb temperature, an extension of this work for which we have great hope.

Resistance thermometers especially show the considerable advantages of higher accuracy, faster response time, and a wider application range (Telford and Warner, 1962). However, when measuring temperature in cloud the special circumstances mean that the resistance thermometer has a serious weakness. When the sensing zone of the thermometer comes in contact with waterdrops, ice particles or bugs, it may stretch the sensing zone or might break it; this actually happens frequently. If the element is shielded from airborne particles by accelerating the air around a shield, the temperature changes, and in cloud this temperature change is an unknown amount because of the cooling from partial drop evaporation along the accelerating streamlines. True cloud temperature is best measured by a directly exposed element. The problem is not the cost of the element, since substitute elements can be flown together with all but one shielded, and exposed as breakage occurs. Rather, the problem is an undetected calibration drift, which can falsify the data without allowing a correction, since the time of change is unknown. The resistance thermometer loses its calibration on stretching because the wire lengthens and decreases in area; both changes increase its resistance. It is very difficult to determine whether the data is correct at any point during a flight when this happens. Data can be said to be correct only when, after checking the thermometer very carefully after flight, the thermometer shows no damage at all. This calibration after every flight is impractical on a routine basis.

The alternative of using a rugged, slow-response element as an in situ calibration reference introduces its own problems in data processing. Either an alarm is set when some type of discrepancy is detected by a computer routine, and the data manually examined so a new calibration can be determined, or the two data sources are blended by matching filters and combined on a continuing basis. Experience in blending both dewpoint and Lyman-α humidity data, and pressure altitude and inertial vertical velocity, have shown how considerable effort can be expended on such techniques without providing an entirely satisfactory degree of confidence in the results. We suggest that, in terms of avoiding unending distractions, there is no substitute for a single reliable measurement at each point.

Resistance thermometers also have another problem because a substantial length of wire is needed, and thus a sensing element is usually wound as a spiral around a support. The wire on the support has the temperature of the support, and the airflow for the wire near the support is reduced, so the wire near the support has a large time constant.

Thus, resistance thermometers show a double time constant in their response, with perhaps 10% of the amplitude step occurring with time constants of almost 1 sec, even when most of a step change in temperature occurs with a 30 ms response.

Thermistor thermometers suffer fragility and self-heating effects which reduce accuracy, and are often not small enough to give a very rapid response.

Thermocouple thermometers have not been used very much to measure cloud temperature mainly because of poor accuracy due to their low sensitivity and the need for an accurate reference temperature, although they do have several substantial advantages, such as small sensing zone, flexibility in installation, and low cost. Besides that, the thermocouple thermometer does not have the same weakness to stretching as does the resistance thermometer. As long as the two wires, which constitute the sensing junction, keep contact with each other, the thermocouple thermometer gives good data. When the sensing junction is broken, the thermocouple gives completely different data that can be detected very easily, even by the data computer, which could then call into service a replacement element.

In this project, two new solutions are introduced to make the thermocouple thermometer a more practical instrument.

The first solution is to use a copper–iron pair as the thermocouple. The copper–iron thermocouple has zero gradient at about 260°C. It thus follows that the use of a small oven set at 260°C to maintain one junction at this reference temperature creates a thermocouple wherein the measuring junction is influenced only to the extent of a few times 0.01°C by variations in the oven temperature, after the oven temperature has been adjusted for best performance. As is subsequently described in detail, the oven can readily be maintained within about ±1.5°C for variations of the temperature in the surroundings of the oven from −50 to +50°C, which provides an equivalent temperature error of about ±0.06°C (one standard deviation in the measurements, circuitry at room temperature) at the measuring element.

The second advance is to use a preamplifier with ultralow drift in front of the A/D converter to get high accuracy and low noise. This is important when using a copper–iron junction, which has a relatively low sensitivity of about 11μV/°C near 0°C. The preamplifier, as described in the next section, shows about ±0.4 μV total drift error, which thus corresponds to an equivalent error of about ±0.035°C for temperature changes of the preamplifier unit between −50°–+50°C. Since the operational amplifiers in the preamplifier achieve their low offset by chopper-stabilization, they typically generate 0.7 μVP-P input noise voltage for an equivalent error of about ±0.06°C, but this can be reduced during processing by removing peak values before averaging.

