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A SUPERHEAT METER OR DIFFERENTIAL THERMOMETER FOR AIRSHIPS

BY

D. H. STROTHER, Assistant Physicist
H. N. EATON, Engineer
Bureau of Standards

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A SUPERHEAT METER OR DIFFERENTIAL THERMOMETER FOR AIRSHIPS[1]

By D. H. Strother and H. N. Eaton

ABSTRACT

This paper describes a superheat meter or differential thermometer built at the Bureau of Standards for the Bureau of Aeronautics, United States Navy, to measure superheat, which is defined as the difference in temperature between the confined air and lifting gas in lighter-than-air craft and the external air. Formulas are first developed for the lift and the effect of superheat on the lift of a rigid airship. The instrument, which consists of a thermopile having one set of junctions in the gas cells and the other set in the free air, is next described. Unusual conditions of use and some special features of construction necessitated by these conditions are given particular attention. The facts that the temperatures of both junctions may vary considerably, that the distance between junctions was 90 feet, and that the galvanometer had to combine high sensitivity with steadiness of reading when subjected to the surging of an airship in flight all had an important influence on the design of the instrument. The errors in reading due to variations in temperature of the air junctions from the standard temperature at which the instrument was calibrated and those due to the effect of temperature on the galvanometer are discussed.

CONTENTS

I. DEFINITION OF SUPERHEAT

The term "superheat" as used in relation to lighter-than-air craft is defined as the difference between the temperature of the lifting gas and air within the balloon envelope and that of the external air. If the gas temperature is higher than that of the free air, the superheat is termed "positive"; if the free air temperature is the higher, it is considered negative. The importance of a knowledge of superheat in maneuvering an airship is evident when the dependence of the lift or buoyancy on this quantity is appreciated.

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[1] This instrument was developed in the aeronautic instruments section at the request and with the financial assistance of the Bureau of Aeronautics of the U. S. Navy. The assistance and cooperation of the pyrometry section in the selection and calibration of the thermocouples, of J. B. Peterson in the preparation of the section on "errors," and of C. P. Burgess in the preparation of the section on the "derivation of formulas" are acknowledged.

II. DERIVATION OF FORMULAS

The lifting power of an airship is given by the equation

$$L = VP\ (W - w) \tag{1}$$

where

L is the gross lift of the ship.

V is the gas volume corresponding to the specific weight w.

P is the purity of the gas with which the ship is inflated, expressed as a fraction of unity.

W is the weight per unit volume; that is, the specific weight of the external air.

w is the weight per unit volume of a pure specimen of the gas with which the ship is inflated.

In applying this and the following equations to an airship of the rigid type it must be remembered that it is usual practice to fill the gas cells only partially, so as to allow for expansion of the gas with the reduction in barometric pressure which corresponds to increasing altitudes.

Let T be the temperature of the external air in absolute degrees,
t the temperature of the gas in absolute degrees, and
B the barometric pressure under which L is determined.

Now W and w in (1) may be replaced by

$$\frac{W_s T_s B}{T B_s} \text{ and } \frac{w_s T_s B}{t B_s}, \text{ respectively,}$$

where W_s and w_s represent the specific weights of the air and the inflating gas at the standard temperature T_s, in absolute degrees, and standard barometric pressure B_s. The expression for the lifting power of the ship then becomes

$$L = \frac{VPBT_s}{B_s}\left(\frac{W_s}{T} - \frac{w_s}{t}\right) \tag{2}$$

In computing the change in lift of an airship due to superheat it should be remembered that the effect of superheat, not only on the gas in the cells but also on the air which is inclosed in the envelope and which surrounds the cells, must be considered, since the temperatures of the two gases vary together (approximately). If the pressure and temperature of the external air remain constant, the change in lift due to superheat will be equal to the weight of the air which enters or leaves the envelope of the ship while the temperature of the contained lift gas and air changes from the temperature of the external air T to its existing average temperature t. Since the expansion of a cubic foot of the inflating gas is the same as that of a cubic foot of air under identical temperature changes, the flow of air into or out of the envelope can be computed most easily by assuming the envelope to be entirely filled with air. This change in volume multiplied by the specific weight of the air corresponding to the superheat temperature t gives the change in weight of air inside of the envelope; that is, the change in lift.

