Measurement of Gas Temperature and the Radiation Compensating Thermocouple

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ABSTRACT

The achievement of a high degree of accuracy in gas temperature measurement has been a problem in many investigations. The theory of such measurement is presented together with an analysis of a device known as the Radiation Compensating Thermocouple, which is designed to cancel out errors from the radiation environment inherent in other systems of measurement. The mathematical concepts and results of experimental work are included.

Results of tests provided data on the errors of air temperature measurement with single thermocouples used without shields and proved that carefully fabricated Radiation Compensated Thermocouples measure the true air temperature with very small errors.

1. Introduction

The measurement of air temperature, or, more broadly, the temperature of any gas, presents many problems because of various factors which result in errors. The Radiation Compensating Thermocouple[1] can measure gas temperatures much more accurately than other thermometers.

When the idea of the Radiation Compensating Thermocouple was first conceived, the physical design was determined by using empirical data obtained from actual measurements since no literature was available related to the problem. The knowledge that thermometers do not usually measure the correct temperature of a gas is not new. In his studies of the formation of dew over the period 1800–1815, Wells (1815) realized that the air temperatures measured by his thermometers were not always correct. The Annual Report of the Chief Signal Officer (1887) included a detailed discussion of the errors of thermometers used to measure air temperatures and of the errors of air temperature measurements when weather shelters are used.

Since these early reports, a large number of studies and tests on the problems of gas temperature measurement have been reported; for example, Circular 513 (Freeze, 1951) of the National Bureau of Standards lists approximately 400 references on the measurement of gas temperatures published between 1929 and 1951.

In many articles, the factors which cause a sensor to indicate a temperature different from the gas temperature have been described as "errors of the sensor." Actually, the temperature indicated by a sensor is a very accurate measurement of the equilibrium temperature a properly calibrated sensor has reached while exposed to the gas and to its surroundings; it may differ considerably, however, from the gas temperature.

2. Theory of gas temperature measurement

The temperature which a temperature sensor (thermometer) indicates is not usually the temperature of a gas. It is a temperature which is a result of the rate of heat transfer from the gas and its surroundings to the sensor by radiation, balanced against the rate of heat transfer from the sensor by radiation and convection-conduction to the gas and surroundings, and by conduction from the sensor to its support (Fig. 1).

The amount by which the temperature of a sensor differs from the actual gas temperature is directly related to the amount by which the balance of the heat transfers differs from the balance that would be reached if the temperature of all the surroundings were at the same temperature. If all the surroundings were at the same temperature as the gas temperature, the sensor would indicate the gas temperature. For simplicity, the amount the sensor temperature differs from the actual gas temperature will be referred to as an error (not an error of the sensor, but an error of the system to provide measurement of gas temperature).

Several factors may enter into the measurement of gas temperatures:

1) Radiative heat transfer[2] H_{RS} between the sensor and its surrounding objects occurs when the surroundings have a temperature different from that of the gas; e.g., the sun, as a source hotter than the gas, will cause an unshielded thermometer to indicate too high a

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[1] Patent 3,049,012, issued 14 August 1962, with rights assigned to the United States Government, inventor Glenn E. Daniels.

[2] Definitions of all symbols used are given in Appendix 1.

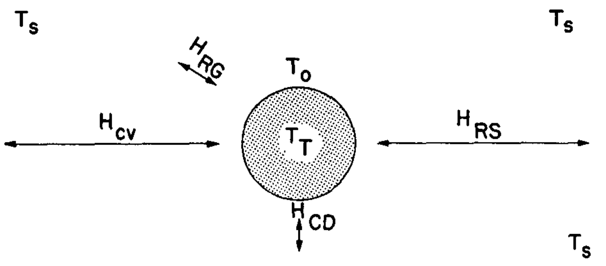

FIG. 1. Heat transfers between an object and gas.

temperature, while a clear sky, as a source colder than the gas, will cause an unshielded thermometer to indicate too low a temperature. The addition of thermal radiation shields reduces, but does not eliminate, the radiation error because the shield (a surrounding object) also becomes a source for heat transfer by radiation and will have a temperature different from the gas temperature. If the radiation source is reduced in intensity (e.g., clouds covering the sun), the error of measurement will be reduced. Radiation heat transfer occurs in a vacuum. In fact, because of its transparency to visible wavelength radiation when clouds are not present, our atmosphere at sea level does not significantly reduce the incoming solar radiation.

2) Radiative heat transfer H_{RG} between the sensor and the surrounding gases is of particular concern in furnaces and boilers when the gases have luminous molecules or particles. This heat transfer is identical to that between the sensor and its surroundings, since the gas molecules (or particles) become part of the surroundings. In meteorological air temperature measurements, this heat transfer has no significance because atmospheric gas molecules are nonluminous.

3) Convective-conductive heat transfer H_{CV} between the sensor and the gas is the main process through which the temperature sensor approaches the gas temperature. If this were the only heat transfer involved in gas temperature measurement (i.e., no radiative heat transfer), the sensor would always indicate the true gas temperature if its response time were fast enough. This heat transfer varies with the speed of motion of the gas across the sensor, being lowest with calm winds and increasing as a function of the wind speed. The greater this heat transfer the faster and closer the temperature sensor will approach the desired gas temperature. This heat transfer decreases with decreasing gas pressure and becomes zero in a vacuum.

4) Conductive heat transfer H_{CD} from the sensor to the sensor supports causes large errors in poorly designed gas temperature measuring systems. This heat transfer increases as the thermal conductivity increases, but decreases with decrease of the cross section of the supports. Such heat transfer needs to be small for accurate temperature measurement. A thorough discussion of the conduction errors of thermistors and their lead wires has been presented by Thompson (1966).

