A STURDY THERMOELECTRIC PSYCHROMETER FOR MICROCLIMATIC MEASUREMENTS

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To the microclimatologist who wishes to record the fine structure of the variations with time or space the measurement of humidity presents certain instrumental problems as the instruments generally used in meteorology prove to be unsuitable for this purpose. The conventional hair-hygrometer which has too large dimensions can only be used for the measurement of the mean humidity of air layers. The psychrometer which is the other instrument most commonly used in meteorology for the measurement of humidity does not function satisfactorily without aspiration and disturbs the microclimatic structure of a small space completely. Moreover, both instruments mentioned above, have too long time constants which do not permit their use for observations of rapid changes in humidity.

In 1932, Wald[1] and in 1936 Koch[2] developed psychrometers which employed wet elements with a diameter of only 1 mm. which did not require any ventilation. These two workers as well as Rossi (1933)[3] utilised small thermocouples for the translation of temperature differences into emfs thus permitting distant reading and recording. But non-ventilated thermocouple psychrometers have not come into general use by microclimatologists on account of their not yet having reached technical perfection.

Only recently a thermocouple psychrometer developed by Diem and reported to be working satisfactorily is mentioned in a paper of Trappenberg[4] but no technical details have been given. The present writer has designed a non-ventilated thermo-electric psychrometer for microclimatic measurements. When the instrument was completed a publication by Unger[5] on thermocouple psychrometers appeared. The instrument to be described in this paper differs from Unger's in certain features especially in the construction of the "wet" thermocouple. Furthermore, the radiation error being the only error of the instrument larger than the accuracy of the usual recording devices, it can be compensated utilising a new method. The instrument was designed for use even in heavy rains and gusts.

The psychrometer to be described in this paper employs a "wet" junction having a diameter of less than 1 mm. similar to the "wet" junctions of the instruments of Wald and Koch. In case the " wet " junction has the dimensions mentioned above, the psychrometric difference has already reached its maximum in still air and ventilation has no further influence on it. Hence the temperature of the " wet " junction depends only on the saturation deficit of the surrounding air.

The " wet " element is kept moist by means of a cotton thread twisted round the thermocouple and which passes into a small feed tank containing distilled water. Since the water evaporating from the exposed part of the wick influences the humidity of a small space the exposed evaporating surface of the wick should be kept at its minimum. To make a rough estimate of the minimum dimensions of the evaporating part, we assume a thread consisting only of water (the heat conductivity of cellulose is only about one-third of that of water) connected to a water reservoir, the temperature of which is assumed to be at air temperature. Each slab of the thread gains heat by conduction from the water reservoir and loses heat partly by evaporation and by conduction to the next slab. Another quantity of heat is received from the surroundings by convection and radiation and is a function of the temperature difference between the air and the slab. The temperature distribution along a wet thread may be represented by

$$\frac{\partial\theta}{\partial t}=\frac{K\partial^2\theta}{c\rho\partial x^2}-\frac{Lp}{c\rho\omega}+\frac{Hp\theta}{c\rho\omega} \tag{1}$$

where

L = heat lost by evaporation per unit area per unit time (a function of the saturation deficit of the air),

H = heat transfer coefficient of the thread,

K = heat conductivity of the thread,

c = specific heat of the thread,

ρ = density of the thread,

p = perimeter of the thread,

ω = cross-section of the thread.

For the steady temperature state we get

$$O=\frac{d^2\theta}{dx^2}-\frac{Lp}{K\omega}+\frac{Hp\theta}{K\omega}\,. \tag{2}$$

Since there is no flow of heat from the end of the thread, our solution is given by

$$\theta_e=\theta_w\,\frac{\cosh\mu\,(l-x)}{\cosh\mu l} \tag{3}$$

on putting

$\mu = \sqrt{\frac{Hp}{K\omega}}$

l = length of the evaporating part of the thread,

θ_w = psychrometric difference,

θ_e = temperature error.