Thus, if the volume of the envelope is V_e, and if the temperature of the air and inflating gas inside of the envelope changes from T to t, producing the superheat

$$S=t-T \tag{3}$$

while the barometric pressure B remains constant, the change in volume of the air and inflating gas is

$$\Delta V=V_e\frac{S}{T} \tag{4}$$

and the change in lift due to superheat is

$$\Delta L=V_e W_t\frac{S}{T} \tag{5}$$

or replacing W_t by W_s through the relation

$$W_t=W_s\frac{T_s}{t}$$

$$\Delta L=V_e W_s T_s\frac{S}{Tt}=K\frac{S}{Tt} \tag{6}$$

where K is a constant.

As an illustration of change in lift, a rigid airship whose envelope volume is 3,000,000 cubic feet containing 2,400,000 cubic feet of hydrogen at a barometric pressure of 29.92 inches of mercury and having a purity of 95 per cent will be used. The external air temperature is assumed to be 60° F. From (1) the lift is found to be

$$L=2{,}400{,}000\times 0.95\ (0.076-0.005)=162{,}000 \text{ pounds}$$

Assuming that the average gas and air temperature t inside the envelope increases to 80° F., which causes a positive superheat S of 20° F., the increase in lift (equation (6)) is

$$\Delta L=3{,}000{,}000\times 0.0807\times 491.6\times\frac{20}{539.6\times 519.6}=849 \text{ pounds}$$

In the preceding discussion the assumption was made that the gas cells were partially filled at all times. This state is both the usual and desirable condition. However, negative or positive superheat might occur with the gas cells full initially. Under these conditions, if the superheat is negative, equation (6) applies, since the gas cells contract in volume, as shown by equation (4).

If the superheat is positive when the gas cells are initially full and if excess pressure is allowed to build up inside the gas cells, the change in lift is due only to the expansion and consequent flow of air out of the envelope. The change in lift is then given by

$$\Delta L = (V_e - V)\,W_s \frac{T_s S}{Tt} \tag{7}$$

If, as is more usual, gas is valved to prevent pressure from building up inside of the gas cell, but the gas cell remains full, the lift is also increased by the weight of the inflating gas which is allowed to escape. For this case

$$\Delta L = \left\{ V_e W_s - V(W_s - \overset{w}{\cancel{W}}_s) \right\} \frac{T_s S}{Tt} \tag{8}$$

More complicated cases of superheat can be imagined, but the above formulas cover the ones which are common.

III. MAGNITUDE OF SUPERHEAT EXPERIENCED

In a series of papers by K. Bassus and A. Schmauss [2] the maximum value of the superheat which they found for a free balloon filled with illuminating gas is given as +72° F. With the United States Navy airship *Los Angeles*, values ranging from −8° to +27° F. superheat have been observed, and greater values may be expected. Usually superheat is a positive quantity, but, under certain conditions, such as during a rain, or when the ship emerges from a cloud bank, superheat may be negative. With a helium-filled ship, negative superheat occurs more frequently than with one filled with hydrogen, owing to the difference in behavior of these gases.

IV. METHODS OF MEASURING SUPERHEAT

In measuring superheat it has been the custom to install a thermometer in the gas cell and another in the free-air stream, observe both, and note the difference. This method, while giving the superheat, has the disadvantage that it allows a greater chance for observational errors being introduced than if the superheat were indicated directly, when a single reading would be taken, as well as the chance of mistake in subtracting the two readings. This method requires also more time to obtain the value of the superheat. Because of these facts the Bureau of Standards was requested by the Bureau of Aeronautics of the United States Navy to construct an instrument which would read superheat directly.