5) The impact of gas molecules on a sensor causes an error by heating the sensor. For low gas velocities (normal wind speeds), these errors are negligible, but at high velocities, such as space vehicle velocities, these errors become important.

6) The response time of a sensor introduces an error in measurement when a sudden change in gas temperature occurs. The faster the sensor response, the smaller is the magnitude of this error and the shorter the time in which it occurs.

Many methods have been used to improve gas temperature measurements. The three most generally accepted, i.e., reducing the size of the sensor, reducing the surface emissivity, and increasing the speed of the gas over the sensor, only partially eliminate the error. This is shown as follows:

a. Error reduction methods

1. SENSOR SIZE. While reduction of the sensor size does not reduce the heat transfer per unit area from radiation, it does increase the heat transfer per unit area from convection-conduction. Since heat transfer from radiation increases the error and that from convection-conduction decreases the error, reduction of sensor size results in a reduced error because of the changes in the ratios of the heat transfers; thus, a smaller sensor will measure closer to the true gas temperature. Fishenden and Saunders (1932) have given a comprehensive discussion in this respect of heat transfer by convection and conduction for cylinders of various sizes.

Waggener (1898) proposed, probably for the first time, the use of a group of thermocouples of various sizes to determine the true temperature of a Bunsen burner flame (a hot gas surrounded by colder objects). He placed several thermocouples of different sizes in a flame and plotted the resulting temperatures as a function of the size of the thermocouple wires. By extrapolating the resulting temperature curve to zero wire size, the true gas temperature is determined because a thermocouple of zero mass and size will theoretically indicate the correct gas temperature (Fig. 2).

Kreisinger and Barkley (1918) used thermocouples of various sizes to measure temperatures of gases in boilers. They found, when measuring temperatures of hot gases surrounded by cooler surfaces, that the temperatures measured by small thermocouples were higher than those of large thermocouples, the smaller thermocouple reading closer to the true gas temperature. They also found that the higher the gas temperature in relation to the temperature of the boiler walls, the greater was the error of measurement of the true gas temperature for a sensor of a specific size. When using a thermocouple 0.020 cm in diameter, the errors exceeded 55C (100F) for a gas temperature of about 1090C (2000F).

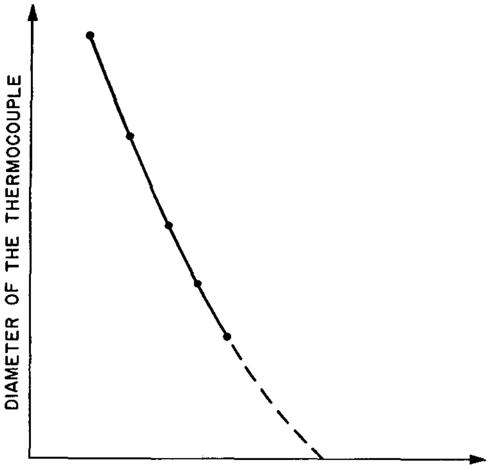

FIG. 2. Use of thermocouples of various sizes to find the gas temperature T_0.

Using copper and constantan butt-joined thermocouples of various sizes and without shields or special reflective coatings, the author has collected data showing errors of 1C for AWG No. 35 gage wire (0.014 cm diameter) during clear days and one-half this value on clear nights. If the thermocouple is reduced sufficiently in size to provide accuracies of air temperature measurements of ±0.06C (0.1F), a thermocouple no larger than 0.0008 cm diameter (AWG wire size about No. 58) will be required. Such a thermocouple would be difficult to fabricate, install and maintain, and could not be expected to remain intact for more than a short period of time.

2. SURFACE EMISSIVITY. If the surface emissivity of the sensor is reduced for all wavelengths of incident radiation (i.e., reflectivity increased), the absorption of radiation will be lower and there will be less heat transfer by radiation. Therefore, the sensor will read closer to the temperature of the gas. It should be kept in mind, however, that coatings with high values of reflectivity in the visible region of the spectrum (appear white) may have low reflectivities in the infrared region of the spectrum and thus act as a blackbody (Thompson, 1966; University of Minnesota, 1957).

Coatings of temperature sensors for radiosondes have been intensively studied by the University of Minnesota (1957) and published in their annual progress report. One of the best coatings they found was aluminum which has a high reflectivity (94%) in both the visible and infrared region of the spectrum.

Such a coating on a thermocouple made of AWG No. 35 gage wire would result in a radiation error of about 0.17C (0.3F) when used in the sun without shields. Continuous measurements of air temperatures with this small error would be of great value for micrometeorological use. However, such a thermocouple is very small and would cause fabrication, installation and maintenance problems. Also, small particles of dust accumulating on the thermocouple would greatly increase the measurement errors.