Some uncertainty remains in regard to overall performance of the instrument mounted on an aircraft because the temperatures around the oven and the circuit components will not vary over the extreme ranges used in these tests. Performance should be considerably better than that found under these extreme test conditions. The components will be thermally enclosed and shielded from the airstream. It further seems likely that measuring the temperature of the circuitry and the outside of the oven with a thermistor would allow a correction to give an overall accuracy of 0.05°C even without significant improvements, because all of our tests on the components have shown that the changes in the output are fairly linear with respect to the temperature of the components. Tests with all the components in a temperature-controlled chamber over the temperature range from −10° to +50°C gave a temperature accuracy of ±0.2°C. These combined errors are generally not front-end errors, and hence an overall accuracy of 0.05°C should be attainable with wider temperature range components and some improvement in oven temperature control. The −10°C limitation will extend to −50°C when military temperature range chips are installed in the digital section, since the microprocessor stops oscillating at just below −10°C.

2. Construction

A picture and the block diagram of the new thermocouple thermometer are shown in Figs. 1 and 2. The voltage difference between the reference junction and the sensing junction of the thermocouple is amplified through the preamplifier with the gain chosen so that each 1 mV in the output voltage from the preamplifier corresponds to 0.01°C in the measured temperature. An offset voltage is applied to the thermocouple signal in the preamplifier to make the output voltage of the preamplifier zero when the sensing junction is exposed at the freezing point in an ice–water

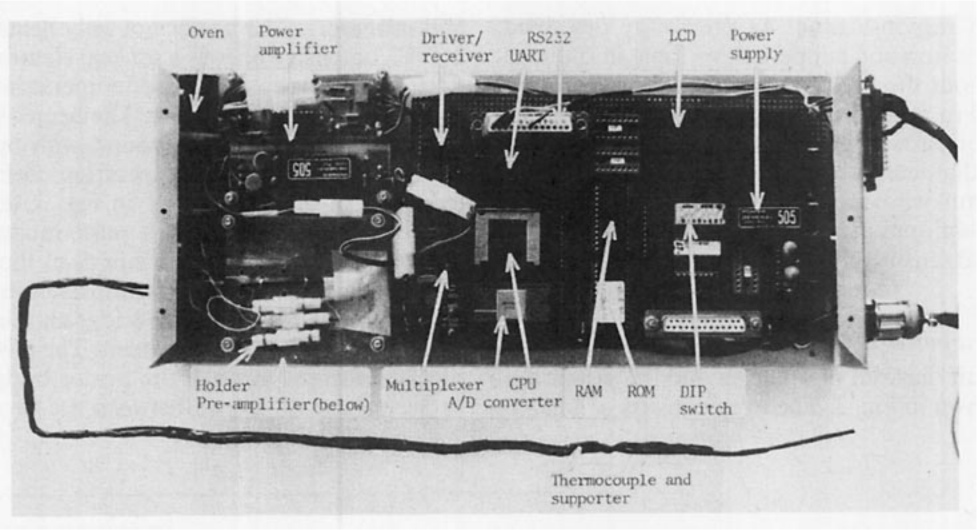

FIG. 1. Picture of the new thermocouple thermometer showing the whole device which includes the thermocouple sensor oven preamplifier, computer, and liquid crystal display (LCD). The four connectors are the RS232 port on top, which connects internally to the RS232 data output on the right. On the bottom of the circuit is a subminiature D connector which provides access to the circuit for testing. The bottom right-hand connector brings in the power.

mixture. The reference junction is placed at the center of the oven to achieve the best temperature control at 260°C. The power amplifier supplies current to the oven in inverse proportion to the incremental temperature of the oven below 260°C. The data processing unit converts analog voltages from the preamplifier into 12-bit digital data, and then calculates the corresponding temperature by reference to the emf-temperature look-up table stored in the erasable, programmable read-only memory (EPROM). The details of each component are described in the following sections.

a. Thermocouple

The copper–iron wires of 0.025 mm diameter are used as the sensing junction of the thermocouple to