In the development of this instrument three methods were considered. The first was the use of a gas thermometer consisting of two bulbs and a pressure-tight line running from each to an indicator

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[2] Zeitschrift für Flugtechnik und Motorluftschiffart, 2, pp. 216–219, 295–297; 1911.

containing two air-tight chambers separated from each other by a flexible diaphragm. One bulb would be placed in the gas cell, the other in the air stream. Any difference in temperature between the two bulbs would cause a difference in pressure, which, in turn, would cause a deflection of the diaphragm proportional to the temperature difference—the superheat. It may be observed that the effect of the air temperature inside the envelope of the ship on the air tubes connecting the bulb in the gas cell with the manometer would tend to increase the accuracy of indication, rather than to diminish it, as is usually the case. This scheme, while simple and involving pressures which are of a convenient magnitude to measure, was abandoned because of difficulties which would be encountered in its construction and installation, such as maintaining the system air-tight, supporting the system in the gas bag, etc.

The second plan considered the use of a differential resistance thermometer consisting of two coils of nickel wire as the thermal elements—one placed in the gas cell, the other in the external air—a differential ammeter, and a battery. Current from the battery would divide and flow through the resistance elements to the differential ammeter, where the two currents would oppose each other in the coils of this instrument. Any difference in temperature would cause a change in resistance of the coils of the thermal element, which would allow more current to flow in one branch of the circuit than in the other. This difference in current would be read on the differential ammeter and would be proportional to the temperature difference. This scheme, while feasible, necessitates the use of a storage battery and some means of voltage regulation, which are obvious disadvantages.

The third plan, which is the one adopted, was the use of a differential thermocouple thermometer, the principles and construction of which will be discussed in this paper.

V. PRINCIPLE USED AND DESCRIPTION OF INSTRUMENT

It is well known that if a circuit is formed of two dissimilar metals whose junctions are at different temperatures a current will flow in the circuit, the magnitude of which is determined by the difference in the temperature of the two junctions, the temperature of one junction, the metals used to form the circuit, and the resistance of the circuit. In ordinary thermocouple work one junction is kept at a fixed temperature (or nearly so), while the other is placed so that it is at the temperature to be measured. In such cases it is not essential that the calibration curve of such a couple—that is, the temperature-electromotive force curve—be a straight line. In this instrument, however, the temperature of both junctions may vary, so it is desirable that, throughout the range of the instrument, each degree of temperature difference between the two junctions shall cause the same difference in potential between these junctions, no matter what the temperature of the two junctions may be; that is, the calibration curve plotted between temperature and electromotive force should be a straight line for this range.

This relation does not hold true exactly for any two metals, but an iron-nickel couple gives the closest approximation which could be found for the temperature range involved. However, iron corrodes badly and nickel has a very high temperature coefficient of resistance. Furthermore, it is very difficult to obtain these metals in a pure state in the size wire desired. It was found that, if a couple composed of alumel (*P*) and chromel (*P*)—alloys developed for thermocouple work—was employed, the calibration curve of the couple would be sufficiently near a straight line for the use intended. The equation of a couple formed of these metals between the values $-20°$ and $+50°$ C. calibrated with the fixed junction at 0° C., was found to be [3]

$$E = 39.04\,\tau + 0.0232\,\tau^2 \qquad (9)$$

where E is the electromotive force in microvolts and τ is the temperature in degrees centigrade. This equation is accurate within ± 20 microvolts over the range $-20°$ to $+50°$ C.

Alumel (*P*) was found to have a resistance of 0.110 ohm per foot and chromel (*P*) a resistance of 0.212 ohm per foot for No. 18 American Wire Gauge at 24° C. These resistances, as compared with those of most metals, are high, which is a distinct disadvantage, as it lessens the current available for measurement. This was a very important factor, since a distance of 90 feet between junctions was called for in the specifications.