3. GAS FLOW. Since increasing the speed of the gas over the sensor increases the heat transfer from conduction and convection in the gas, sensor aspiration has long been a favorite method of reducing the error of gas temperature measurement. The "high velocity" thermocouple is most useful in measurement of gases in furnaces where errors of 200C are common with large thermocouples. The "high velocity" thermocouple can be placed parallel to the flow of the gases. In meteorological measurements of air temperatures, aspiration draws in air samples not from a point or horizontal plane outside the shield but from a spherical volume, whose radius is related to the rate of aspiration. Wind, with its changing direction and velocity, and the earth's surface, especially near the ground, distort the sphere so that the center of the sphere will not coincide with the location (height above the ground) where the measurement is required (Bartels, 1930; Nyberg, 1939).

b. *Error evaluation*

Many methods have been reported to eliminate, reduce or correct the error in gas temperature measurement. Moffatt (1949), Dahl (1950), Bolles (1948), Severinghaus (1937) and Scadron *et al.* (1952) have all discussed gas temperature errors and given methods for estimating the errors. The National Advisory Committee for Aeronautics (NACA) studied this problem in research on jet engines (Scandron and Warshawsky, 1952; Scandron *et al.*, 1952; Simmons, 1954). In NACA Technical Note 3766, Glawe *et al.* (1956) gave the following equation for computing the error of bare-wire thermocouples:

$$\text{Radiation correction} = (K^*_{\text{rad}}/\sqrt{M_P})(T_w/T_R)^{0.18} \times[(T_w/T_R)^4 - (T_d/T_R)^4], \quad (1)$$

where

$$K_{\text{rad}}^* \approx 27 e_w \sqrt{d}.$$

Since many of the parameters in Eq. (1) are the same for thermocouples of different size but of identical construction (type, same materials, etc.), when exposed to the same environment, Eq. (1) can be written for these identically constructed thermocouples, for forced convection, as

$$\text{Radiation correction} = f(\sqrt{d}/v). \quad (1a)$$

Eq. (1a) shows that the smaller the sensor the smaller the error; likewise, the higher the aspiration rate the smaller the error. Since the velocity of the gas can be assumed constant for short time periods, the radiation correction is then a function of wire size only.

If the gas is at a temperature T_0 and the surrounding objects are at a different temperature T_s (represented as the sum of all the objects at temperatures T_{s_1}, T_{s_2}

$T_{s_3}, \cdots, T_{s_n}$), the various heat transfers and the flow of heat are as shown in Fig. 1.

The condition for equilibrium of the sensor can be represented by

$$\dot{H}_{CV}+\dot{H}_{RG}+\dot{H}_{RS}+\dot{H}_{CD}=0, \tag{2}$$

where the terms are negative or positive depending on whether the surrounding objects are warmer or colder than the gas and whether the sensor is warmer or colder than the gas or the supports. If it is assumed that the equilibrium is at some instant and the gas is transparent to radiation (as in air), H_{RG} is zero; we can then write Eq. (2) as

$$h_c(T_0-T_t)A_1+\sigma e e_s(T_s^4-T_t^4)A_1X + (KA_2/a)(T_t-T_s)=0. \tag{3}$$

The term $\sigma e e_s(T_s^4-T_t^4)A_1X$ will nearly always consist of a sum of several terms, one for each variety of the surrounding sources of radiation, varying in temperature or emissivity. The term for conduction, $(KA_2/a)(T_t-T_s)$, likewise may consist of several terms, one for each type of material used in the sensor or support.

Eqs. (1) and (2) show that when the net temperature of the surroundings differs from the gas temperature, a sensor will indicate not the temperature of the gas, but some value between the gas temperature and the surrounding temperatures.

Therefore, a single temperature sensor theoretically never reads the true temperature of a gas except where no heat transfer occurs. This fact is important because we do not have a direct method of precisely measuring the correct temperature of a gas and therefore have no reference to use to determine directly the error of any gas thermometer from the true gas temperature. Too often experimenters state that their thermometers have no error when they actually have no way of determining the errors of their measurements.

3. The Radiation Compensating Thermocouple

The idea leading to the invention of the Radiation Compensating Thermocouple originated when a series of thermocouples of similar construction but of different sizes was being used to evaluate the magnitude of the radiation error of various thermocouple sensors and shields then in use.

In Fig. 3, a modification of Fig. 2 for a condition where the gas temperature (air temperature) is lower than the surrounding source (sun plus sky on a clear day), temperature increases with sensor size (thermocouple wire size). Extrapolating the curve to zero sensor size gives the true air temperature T_0. Here, we are considering one individual static case with unchanging air temperature and surrounding temperatures occurring for a short time. If three sensors of three sizes (small, medium and large) are selected, the temperatures measured by these sensors can be represented by T_S, T_M and T_L, respectively, with errors ΔT_S, ΔT_M and ΔT_L from the true air temperature T_0. Therefore,

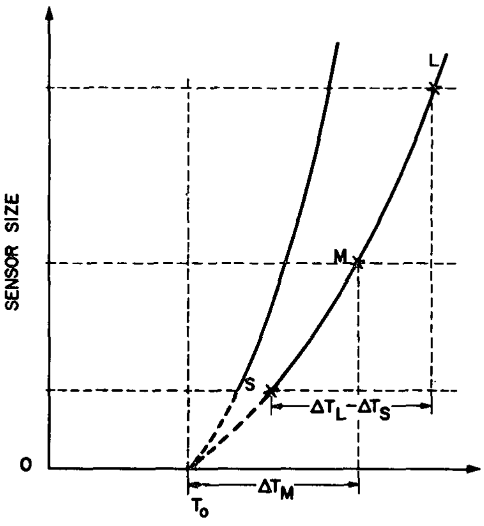

FIG. 3. Theory of Radiation Compensating Thermocouple—static condition.

$$\left.\begin{aligned} T_S&=T_0+\Delta T_S \\ T_M&=T_0+\Delta T_M \\ T_L&=T_0+\Delta T_L \end{aligned}\right\}. \tag{4}$$

If the three thermocouples are wired together so that thermocouple T_L opposes the other thermocouples electrically, then the three thermocouples will read a temperature[3] T_x, and we can write

$$T_x=(T_0+\Delta T_M)-(T_0+\Delta T_L)+(T_0+\Delta T_S), \tag{5a}$$

or

$$T_x=T_0+\Delta T_M-(\Delta T_L-\Delta T_S). \tag{5b}$$

If we select three single thermocouples such that their errors satisfy the equation

$$\Delta T_M=\Delta T_L-\Delta T_S, \tag{6}$$

then, from Eq. (5b) we have

$$T_x=T_0. \tag{7}$$

In other words, by proper selection of the three thermocouples, the system can be made to read the true gas temperature directly. The schematic of such a system is shown in Fig. 4.