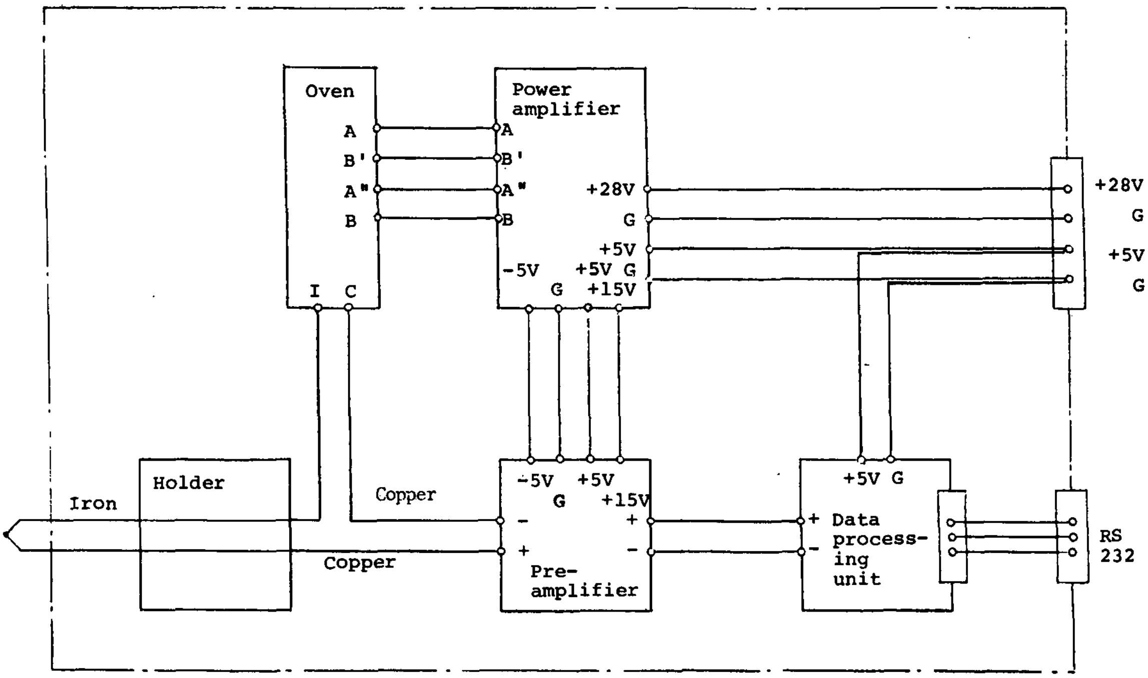

FIG. 2. Block diagram of the new thermocouple thermometer.

achieve fast response time. As previously described, the choice of iron and copper allows high absolute accuracy without the use of an ice bath, which is commonly used in many thermocouple applications.

The other parts of the thermocouple are made of 0.075-mm diameter, Teflon-coated copper–iron wires. The 0.025-mm wires are coated with gold for protection against contamination and iron rusting. Both reference junction and sensing junction of the thermocouple are welded.

b. Oven and power amplifier

The circuit diagram of the oven and the power amplifier is shown in Fig. 3. The oven consists of a heater and insulators. The heater not only heats the oven to 260°C, but also works as a sensing element to give the difference between the actual temperature of the oven and the desired temperature. The heater itself forms a sensing bridge, since it is wound with opposite arms of metals with different temperature coefficients. Two terminals of the bridge, AA″ in Fig. 3, are connected to the output terminals of a pulse-modulated power amplifier. The other two terminals of the bridge, BB′, are connected to the input terminals of the power amplifier through resistors. The bridge and the power amplifier compose a feedback circuit. The power amplifier supplies current through the heater bridge according to the voltage difference between the two sensing ter-