Hence the temperature error at the end of the thread is

$$\theta_e = \frac{\theta_w}{\cosh \mu l}$$

and the minimum length $l_{\min}$ of the wet thread for the maximum permissible error $\theta_{e\max}$ is

$$l_{\min} = \frac{\cosh^{-1} \theta_w / \theta_{e\max}}{\mu}. \tag{4}$$

If we use

K $= 0 \cdot 0014$ cal °C.$^{-1}$ cm.$^{-1}$ sec^{-1},

H $= 0 \cdot 0007$ cal cm.$^{-2}$ sec^{-1},

p $= 0 \cdot 157$ cm. (diameter of the thread $= 0 \cdot 05$ cm.),

ω $= 0 \cdot 00196$ cm.^{2},

and if we permit a maximum error of 0·1° C. at a psychrometric difference of 20° C. we obtain

$$l_{\min} = \frac{\cosh^{-1} 200}{6 \cdot 3} = \frac{6}{6 \cdot 3} = 0 \cdot 95 \approx 1 \text{ cm.}$$

This value is in good agreement with the experimental results obtained with " wet " thermocouples of different lengths at low humidities.

The question for the minimum length of a wire placed in the centre of a wet thread of uniform temperature and adopting the temperature of the wick now remains to be considered. The wire is assumed to be made of constantan (conductivity 0·05) with a diameter of 0·01 cm., and to be coated with an insulating layer (conductivity 0·0005) of 0·005 cm. thickness. For 1° C. temperature difference between inner and outer surface of the insulating layer 0·1 cal. are conducted through an area of 1 cm.^{2} coating per second. This is the heat transfer coefficient of the wire.

Again we use the equation of conduction

$$\frac{\partial \theta}{\partial t} = \frac{K \partial^2 \theta}{c p \partial x^2} - \frac{H p \theta}{c p \omega}. \tag{5}$$

where the thread is supposed to be at zero temperature*. For a finite wire we obtain the special solution analogous to (3)

$$\theta_e' = \frac{\theta_w' \cosh \mu' (l' - x)}{\cosh \mu' l'}$$

where θ'_w is used for the temperature of the wire before entering the wet thread. The equation for the minimum length is analogous to (4)

$$l'_{min} = \frac{\cosh^{-1} \theta_w'/\theta_e'}{\mu'}$$

Using 20° C. for θ'_w and 0·01° C. for θ'_e we get

$$l'_{min} = \frac{\cosh^{-1} 2000}{28} = \frac{8 \cdot 3}{28} = 0 \cdot 3 \text{ cm.}$$

The minimum length for a copper wire of the same dimensions but with a heat conductivity of 0·9 is

$$l'_{min} = \frac{\cosh^{-1} 2000}{6 \cdot 7} = \frac{8 \cdot 3}{6 \cdot 7} = 1 \cdot 2 \text{ cm.}$$

Two types of "wet" thermocouples can be used. In the first pattern the thermocouple is strung between two points the junction being somewhere between the points of suspension (Fig. 1 *a*). A wet wick covers the junction as well as a part of both the copper and the constantan wires. The wick is

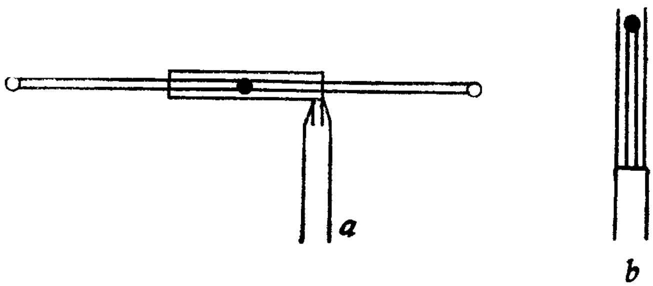

FIG. 1. "Wet" thermocouple, *a*: "L" type, *b*: needle type.

fed on the constantan side. If we assume the dimensions given in the examples calculated above, the wick has attained the correct "wet bulb" temperature after 1 cm. evaporating length. The constantan wire in its centre will obviously have adopted the same temperature at the junction. According to our estimations, the wick should cover at least 1·2 cm. of the copper arm of

* The heating of the thread by the wire has been neglected in this calculation as well as in the following estimations.

the element. Therefore the minimum total evaporating length of this type of " wet " thermocouple amounts to 2·2 cm.