Therefore, it is possible to build a thermometer by selecting and properly connecting several sensors, identical except for size, so that the error of each sensor, when summed up with proper sign, will give a net error of zero (i.e., all errors will cancel out). This

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[3] When we say that a single thermocouple reads a specified temperature, we are considering that the single thermocouple is connected into a proper measuring system with a reference thermocouple.

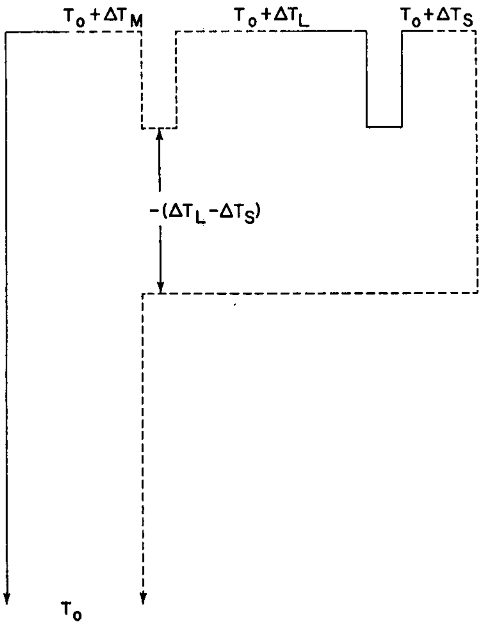


FIG. 4. Schematic of Radiation Compensating Thermocouple.

thermometer is designed so that it can be connected directly in place of any single thermocouple of like materials (i.e., it only has two wires of thermocouple materials to connect), but will measure gas temperatures directly with no error. Not only can the shields or aspiration required for a single thermocouple be eliminated, but the types of thermocouple materials used are unimportant as long as the same combination is used throughout the system.

The previous discussion is based on a single static condition of radiation error. Eq. (1a) shows that the radiation correction (radiation error) is a function of the square root of the diameter of the thermocouple; therefore, a change of radiation from the surroundings, a change of gas temperature, or a change of wind speed to new constant values (for new static conditions) will shift the curve in Fig. 3 to a new position but with no change in its mathematical shape. Thus, while the individual errors of each single thermocouple may be smaller or larger, the parallel nature of the wire size intersections with new curves shows that the ratio

$$\Delta T_M/(\Delta T_L-\Delta T_S) \tag{8}$$

will remain a constant, which, for the ideal thermocouple design, is equal to 1.

Although the theory of the Radiation Compensating Thermocouple is simple, the actual design of a working unit, i.e., finding the correct wire sizes, required careful and precise tests to evaluate all phases of construction.

The Radiation Compensating Thermocouple, when evaluated in terms of the errors discussed earlier, has the following advantages:

1) The error due to the fact that heat transfer by radiation between the sensor and the surroundings is not in balance with the heat conduction-convection between the gas and sensor, can be reduced to any desired limit depending on the precision of design and fabrication.

2) The error due to heat conduction between the sensor and support can be considered in the design; at present, this error is small enough to be ignored.

3) The Radiation Compensating Thermocouple does not compensate for response time error; in fact, if the thermocouples selected vary too greatly in size, the compensating balance will change, for short periods of time, with rapid temperature changes. It was for this reason that the original design using three thermocouples was changed to one using five thermocouples.

With five thermocouples, Eq. (6) becomes

$$\Delta T_M=(\Delta T_{L_1}-\Delta T_{S_1})+(\Delta T_{L_2}-\Delta T_{S_2}), \tag{6a}$$

or, if the two large and the two small thermocouples are the same size,

$$\Delta T_M=2(\Delta T_L-\Delta T_S). \tag{6b}$$

or

$$\tfrac{1}{2}\Delta T_M=\Delta T_L-\Delta T_S. \tag{6c}$$

This permits fabrication with thermocouples more nearly the same size and reduces the effect of response time error. Since the Radiation Compensating Thermocouple is used without shields in gas temperature measurements, its response time is considerably shorter than a single thermocouple used in a shield. Response times <1 sec were estimated in the tests.

The Radiation Compensating Thermocouple was invented through tests conducted on a meteorological tower exposed to normal atmospheric temperature ranges in a desert area. The equipment available for recording temperature in the tests strongly influenced

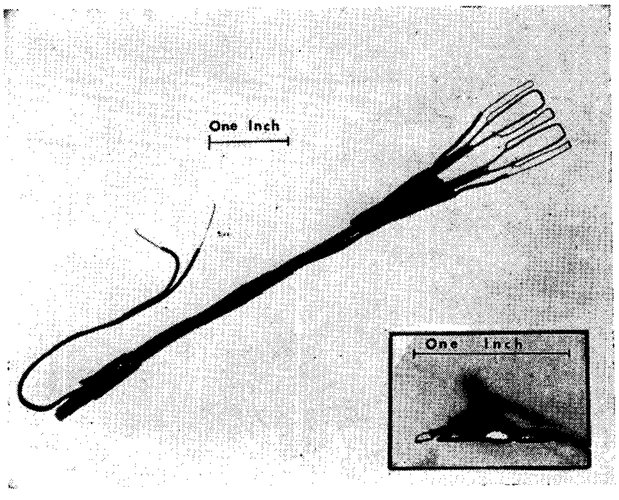


FIG. 5. Photograph of Radiation Compensating Thermocouple as viewed from top with insert showing view from front end.