With the sizes of wire available (No. 18 American wire gauge), it was apparent that the difference in potential between the junctions of one couple was not sufficient to cause a large enough current to flow for measurement by any suitable commercial instrument. Accordingly, four couples were placed in series, forming a thermopile. As a further means of enlarging the current an additional wire of chromel was placed in each couple, paralleling the original chromel wire, and thus materially lowering the resistance of the circuit.[4] In this way the resistance of the circuit, exclusive of the galvanometer, was found to be 88.1 ohms. The individual wires were varnished and covered with silk enamel and the whole thermopile formed into a cable and covered with rubber with the junctions protruding at the ends. With this arrangement the cable is composed of 12 wires.

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[3] Calibration made by the pyrometry section.

[4] This was done to avoid the loss of time and difficulty attendant on obtaining a larger size of wire and having it insulated.

A lighter and less bulky cable would have resulted if No. 16 size wires of each material had been used or if a larger chromel wire were used. If No. 16 wire had been employed throughout, the number of wires in the cable would have been reduced to 8, and the resistance would have been slightly lower, approximately 83 ohms. Figure 1 is a wiring diagram of the instrument.

It was necessary to select a galvanometer for the indicating instrument which was fairly compact, light in weight, sufficiently sensitive, and so damped that it would be unaffected by the oscillations experienced on board an airship. The most suitable and available commercial galvanometer for this purpose appeared to be the Weston model 440; the one actually used had an internal resistance of 62.2 ohms, a critical damping resistance of 160 ohms, and a sensitivity of 0.5 microampere per scale division, or 30 microamperes over the full scale. This instrument was well suited for use, as it was fairly rugged, and when the instrument was a little overdamped the pointer would hold comparatively steady, even though subjected to oscillations such as are experienced on board an airship.

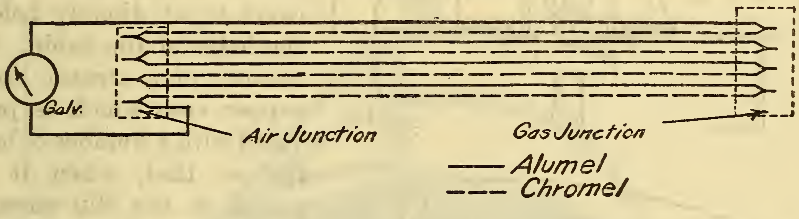

FIG. 1.—*Wiring diagram of superheat meter*

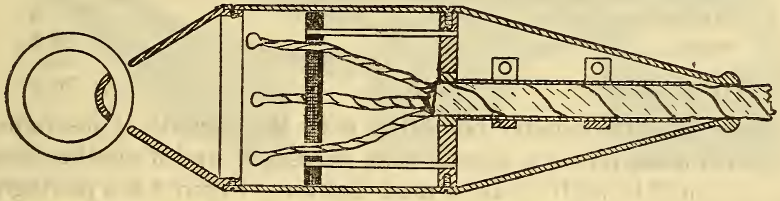

FIG. 2—*Diagram of gas cell junction cover*

With the galvanometer here described in the circuit, the total resistance was found to be 150.3 ohms. The scale of the instrument was graduated to read from −12° to +36° F. superheat. One degree of superheat Fahrenheit was found to correspond to about 1.2 divisions on the original scale.

The gas junction cover is shown in Figure 2. It is made of brass with holes drilled throughout the surface to provide free ventilation. The surface is smooth and has no sharp edges, so that it will not injure the lining of the gas cell. A ring is provided on top of the cover for attaching to a suspension from the top of the gas cell, so that temperature ranging can be done in the cell. The weight of the cable is supported by this cover, so clamps are provided in order that the cable may be secured.