The second type of " wet " thermocouple has the shape of a needle with the junction at its tip (Fig. 1 *b*). Since in this pattern the copper and constantan wire form a self-supporting thermocouple, the mechanical strain is much smaller than in the first pattern which enables a much thinner copper wire to be used. The use of the thin wire requires a shorter length of the evaporating wick for the copper wire to attain the correct " wet bulb " temperature, *e.g.*, 0·9 cm. for a copper wire of 0·005 cm. diameter if there is no temperature gradient along the wick. Since the temperature of the wick changes with increasing distance from the feed tank according to (1), equation (4) is to be changed into

$$\frac{\partial\theta}{\partial t} = \frac{K\partial^2\theta}{c\rho\partial x^2} - \frac{Hp}{c\rho\omega}\left(\theta - \frac{\theta_w \cosh\mu\,(l-x)}{\cosh\mu l}\right)$$

from which we obtain for the temperature error at the end of the needle

$$\theta_e = \frac{\theta_w}{(l-\mu^2/\mu'^2)}\left(\frac{1}{\cosh\mu l} - \frac{\mu^2/\mu'^2}{\cosh\mu' l}\right).$$

For a self-supporting " wet " thermocouple of 1 cm. length and 0·05 cm. diameter made of a 0·01 cm. constantan wire and 0·005 cm. copper wire the error is calculated to be 0·13° C. at a psychrometric difference of 20° C. Actually, the error will be smaller as the coating of the thermocouple is usually thinner than 0·005 cm. as assumed above, and it was experimentally determined that a needle-shaped " wet " thermocouple of the dimensions already mentioned developed an emf corresponding with the correct " wet bulb " temperature even at very low humidities. Therefore, we arrive at the conclusion that the needle pattern is preferable to the ' L ' pattern as it needs for the same maximum permissible error only half the evaporating surface of the ' L ' pattern. This means that a needle pattern " wet " thermocouple using an equal evaporating surface has a much smaller error than an ' L ' type thermocouple.

For the construction of the " wet " needles, enamelled copper wires with a diameter of 0·005 cm. (47 S.W.G.) and constantan wires with a diameter of 0·01 cm. (42 S.W.G.) have been used. The tip of the copper wire is soldered to the constantan wire at a distance of 0·5 cm. from its end (Fig. 2). Both wires are twisted together, dipped into a Bakelite solution and baked for several hours at 120° C. Special precaution should be taken that no free metallic surface is left exposed, otherwise the wet wick is liable to get spoiled by the corrosion products.

The thermocouple is passed through a capillary tube together with a white cotton thread. Then the thread is split and its fibres are twisted round the thermocouple (Fig. 2) and fixed to the tip of the constantan wire by means of a tiny drop of a cellulose cement. Under no circumstances the cement should be allowed to penetrate through the wick upto the junction.

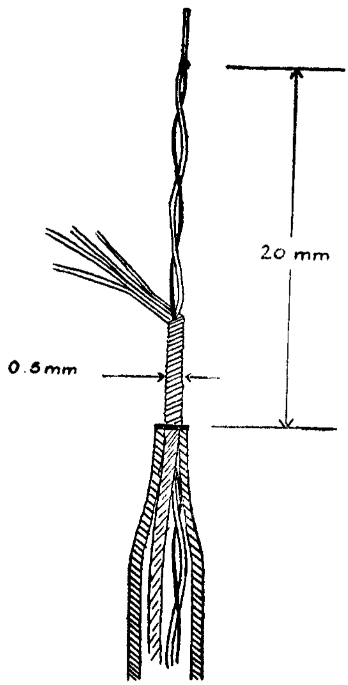

FIG. 2. Construction of the "Wet" needle, black: copper, white: constantan.

A length of 2 cm. has been chosen as a standard size of the " wet " needles and the diameter of this needle soaked with water is about 0·05 cm. It is advisable to have at hand a few extra " wet " elements inserted in suitable corks as replacement for dirty ones, whenever required.

The " dry " thermocouple of the psychrometer has been made of 0·01 cm. diameter (42 S.W.G.) copper and constantan wires joined together over a small spirit lamp using silver solder and borax as a flux. Such junctions are only slightly thicker than the diameter of the wire and are more resistant to mechanical strains than the copper wire of the thermocouple. The length of the " dry " element is determined by the maximum permissible error caused by heat conduction between junction and the support of the thermocouple. Using the copper constantan combination mentioned and taking 0·1° C. as the maximum error permitted at a temperature difference of 5° C. between the support and the air, the constantan wire should be made 2 cm. long and the copper wire 8 cm.

A fork has been found to be the most suitable design of the support. Its prongs are made of Perspex, a transparent plastic, which absorbs no radiation in the visible part of the spectrum and is a poor heat conductor. This eliminates the errors caused by heat conduction during periods of strong insulation.