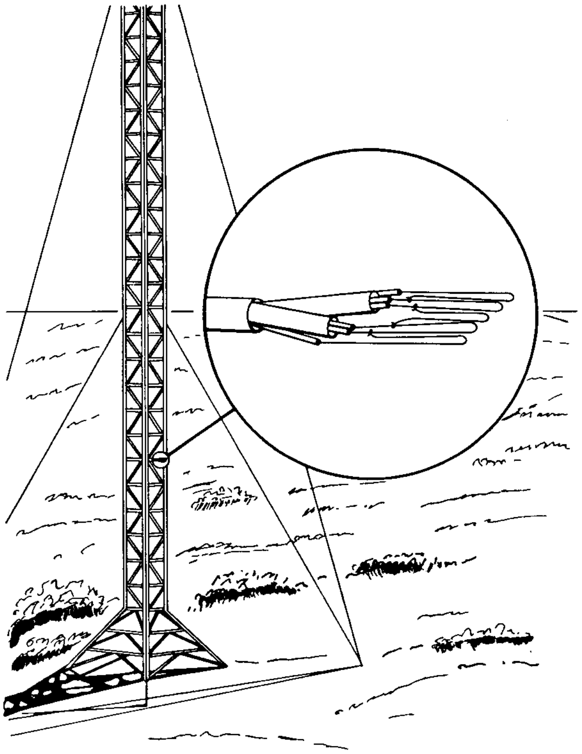


FIG. 6. Installation of Radiation Compensating Thermocouple.

the physical design of the prototype models. Copper-constantan thermocouples were mounted on a tower with the thermocouples facing south. This required a design of the Radiation Compensating Thermocouple with the five junctions and the wire leads connecting the junctions forming a flat surface parallel to the ground (Figs. 5 and 6). The five junctions were along the south-facing edge of the plane. In this way, all the thermocouple junctions had similar exposure to the sun (the largest contribution of point radiation during the tests). If the Radiation Compensating Thermocouple is rotated around its axis so that the five thermocouples are arranged with one above another, the compensating ability will not change except for convection between individual thermocouples unequally affecting other thermocouples in the system. This convection would exist in its worst condition when the plane of the thermocouple system is vertical, since the lowest thermocouple receives no convection from the other thermocouples while the other four thermocouples would be affected by different amounts of convection from below.

All tests were controlled by five individual thermocouples of different sizes to give a reference true air temperature. Except for size, these thermocouples were identical in construction.

Data collected from the five single thermocouples on 8 April 1960 were selected for use in the design of models of the Radiation Compensating Thermocouples. Because the wind was calm and the air very clear on the day these data were obtained, the radiation errors measured were larger than on any other test (Table 1). The use of such large radiation error data in the design of the instrument was deliberate since under normal use the errors would usually be less than those used for design; therefore, the Radiation Compensating Thermocouple would perform better than the design data indicated.

TABLE 1. Average values of temperature recorded at Fort Huachuca, Ariz., 0900 8 April 1960, by various size thermocouples (all thermocouples painted black and exposed without shields).

Thermocouple Wire size (AWG)	Diameter* (inches)	Average temperature (°F)
16	0.053	81.06
20	0.0335	77.26
24	0.022	74.79
28	0.014	72.91
35	0.006	70.70
Model 42—Radiation Compensating Thermocouple		68.91

* Actual wire diameter measured after painting.

TABLE 2. Temperature errors of single thermocouples obtained from data in Table 1 compared to actual measured error if $T_0=69.11$F. Computations were made from Eqs. (11a) and (11b).

Wire size (AWG)	Wire diameter (d) (inches)	Wire diameter (d) (mm)	Temperature error (ΔT) (°F)	Temperature error (ΔT) (°C)
16	0.0508	1.2903	11.54	6.41
18	0.0403	1.0236	9.60	5.33
20	0.0320	0.8128	7.89	4.38
22	0.0254	0.6452	6.43	3.57
24	0.0201	0.5105	5.20	2.89
26	0.0159	0.4039	4.19	2.33
28	0.0126	0.3200	3.36	1.87
30	0.0100	0.2540	2.70	1.50
32	0.0080	0.2032	2.17	1.21
34	0.0063	0.1600	1.72	0.96
35	0.0060	0.1524	1.64	0.91
36	0.0050	0.1270	1.37	0.76
50	0.0010	0.0254	0.28	0.16

Using the data in Table 1 and assuming a relationship of the form

$$T_t = A + Bd + Cd^2, \tag{9}$$

the constants A, B, C were determined by a least squares solution, with the result that

$$T_t = 69.112 + 279.832d - 1033.06d^2. \tag{10}$$

Substituting a wire diameter of zero into the equation, a value for T_0 (zero wire size) of 69.11F is obtained; i.e., the true air temperature was 69.11F at the time.