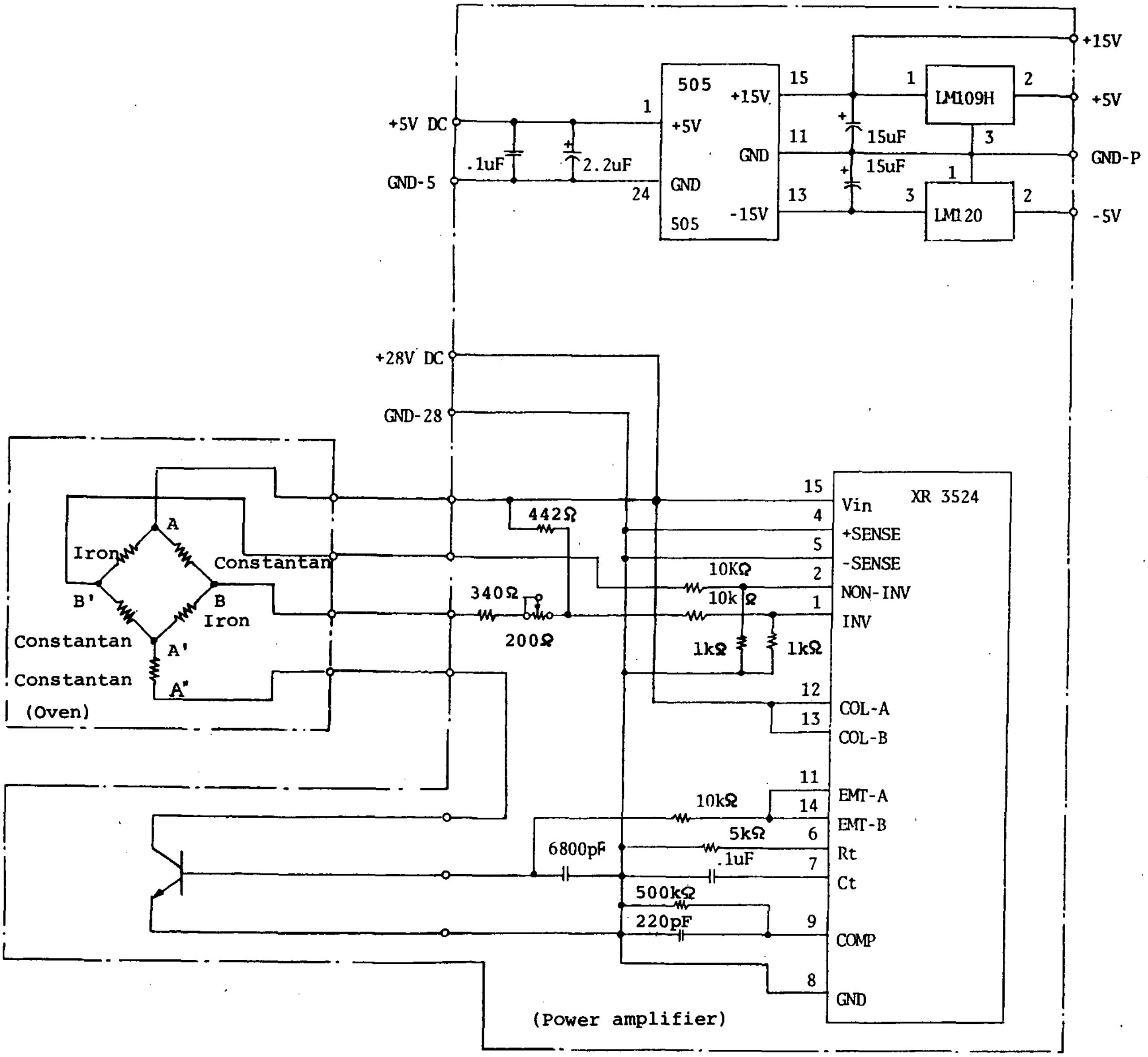

FIG. 3. Circuit diagram of the oven and the power amplifier.

minals of the bridge output, BB′; this provides power to the oven. At a temperature of 260°C, the bridge is in balance, so the output, and hence the power input, are reduced as this temperature is approached.

The two kinds of wires with different temperature coefficients, comprising the heater-bridge, are constantan (55% Cu, 45% Ni) and iron. The temperature coefficient of the constantan is very small. The resistance of the constantan wire arms of the bridge, AB and A′B′, are 4.8 Ω each. The iron arms of the bridge, AB′ and A′B, have a resistance of about 1.2 Ω each at 25°C, while at 260°C they have a resistance of about 4.3 Ω. Hence, with a little exterior resistance padding, the bridge comes into balance at this temperature. Therefore, the voltage difference between the sensing terminals, BB′, is in proportion to the departure of temperature of the bridge from 260°C, and this voltage can be used to control the period during each cycle when the voltage is applied to the heater since a pulse-modulated drive is employed. When the bridge is heated to 260°C it reaches equilibrium, because the voltage difference from the sensing terminals, passed through the two resistors which are used to give a fine adjustment for the temperature, tends to zero.