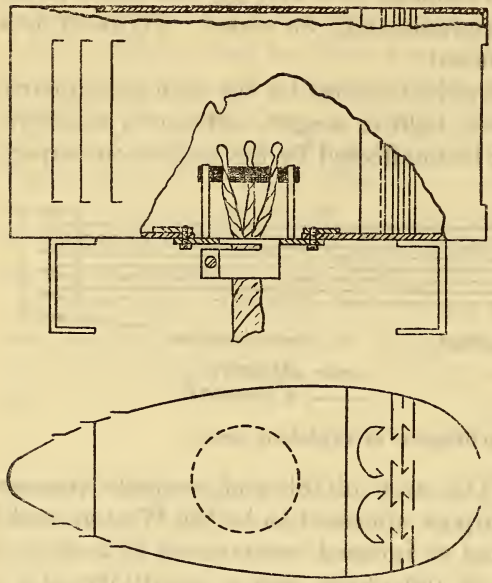

FIG. 3—*Diagram of air junction cover*

A diagrammatic sketch of the air junction cover is shown in Figure 3. This cover is set directly below the ledge of the cabin. It consists of a stream lined copper case which is provided with a number of baffles so that, when it is placed in the slip stream, circulation of air around the junction is provided, but any water which enters is caught by the baffles and falls out at the bottom of the case. Some error may be introduced by the condensation of water on the junctions, but it is not believed that this will cause serious difficulty.

The weights of the different parts are—

	Pounds
Galvanometer	2. 8
Gas cell junction cover	. 6
Air junction cover	. 5
Cable	12. 5
Total	16. 4

This weight compares favorably with the weights of instruments hitherto used, but it is greater than necessary, and if another instrument should be built it can be made lighter. Figure 4 is a photograph of the instrument showing the galvanometer, cable, and the gas and air junction covers.

When calibrated, the instrument was found to have a uniform scale within the limits of observational error. The scale was graduated to read correctly when the air junction is at a temperature of 10° C. This value was selected on the basis of the following values of mean temperature[5] in the altitude interval 2,000 to 3,000 feet at 40° latitude: Winter average, −3° C.; summer average, +22° C.; and yearly average, +10° C.

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[5] W. R. Gregg, Standard Atmosphere, National Advisory Committee for Aeronautics Technical Report No. 147; 1922.

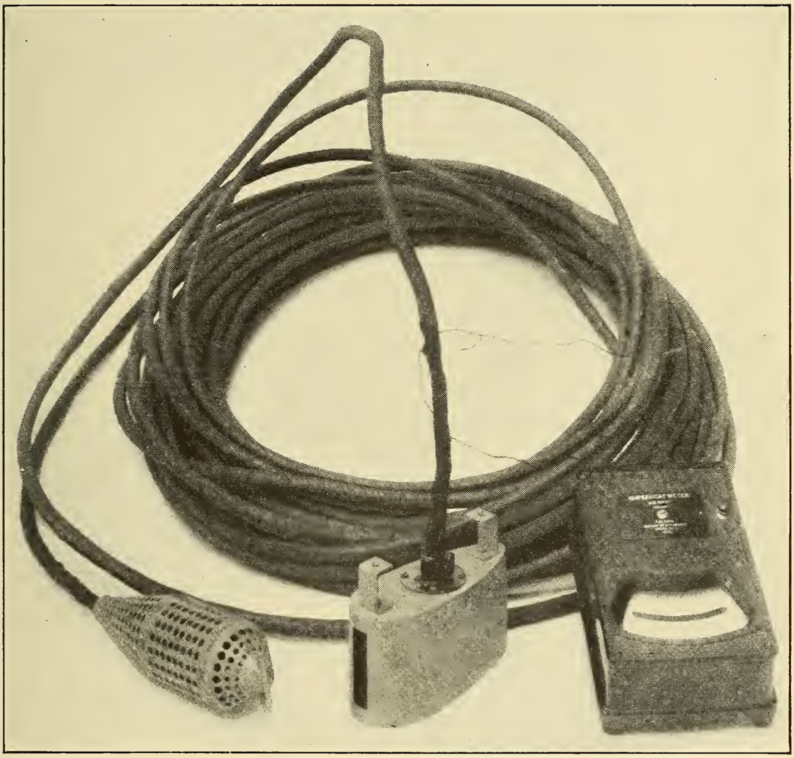

FIG. 4.—*The superheatmeter*

VI. ERRORS

Errors are introduced by variation of both the temperature of the air junction and of the galvanometer. The error due to change in resistance with temperature of the chromel-alumel couples was found to be negligible, and is not considered further in this paper. The first two effects will be considered separately, the air junction error first.