If we now let

$$\Delta T = T_t - T_0,$$

and substitute into Eq. (9), we obtain

$$\Delta T = 279.832d - 1033.06d^2 \qquad (\Delta T,\ ^\circ\text{F},\ d,\ \text{inches}), \tag{11a}$$

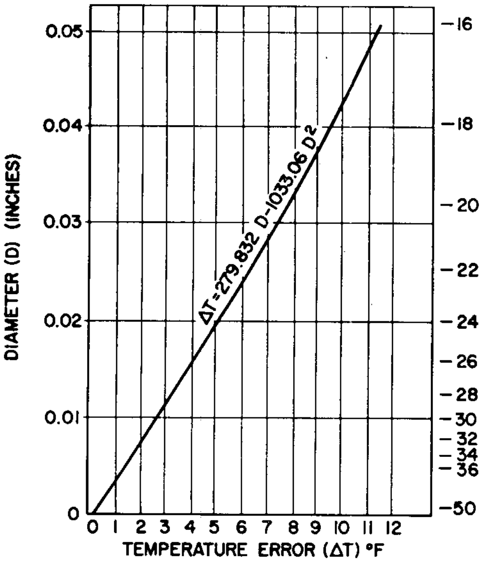


FIG. 7. Errors of single thermocouple sensors (black, butt-joined) for various wire sizes. Scale on right ordinate refers to AWG numbers.

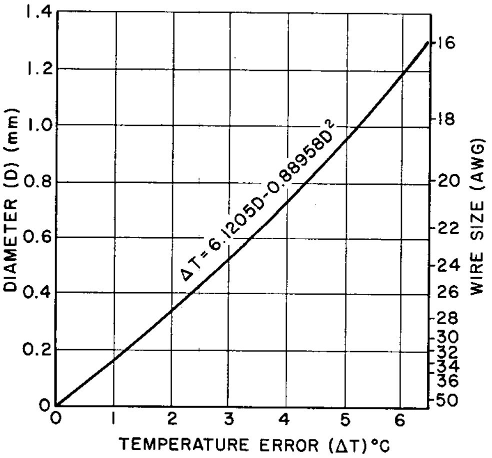


FIG. 8. Errors of single thermocouple sensors (black, butt-joined) for various wire sizes, metric units.

TABLE 3. Temperature errors of single thermocouple sensors (black, butt-joined) for various wire sizes, exposed in bright sunlight.

Wire size (AWG)	Diameter (inches)	Temperatures Computed (°F)	Temperatures Actual (°F)	Errors, computed minus actual (°F)
16	0.053	11.93	11.95	−0.02
20	0.0335	8.21	8.15	+0.06
24	0.022	5.65	5.68	−0.03
28	0.014	3.72	3.80	−0.08
35	0.006	1.60	1.59	+0.01

Note: Model 42 of the Radiation Compensating Thermocouple (data in Table 1) had an error of 0.20F from the computed T_0. This is within the measuring accuracy of the equipment being used.

TABLE 4. Characteristics of specific designs of the Radiation Compensating Thermocouples.

Thermocouple	Wire size (AWG)	Wire size (inches)	ΔT	$\Delta T_L - \Delta T_S$
		Design I		
S	24	0.0201	5.20	2.69
L	20	0.032	7.89	
M	22	0.0254	6.43	
L	20	0.032	7.89	2.69
S	24	0.0201	5.20	
	$\Sigma(\Delta T_L - \Delta T_S)$			5.38
		Design II		
S	28	0.0126	3.36	4.53
L	20	0.032	7.89	
M	24	0.0201	5.20	
L	20	0.032	7.89	3.70
S	26	0.0159	4.19	
	$\sum(\Delta T_L - \Delta T_S)$			8.23
		Design III		
S	28	0.0126	3.36	1.84
L	24	0.0201	5.20	
M	26	0.0159	4.19	
L	24	0.0201	5.20	2.50
S	30	0.0100	2.70	
	$\sum(\Delta T_L - \Delta T_S)$			4.34

or

$$\Delta T = 6.1205d - 0.88958d^2 \quad (\Delta T,\ ^\circ\mathrm{C},\ d,\ \text{millimeters}). \qquad (11\text{b})$$

Eqs. (11a) and (11b) are empirical equations which can be used to find the maximum error to be expected from any small black temperature sensor in the sun. Table 2 gives the errors of various sized thermocouples computed from Eqs. (11a) and (11b) while Figs. 7 and 8 show the data graphically. If the error is desired for a sensor having an emittance different from that of a blackbody, the error can be found by correcting the error obtained from Eq. (11a) or (11b) by the ratio of the emittance of the sensor to that of a blackbody.

The actual errors of the single thermocouples are compared to the errors computed from Eq. (11a) in Table 3.

The computed values minus the actual values given in Table 3 represent the accuracy of fit of Eq. (10) to the measured data. Eq. (1a) indicated that a second-degree equation should fit the data. Higher degree equations were computed, but the accuracy of fit was not improved.

Eqs. (11a) or (11b) can be used to determine the wire combinations needed to construct a Radiation Compensating Thermocouple. The method used involves the initial selection of a specific size for the largest thermocouple; and then, by trial and error, the size of the medium thermocouple and the size of the small thermocouple are found such that the medium thermocouple is approximately halfway in error between the large and small thermocouples on the error curves.

As examples of verification of the amount of error in specific designs of the Radiation Compensating Thermocouple, designs I, II and III are analyzed with the aid of Eqs. (11a), (6a) and (8) in Table 4.

Using Eq. (8), we obtain for Design I

$$\Delta T_M/(\Delta T_L-\Delta T_S)=6.43/5.38=1.20.$$

This means that Design I still has a residual error of about 20% in the measurement, i.e., 80% of the error is removed. For Design II, we have

$$\Delta T_M/(\Delta T_L-\Delta T_S)=5.20/8.23=0.63,$$

i.e., an overcorrection of the error by about 37%. This means that this Radiation Compensating Thermocouple will read a temperature lower than the actual gas temperature when a radiation source hotter than the surroundings is present, i.e., the temperature would be higher when shaded than when in the sun. A Radiation Compensating Thermocouple confirming this was actually constructed.