The oven consists of an inner brass tube carrying the heater windings, which are surrounded by thermal insulators made from five brass tubes separated by air gaps, with diameters of 16.7, 15.1, 13.5, 11.9 and 10.3 mm. Thin brass sheets close both ends of each tube.

The temperature change of the oven is about ±1.5°C, for a −50° to +50°C temperature change in the ambient environment around the oven corresponding to an error of about ±0.06°C at the reference junction of the thermocouple. This should be easy to improve with a little feedback from a thermistor measuring the temperature of the environment around the oven.

The power amplifier uses a pulse-width modulating regulation to improve power efficiency and to avoid the need for a heat sink for the power transistor. The larger the differential output voltage from the bridge going to the power amplifier input during the short sensing period, the longer the duty cycle of pulses it generates.

c. *Preamplifiers*

As shown in Fig. 4, the signal preamplifier consists of the first-stage amplifier, the RC low-pass filter, the second-stage amplifier, and the voltage reference circuit. The preamplifier is enclosed within an aluminum box of 5-mm thickness so that the preamplifier is kept under very stable ambient temperature to avoid thermoelectric effects. The temperature itself is not very important, but temperature gradients are crucial.

The first-stage and second-stage amplifiers are the differencing amplifiers, which reject common mode noise. These are extremely low-input offset voltage operational amplifiers, with typical input noise of 0.7

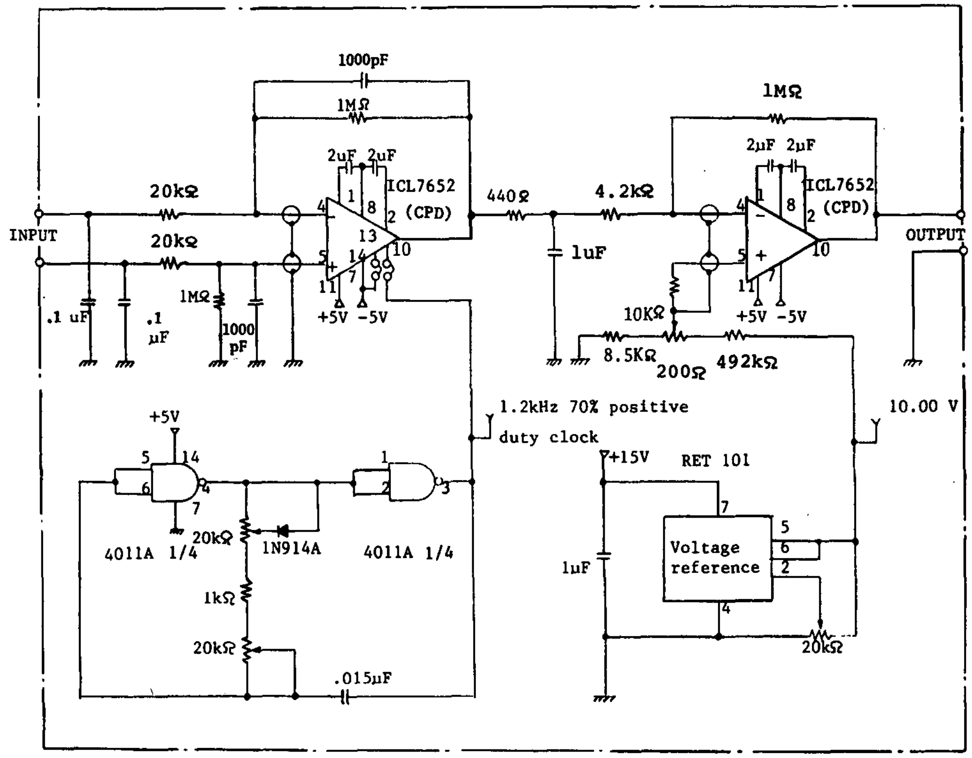

FIG. 4. Circuit diagram of the preamplifier.