As already stated, the equation of the thermocouple when the temperature of the air junction is 0° C. is

$$E_0 = 39.04\ \tau + 0.0232\ \tau^2 \tag{9}$$

where E_0 is in microvolts.

τ is the temperature of the gas junction in degrees centigrade.

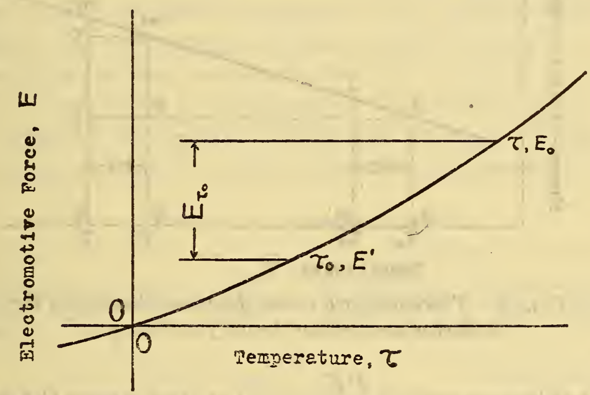

Fig. 5—*Diagram showing the change in electromotive force developed with change in temperature of air junction*

If the air temperature junction at some other fixed temperature τ_0, the electromotive force developed when the gas temperature junction is at τ is

$$E_{\tau_0} = E_0 - E' = 39.04\ (\tau - \tau_0) + 0.0232\ (\tau^2 - \tau^2{}_0) \tag{10}$$

See Figure 5 for definition of terms used in the equation.

What is meant by the error due to variation of the air junction temperature should be considered; that is, the change in E_{τ_0} due to a change in τ_0 for the same temperature difference (superheat) $\tau - \tau_0$. The expression for this error can be obtained by differentiating equation (10) with respect to τ_0, holding $\tau - \tau_0$ constant, but consideration of the thermoelectric power diagram makes the procedure more obvious.

In Figure 6 is plotted a thermoelectric power curve—a straight line—corresponding to the curve in Figure 5. The electromotive force developed when one junction of the thermocouple is at τ_0 and the other is at τ is represented by the area *rlmq*. Now, if the temperatures of both junctions are raised by the same amount $\Delta\tau$, so that one junction is now at the temperature τ'_0, the other at τ', the difference in junction temperatures remains the same, but the electromotive force is now represented by the area *r'l'm'q'*. The change in electromotive force due to this change in temperature of the junctions may be expressed as the difference of these two areas, this difference being equal to the area of the rectangle *mnpp'*. But

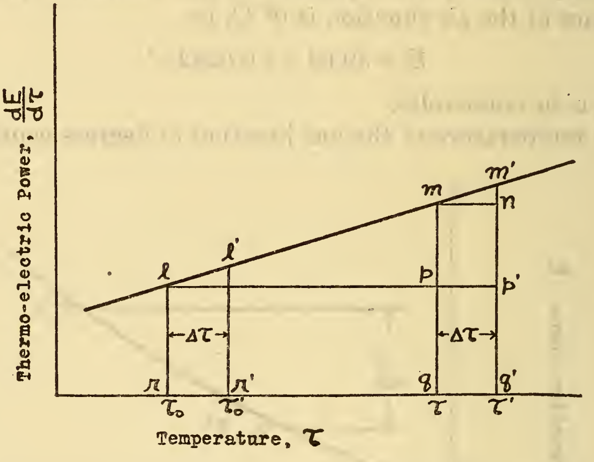

FIG. 6.—*Thermoelectric power diagram illustrating the method of computing the air junction error*

the area of this rectangle is $\frac{d^2E}{d\tau^2}(\tau-\tau_0)\Delta\tau$, and hence the error in the electromotive force is

$$\Delta E_{\tau_0}=\frac{d^2E}{d\,\tau^2}(\tau-\tau_0)\Delta\tau \tag{11}$$

or the proportional error is

$$\frac{\Delta E_{\tau_0}}{E_{\tau_0}}=\frac{\frac{d^2E}{d\tau^2}}{39.04+0.0232\,(\tau+\tau_0)}\Delta\tau \tag{12}$$

whence

$$\frac{\Delta E_{\tau_0}}{E_{\tau_0}}=\frac{0.0464}{39.04+0.0232\,(\tau+\tau_0)}\Delta\tau \tag{12'}$$