Finally, for Design III, we have

$$\Delta T_M/(\Delta T_L-\Delta T_S)=4.19/4.34=0.97.$$

This design results in an approximate 3% error in measurement of the true gas temperature, the measured temperature being lower than the actual gas temperature.

All computations and discussions of the designs were based on the worst conditions, i.e., a clear, sunny, calm day and black thermocouples. The performance to be expected of a Radiation Compensating Thermocouple made from Design III as compared to that of a single AWG size 24 thermocouple under similar conditions with all thermocouples black is as follows: The single thermocouple would have an error of 4.19F, while the Radiation Compensating Thermocouple would have an error of $4.19\text{F}-4.34\text{F}=-0.15\text{F}$, i.e., it would read 0.15F too low. This is the "worst" error to expect. These computations were made on the assumption that in the fabrication the diameters of the wires would not be increased at the junction. Actually, about 0.001 inch increase of diameter is normal in fabrication and should be added to each wire before making computations. From actual tests it has been found that the wire sizes in Design II provide the best design for the Radiation Compensating Thermocouple, because of this factor.

Tests of 25 models of the Radiation Compensating Thermocouple were made over a two year period. Besides comparing the Radiation Compensating Thermocouple with single thermocouples, two identical Radiation Compensating Thermocouples, designed to give very small errors, were fabricated. One was painted black and the other white using a flat white paint. When these two thermocouples were placed in the sun, the air temperatures recorded were the same from each Radiation Compensating Thermocouple under stable air conditions. This illustrates the usefulness of the Radiation Compensating Thermocouple in gas measurements, since contamination or changes in the surface color do not change the accuracy of the Radiation Compensating Thermocouple if uniform.

Operational tests were made at Fort Huachuca by Carlson (1964). In these tests various test models of the Radiation Compensating Thermocouple were compared with a single AWG No. 24 gage thermocouple. He made simultaneous recordings of temperature data from a single thermocouple and various models of the Radiation Compensating Thermocouple, with different compensating factors. These tests were run on clear and cloudy days and nights with the thermocouples inside and outside a standard instrument shelter.

The results of these tests were as follows:

1) The performance of the test models of the Radiation Compensating Thermocouple was as predicted in design.

2) A properly designed Radiation Compensating Thermocouple used without shields or shelter is superior to a single thermocouple even when the single thermocouple is mounted in an instrument shelter.

3) The single thermocouple read 4-5F higher than the Radiation Compensating Thermocouple when both were exposed in direct sunshine with winds up to 15 mph.

Before the invention of the Radiation Compensating Thermocouple, the Meteorology Department of Fort Huachuca had adopted 24 gage butt silver-soldered thermocouples for temperature gradient measurements, and procedures were later published on installation and fabrication of these thermocouples (Daniels and Becker, 1960). Tests of many single butt silver-soldered thermocouples in the Meteorology Department Standards and Calibration Laboratory showed that these thermocouples had much smaller errors than expected using the standard thermocouple emf curve regardless of the quality of the thermocouple wire used.

A proper butt silver-soldered thermocouple cross section is shown in Fig. 9 with silver soldering instructions being given in Appendix 2. When this cross section is examined, all voids are filled with silver solder; thus, all parts of the two thermocouple materials are connected with a high heat and electrically conductive material (the solder used should be at least 50% silver). It is the belief of the author that the silver solder acts as an integrator to average out the impurities of the thermocouple material.

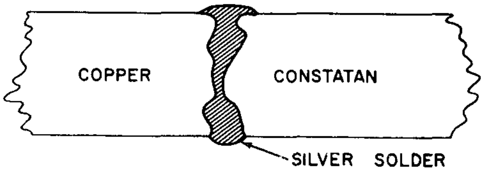


FIG. 9. Cross section of a typical butt silver soldered thermocouple.

4. Effects of pressure changes

Eq. (1) formulated by NACA for computing the radiation error of a thermocouple does not include any term for gas pressure, and is valid only at standard atmospheric pressure. With decreasing pressure, the convection-conduction heat transfer becomes smaller and the radiation heat transfer is about the same; therefore, in a vacuum, since the convection-conduction heat transfer is zero, the radiation error of a thermocouple reaches its largest value. The values of error caused by the size of the sensor (Table 2) were obtained at Ft. Huachuca, Ariz. The average station pressure at Ft Huachuca is about 0.8 atm; therefore, the measured temperature errors in the tests at Ft. Huachuca are a little larger than at sea level.

5. Measurement of temperature difference in a gas

Many systems with elaborate shields have been devised to measure the difference in temperature (ΔT) in the atmosphere. These systems use one or more pairs of thermocouples wired in opposition so that the temperature difference is measured directly. Since the radiation errors on each of these thermocouple groups will be nearly the same, the shields are unnecessary. This system will respond much faster to temperature changes. The Radiation Compensating Thermocouple used in a ΔT system will provide a higher order of precision than the single thermocouples.

6. Conclusions

Gas temperature measurements usually have large errors. These errors are not obvious because there are no "standard" gas temperature thermometers in general use. The Radiation Compensating Thermocouple can provide data on the actual gas temperature more precisely than a single thermocouple with or without shields and is useful as a "standard" gas temperature thermometer. Crudely fabricated Radiation Compensating Thermocouples, where the error is only partially compensated for, provided data superior to that from other sensors now in use.

Additional laboratory and field tests are needed on the Radiation Compensating Thermocouple to provide more information for optimum design and general use in all types of gas measurements.

The accuracy of measurement of the gas (atmospheric) environment is not improved by use of high precision thermometers unless the heat transfer errors are eliminated to the same degree of precision.