μVP-P and typical drift of 0.01 μV/°C, ICL 7652 (Intersil). The total voltage gain is about 10 800. Some input filtering is applied to remove higher-frequency pickup noise. The RC low-pass filter with a time constant of 400 μs between the stages reduces chopping spikes from the first-stage amplifier. The voltage reference circuit gives the reference voltage to the second-stage amplifier so that the output voltage of the preamplifier becomes zero when the sensing junction is at 0.00°C.

d. Data processing unit (DPU)

A block diagram is shown in Fig. 5. The output voltage from the preamplifier is converted into 12 bits of digital signal. The CPU (an Intel 80188) receives the data from A/D converter 17 times, takes out the maximum and the minimum data, and averages the rest of the data to lower the noise error. The averaged data is converted into a corresponding temperature using the emf–temperature look-up table stored in the EPROM. This takes about 960 μs per processed temperature reading, which is fast enough for a time constant of 4 ms.

The look-up table uses linear interpolation between 33 pairs of data points, which are calibrated output voltages from the preamplifier at corresponding temperatures; this process contributes less than 0.01°C to the error.

Output temperature is presented on the liquid crystal display and is sent to a host computer by an RS232 interface, which has a baud-rate software-selectable from 200 baud up to 19 200 baud.

The calibration procedure for the thermometer is to generate a look-up table as follows:

(i) Make a comparison table between the HP quartz thermometer (HP-2801A) and the thermocouple thermometer. This uses a comparison-table-generation program.

(ii) Convert the comparison table into an emf–temperature look-up table by using a host computer, then burn the table into an EPROM.

(iii) Compare the HP-2801A and the thermocouple thermometer with the emf-termperature look-up table over the −50°–+50°C measuring range. If the averaged calibration curve then differs by more than 0.01°C between the thermometer and the reference, modify the look-up table and then try the comparison again.

In the near future, an electrically erasable programmable read-only memory (EEPROM) will be used in the data processing unit, which can eliminate the use of a host computer for calibration so that each unit will be able to generate its own calibration table during the calibration process.

3. Performance and discussions

By utilizing the iron–copper thermocouple and the ultralow-drift operational amplifier, an accurate thermocouple thermometer with fast response and high stability was designed and built.

In this section, the performance of this thermometer is described and discussed.

a. High accuracy

Because the look-up table has 0.01°C resolution, which is the least significant bit of the A/D converter, the maximum error of the look-up table from the standard thermometer (HP-2801A) can be reduced to ±0.005°C if an accurate comparison table between the standard thermometer and the new thermocouple thermometer is made. Comparison between two thermometers can be done very easily because the temperature data are not only sent to a host computer through RS232 interface, but are also displayed on the liquid crystal display of the data processing unit.

The temperature is calculated by 32 piecewise linear

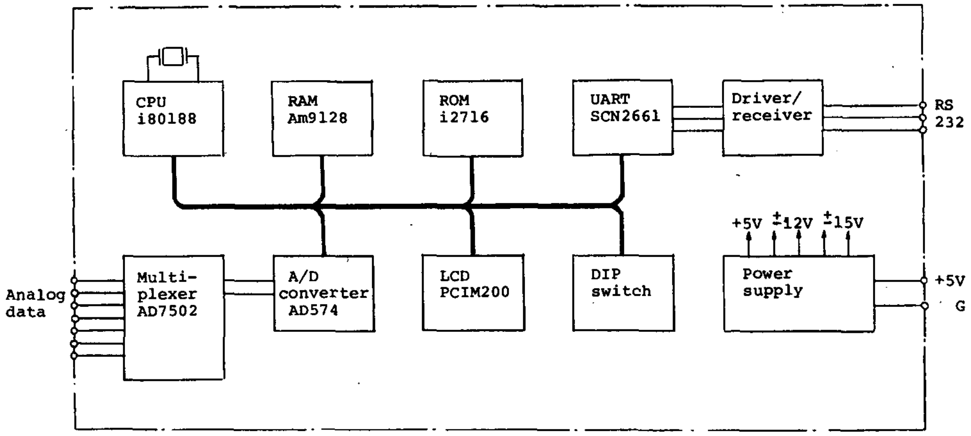

FIG. 5. Block diagram of the data processing unit.

segments between −50° and +50°C. One segment linearizes about the interval of 3.1°C, which is estimated to generate a linearization error of up to about ±0.01°C.