The percentage errors calculated for various air junction temperatures from equation (12′) are given for zero superheat in Table 1 under the heading, "Air junction error." The variations with superheat of the error for a given air junction temperature are so slight that they are not given in the table; for example, when the air junction temperature is −20° C., the error for −10° superheat is −3.67 per cent, while for +20° superheat it is $\overset{-}{\cancel{+}}$3.60 per cent. Consequently, since other errors and uncertainties nullify the utility of any attempt at extreme accuracy here, the variation with superheat is ignored, and the error for a given air temperature is given to the nearest 0.1 per cent.

The galvanometer also has temperature errors due to (1) the temperature coefficient of resistance of the copper winding, (2) the temperature coefficient of elasticity of the hairsprings, and (3) the change in strength of the permanent magnet with temperature. These effects produce the following errors in the instrument reading, $d\tau_0$ being the variation in the temperature of the galvanometer from its temperature at calibration.

(1) Resistance $-0.0017\ d\tau_0$.
(2) Hairsprings $+0.0004\ d\tau_0$.
(3) Magnet $-0.0013\ d\tau_0$.

The sum of the temperature errors of the galvanometer, due to the resistance, the hairspring, and the magnet amounts to $-0.0026\ d\tau_0$. Since these errors are small, it is permissible to add them and apply the resultant error directly. The values of the temperature error due to the galvanometer are given in Table 1. The values are, of course, based on the calibration temperature of +10° C.

TABLE 1.—*Temperature errors*

Temperature of air and galvanometer in degrees centigrade	Air junction error	Galvanometer error	Superheat meter error
	Per cent	*Per cent*	*Per cent*
−20	−3.7	+7.8	+4.1
−10	−2.4	+5.2	+2.8
0	−1.2	+2.6	+1.4
+10	0	0	0
+20	+1.2	−2.6	−1.4
+30	+2.3	−5.2	−2.9
+40	+3.4	−7.8	−4.4

The temperature errors of the entire instrument are equal to the algebraic sum of the percentage errors due to the air junction and to the galvanometer. A plus sign indicates an excess in the indication of the instrument and a minus sign a deficiency. It thus appears that the instrument will indicate a value of superheat which is 4.1 per cent too high when the galvanometer and the air junction are at a temperature of −20° C. and 4.4 per cent too low when at +40° C.

The superheat meter error as given assumes that the galvanometer is at the air junction temperature. Actually, this case represents an extreme condition and would be seldom encountered in use. In most instances the variation in temperature of the galvanometer from the calibration temperature would be considerably less than that of the air junction, owing to the fact that the galvanometer is mounted in the control car. Therefore, the superheat meter error usually would be less than the values given in the table.

VII. USE OF INSTRUMENT

This instrument was delivered to the Navy Department in August, 1925, and was immediately installed on the *Los Angeles.* According to all reports it has been operating in a satisfactory manner. The greatest value of superheat yet encountered is +27° F., which is less than the range of the instrument. If greater values are obtained, it is probable that a new instrument will be built which will be lighter and will have a greater range.

For further information on superheat see—

E. P. Warner, "Aerostatics," The Ronald Press Co., p. 46; 1926.
G. Do, "Le Ballon Libre," Libraire Aéronautique, Paris, p. 82; 1911.
J. D. Edwards and M. B. Long, Effect of Solar Radiation upon Balloons, B. S. Tech. Paper No. 128, 1919.

WASHINGTON, May 6, 1927.

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