APPENDIX 1

Definition of Symbols

T_0	gas temperature
T_s	surrounding temperature
T_t	sensor temperature
H_{CV}	heat transfer by convection and conduction between the gas and sensor
H_{RS}	heat transfer by radiation between the sensor and the surroundings
H_{CD}	heat transfer by conduction between the sensor and support
H_{RG}	heat transfer by radiation from gas molecules to sensor
T_w	indicated thermocouple junction temperature
T_R	1000R, reference temperature
T_d	temperature of duct (surroundings)
M_P	velocity of gas (in terms of Mach number)
e_w	emittance of wire
d	diameter of wire
$K^*_{\mathrm{ad}} \approx 27 e_w \sqrt{d}$	
v	velocity of gas
h_c	coefficient of heat transfer by convection-conduction
A_1	surface area of sensor
A_2	cross-sectional area of sensor
σ	Steffan-Boltzmann constant
e	surface emissivity of sensor
e_s	emissivity of surrounding objects
X	fraction of total solid angle over which the junction sees the surrounding objects
K	coefficient of thermal conductivity of sensor and support
a	depth of immersion of sensor and support in the gas.

APPENDIX 2

Butt Silver Soldering of Thermocouples

To properly butt silver-solder copper and constantan thermocouple wires, the following procedure should be followed:

1) Split the insulation for about $1\frac{1}{2}$ inches from the end with a sharp knife as shown in Fig. 10a.

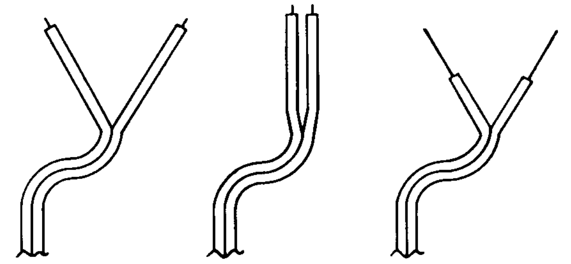
2) Use a pair of heavy scissors (not wire cutters or diagonals) and cut wires perpendicular to length (Fig. 10b). This gives a flat cut across wires.

3) Being careful that wires are not cut, gouged, or scratched, remove insulation (Fig. 10c).

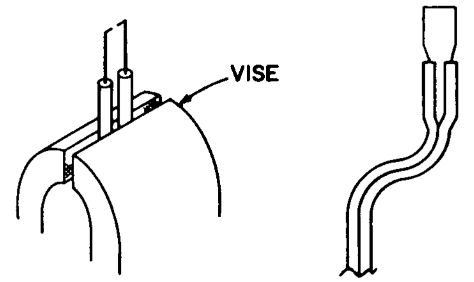
4) Clamp lightly in a vise and with jeweler's smooth jaw chain nose pliers, bend each wire to center, adjusting until the two ends meet, using the spring of the wire to hold together (Fig. 10d).

5) Clean a piece of silver solder with sandpaper and cut a piece of solder about equal to the diameter of the wire. This piece of solder should be very small; otherwise, the resultant thermocouple will be much larger than the wire size. Use silver solder flux on wires and stick the silver solder to the top of the wires with the flux.

6) Using a small flame from a propane torch or other welding torch, slowly heat the thermocouple wires at the junction until the silver solder melts and flows. Immediately remove the flame. By observing the flux, the melting of the silver solder can be anticipated. Just before the silver solder melts, the flux will become glassy looking. Heating too rapidly may cause the flux to crack and the silver solder to fall off. Both wires should



a. SPLIT WIRES b. CUT OFF SQUARE c. CLEAN INSULATION



d. BEND WIRES e. SILVER SOLDERED

FIG. 10. Fabrication of butt silver soldered thermocouples.

be heated evenly or the silver solder will flow to only one wire.

Wiring of the Radiation Compensating Thermocouple is shown in Fig. 11.

As a check for faulty construction, all Radiation Compensating Thermocouples should have a laboratory or field test to compare them with the extrapolated temperature for wire size zero, using a group of single thermocouples. This could be done in a laboratory test chamber.

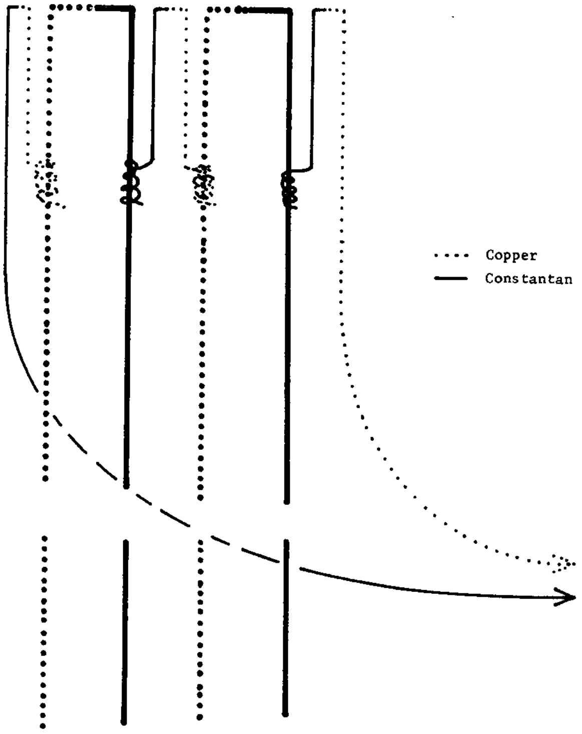


FIG. 11. Wiring of the Radiation Compensating Thermocouple.

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