The end of the prong carrying the constantan leads is shielded against radiation by means of a small polished piece of aluminium (S in Fig. 3) protecting the junction of constantan (thin)—constantan (thick) from being

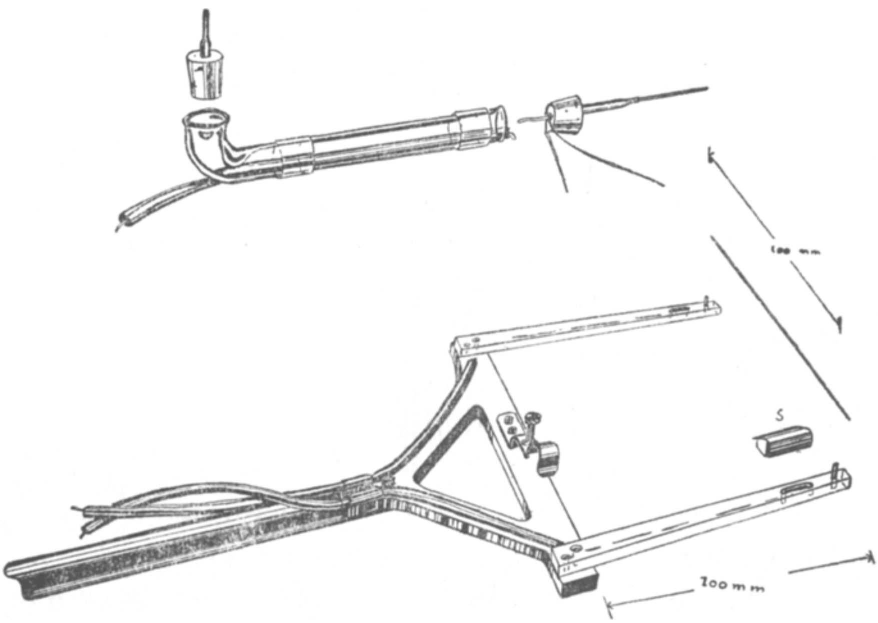

FIG. 3. Exploded diagram of the thermocouple psychrometer (*S*=aluminium shield)

heated above air temperature and thus preventing the introduction of an additional emf into the measuring element†). For the same reason the thick constantan wire is connected directly to the reference junction without an intervening plug.

The common reference junction of the instrument is coated with several layers of a chlorinated rubber paint securing a good thermal contact with the bath of reference temperature and at the same time complete insulation

† It has been observed that a small emf is always produced even in a constantan-constantan junction if a temperature difference is established (in this case it is of the order of 0·9 μV/°C).

against the other junctions kept in the same flask. Each layer of paint should be allowed to dry properly (for 24 hours) before applying the next layer.

The " wet " thermocouple forms together with the water tank the " wet unit " which easily can be replaced in the thermocouple psychrometer whenever required. The fixing rod permits the instrument to be mounted in any required position.

The measurement of the emfs developed is usually made with galvanometers. Since galvanometers are measuring currents the resistance of the " dry " element should be rendered equal to that of the " wet " one so that the same calibration of the galvanometer scale can be used for " dry " as well as for " wet " temperatures. The adjustment of the resistance can be made by taking a suitable length of the thin constantan wire of the " dry " thermocouple, the additional wire being wound round the prong of the support before soldering it to the thicker leading wire.

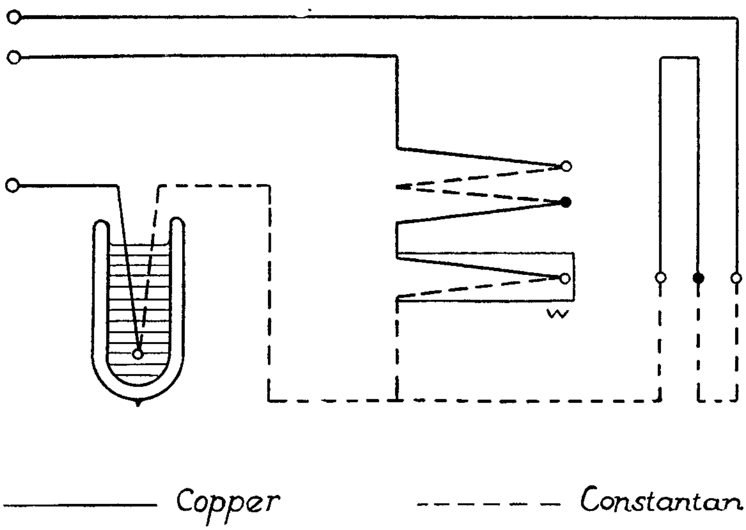

FIG. 4. Circuit of the thermocouple psychrometer compensated for the radiation error