The chopping noise from the preamplifier generates the equivalent noise error of about ±0.06°C. The averaging of data by the data processing unit reduces such noise errors to the standard deviation of 0.04°C.

The prime source of errors is from chopping noise; therefore, utilization of a lower-noise operational amplifier can improve the accuracy of the thermometer.

b. *Fast response time*

The sensing junction of the new thermometer is made of 0.025-mm copper–iron wires. By referring to the thermocouple response time table of Temperature Measurement Handbook and Encyclopedia (Omega Engineering, 1985), the time constant, τ, of the 0.025-mm diameter iron–copper thermocouple in a 20 m s^{-1} airflow is estimated to be 4 ms.

In the cloud, the aircraft flies at a speed of about 100 m s^{-1}, the temperature there changes by perhaps as much as ±1°C s^{-1}. An error of less than ±0.01°C for a 1°C step change in temperature could be achieved in less than 5τ, or 20 ms.

c. *Wider measuring temperature range*

A wider range with the same resolution could be achieved in a number of ways if considered necessary, such as by using an A/D converter with 14 or 16 bits. Alternatively, simply reducing preamplifier gain by a factor of two (or even four) could be allowed before the resolution exceeded the present accuracy, which would double the measurement range.

d. *Wider operating temperature of circuitry*

Although the thermometer was planned for use with the circuitry at ambient temperature of −50° to +50°C, it can only operate from −10° to +50°C as of now because the computer clock stops. The digital components of the data processing circuitry primarily used commercial parts for this project; however, these parts can be readily replaced with military parts, because all critical parts use sockets. An Intel 80188 for the central processing unit which can operate down to −50°C will soon be available. The present digital circuit would need to be thermally controlled if a lower operating temperature is needed. The thermometer presently gives about ±0.2°C change across a temperature range of −10° to 50°C in the temperature of the electronics package, as compared with a 20°C ambient. Alternatively, since the measured temperature error due to the circuit temperature is nearly linear with circuit temperature, it is likely that enclosing the circuit temperature would allow the computer to correct the measured temperature to better than 0.1°C over the whole range.

e. *Very stable*

The sensing junction is coated by very thin gold, and is very stable against rusting or contamination. After several days in a 3% salt solution, a gold-coated wire showed no corrosion, while an uncoated wire completely disintegrated in one day.

f. *Application to wet-bulb temperature measurement*

A wet-bulb thermometer is a very important possible application for such an instrument to measure the mixing ratio of water vapor in the air from an aircraft. The very small sensing zone of the thermocouple thermometer makes irrigation with water to form a wet bulb somewhat easier. Uniform irrigation is a major weakness of a resistance thermometer, which requires adequate wetting of the wick along the whole wire, without flooding.

4. Fundamental concerns and further developments

The gold coating is less than 1 μm thick around a 25-μm diameter wire. In the vicinity of the junction, where the temperature is uniform, the gold can have no effect on the thermocouple voltages. This follows from the thermodynamic argument that no energy can be released to drive currents at a constant temperature. The gold is also very similar to copper in its thermoelectric properties, so its effect on the copper wire can be ignored, even if there is a substantial temperature change along it. Effects will be concentrated in the gold coating along the iron wire.

It is a good approximation to consider the coating to be of copper rather than gold. This indicates that a 1 μm layer around a 25-μm diameter iron wire will have a similar resistance to that of the wire. Thus, the junction will, in effect, be partly along the coated section of the wire where it meets the slower time constant supports which have a different temperature while the air temperature is rapidly changing. Thus, the full benefits of the rapid response from using a 25-μm diameter wire can only be achieved if the gold coating is considerably thinner than 1 μm. The influence is proportionally less on a 75-μm diameter wire.

There is no problem in depositing gold layers thinner than 1 μm by vacuum deposition, but the practical limit where the layer is so thin it fails to protect the wire from corrosion needs to be investigated. *Thermally,* the layer is no different from using a slightly thicker copper wire, and hence the thickness of the gold is not an issue in this regard.

An alternative approach is to deposit aluminum around the wires and then oxidize it to form an insulating layer, with, perhaps, gold on top, if this helps prevent corrosion. This will need to be investigated if the gold is not an adequate corrosion inhibitor when we are sure it is thin enough to be electrically satisfactory.

We can estimate approximately the effects of conduction down the wire by calculating the temperature gradient in the wire needed to give a similar maximum rate of temperature change to that caused by the air. For a cylinder,

$$\rho s \frac{dT}{dt} = \frac{d}{dx}\left(k\frac{dT}{dx}\right).$$

For a copper wire the density is $\rho = 8.89$ gm cm^{-3}, the specific heat is $s = 0.0915$ cal °C^{-1} gm^{-1}, and the conductivity is $k = 0.92$ cal cm^{-2}/(°C cm^{-1}).

Thus,

$$\frac{d^2T}{dx^2} = \frac{8.89 \times 0.0915}{0.92}\frac{dT}{dt} = 0.89\frac{dT}{dt}.$$

For a 20°C step-change in air temperature, with a time constant of 0.004 sec, $dT/dt = 5000$. Thus,

$$\frac{d^2T}{dx^2} = 4450.$$

As a simple approximation, take a half-wave of a cosine curve for the temperature profile along this wire over a distance, d, with a total temperature change of 20°C. Thus

$$T = 10[1 + \cos(\pi x/d)]$$

$$\frac{dT}{dx} = \frac{-10\pi}{d}\sin\left(\frac{\pi x}{d}\right)$$

$$\frac{d^2T}{dx^2} = -10\frac{\pi^2}{d^2}\cos\left(\frac{\pi x}{d}\right).$$

Assuming that the maximum rate of change of temperature with distance affects the time constant the most, then,

$$\frac{d^2T}{dx^2} = 10\frac{\pi^2}{d^2} = 4450,$$

and hence,

$$d = \left(\frac{10}{4450}\right)^{1/2}\pi = 0.15\,\text{cm}.$$

Thus, in this approximation, a few millimeters of thin wire on each side of the junction should be adequate. A more accurate approximation will be needed for the final design in case a greater length of wire should prove to be essential; however, similar distances from supporting structures are commonly used in other resistance thermometer configurations in current use (e.g., Rosemont type 102).

Some sort of shielded entry tube, or forward-facing hood, to the thermometer housing is planned so that large falling precipitation can be kept off the sensing element without any need to appreciably accelerate the airflow and thus change its temperature. This entry arrangement will also shield the element from sunlight. Some care is needed in this design to ensure that water from wetting and ice fragments can escape before passing over the element. A half-tube on the top side may be adequate although a smaller full tube to align the airflow through the sensing support structure is probably necessary.

The effects of adiabatic heating and frictional heating from the airflow will need to be estimated later, if absolute accuracy to the capability of the device is shown to be necessary. However, in most instances the differential changes with the short time constant will reveal the structure at the entraining edges of a cloud, which are of interest without needing absolute accuracy. If the instrument proves to be useful at slower time constants as an absolute temperature measuring device, it will need to be shown that such heating effects do not produce serious perturbations in cloud when the sensing element may not be evenly wetted at all times.

For use as a wet-bulb thermometer it is planned to wrap the sensing wires with fine cotton thread and feed water to the thread from a tiny reservoir kept at the pressure of the airflow through the sensing region. The controlled feed, zero-pressure supply has been designed, but the exact water delivery system still needs development. The time constant of this wet-bulb thermometer will be much slower than for an unwrapped wire, but it should still be relatively fast and accurate. It will only work in clouds warmer than freezing.

We believe the present work has shown the practicability of attempting these developments, but there are still a number of new problems to be solved.

5. Conclusion

A thermocouple thermometer with these advantages is likely to be very useful for measurement of cloud temperature and in various other kinds of applications which especially need both high accuracy and fast response time with stability (such as a temperature sensor for process control, or for human organs).

We are also looking forward to being able to replace some of the components of the thermometer with new, wider temperature-range components to attempt to achieve its potential performance of about 0.04°C without further development.

The prospect of a reliable, fast and accurate wet-bulb thermometer is of particular importance to cloud physics and the future study of entrainment.

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