The radiation error of the instrument can be compensated by introducing into the circuit consisting of the measuring junction, reference junction, and the measuring instrument, a second thermocouple in opposition with both its junctions exposed to the radiation. The junctions of the compensating element are made such that they differ in their radiation errors and that the difference in their radiation errors equals the radiation error[7] of the measuring junction. Details of this method will be given elsewhere, and the circuit is shown in Fig. 4. Instead of one " dry " measuring element of the uncompensated instrument there are three elements strung parallel from prong to prong at a distance of 0·5 cm. from each other. Since the absorptivity of the elements is 0·5 the central element has been blackened by means of camphor soot suspended in a very dilute solution of a cellulose lacquer which resulted in an absorptivity of almost 1·0. The same method has been utilised for the elimination of the radiation error of the "wet" thermocouple. Both arms of the compensating element are constructed as needles like the "wet" measuring element but coated with a cellulose lacquer. The central junction of this set has been made grey such that the radiation error of the "wet" junction was always balanced. Even at very large psychrometric differences (22° C.) the error of the "wet" junction described above, caused by the non-linearity of the emf as a function of the temperature is less than 0·05° C.

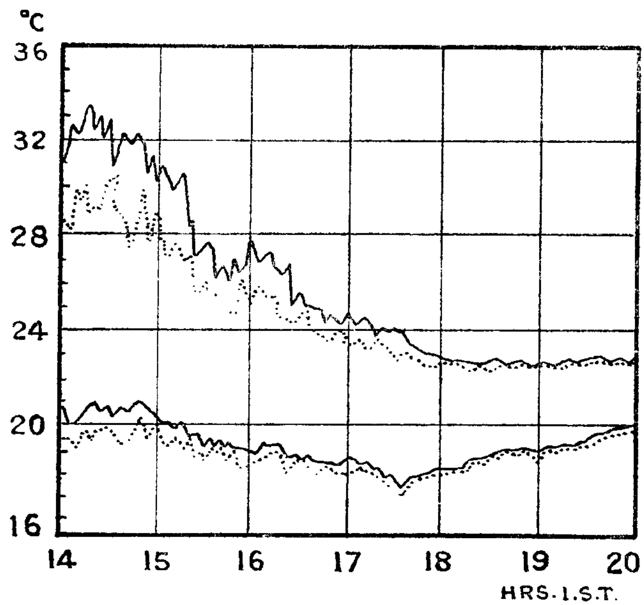

FIG. 5. "Dry" temperatures (upper two curves) and "wet" temperatures (lower two curves) at 10 cm. (straight lines) and 60 cm. (broken lines) above bare soil

Unger[5] has employed another method for the elimination of the radiation error of the "wet" junction of his instrument. He exposed the reference junction of the "wet" thermocouple to the air too. If the radiation error of the reference junction is equal to the radiation error of the "wet" junction the psychrometric difference between the junctions is not affected by the radiation (Robitzsch[6]). If this method is utilised the scale of the galvanometer should be calibrated in mV and not in °C.

A number of the psychrometers described in this paper has been made in the Meteorological Office at Poona and will be used for microclimatological and micro-meteorological studies close to the ground, close to large leaves and inside crops. A typical family of curves drawn after a record obtained by means of a Cambridge Thread Recorder without amplification of the emfs is shown in Fig. 5. In this record the accuracy of the reading is 0·2° C.

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Bibliography

1. Wald, H. .. *Z. f. d. ges Kälteindustrie*, 1932, **39**, H. 6.
2. Koch, W. .. *Gesundheits-Ingenieur*, 1936, **59**, 504–05.
3. Rossi, V. .. *Soc. Scient Fennica*; *Com. Phys. Math.*, 1933, **6**, 25, 1–22.
4. Trappenberg, R. .. *Arch. Met. Geoph. u. Biokl.*, 1952, **B4**, 65–84.
5. Unger, K. .. *Angew. Met.*, 1953, **1**, 279–83.
6. Robitzsch, M. .. In, Kleinschmidt, *Handbuch der meteorologischen Instrumente*, Berlin, 1935, 211.
7. Raschke, K. .. *Arch. Met. Geoph. u. Biokl.*, 1954, A5.

(1, 2 quoted after R. Geiger, "Das Klima der bodennahen Luftschicht," Braunschweig, 1950).