Proceedings of the Physical Society. Section B

Error and Accuracy in Thermocouple Psychrometry

To cite this article: J L Monteith 1954 *Proc. Phys. Soc. B* **67** 217

Error and Accuracy in Thermocouple Psychrometry

By J. L. MONTEITH
Department of Meteorology, Imperial College, London

Communicated by B. J. Mason; MS. received 3rd November 1953

Abstract. The paper discusses the main sources of error in the determination of vapour pressure with a thermocouple psychrometer. The predictions of theory and the results of experiment lead to no general agreement on the value of the constant in the classical psychrometer equation. A new derivation of the equation suggests a reduction of the commonly accepted value by a power of the ratio of diffusion coefficients for heat and water vapour. An expression is derived for the radiation error due to the difference of temperature between the wet bulb and its surroundings. Conduction of heat along the thermocouple wires and extraneous radiation produce errors for which an expression is derived for a particular thermocouple model. Finally, wet-bulb temperature errors are related to the corresponding vapour pressure errors.

§ 1. Introduction

The psychrometric determination of humidity, though theoretically simple, is subject in practice to a variety of errors. First, there is only empirical justification for the use of the classical psychrometer equation and the so-called 'constant' of the equation has never been accurately determined. Second, since the wet bulb is almost invariably at a lower temperature than its surroundings, it gains heat by radiative exchange, a source which is ignored in classical theory. Further errors may arise from conduction of heat to the wet bulb from its supports and from extraneous (e.g. solar) radiation.

Since the thermocouple is an ideal instrument for the measurement of small temperature differences, and since the geometry of the system is simple, the theory of these errors has been developed with reference to the thermocouple psychrometer. Other sources of error exist which cannot be treated mathematically and which have been summarized and discussed by Wylie (1949).

§ 2. The Psychrometer Equation

The classical wet-and-dry-bulb theory first postulated by August in 1825 and elaborated by many later workers leads to an equation of the form

$$e_s(T') - e = Ap(T - T') \qquad \ldots\ldots(1)$$

where T is the air temperature (°c), T' the wet-bulb temperature, p the total atmospheric pressure (mm Hg), e the vapour pressure of the air, $e_s(T')$ the vapour pressure of air saturated at T', and A is the psychrometer 'constant'.

In its fully developed form (Whipple 1933) classical theory gives

$$A = \frac{c_p}{L(T')\epsilon}\left(1 - \frac{e_s(T')}{p}\right) \qquad \ldots\ldots(1\,a)$$

where c_p is the specific heat of air at constant pressure, $L(T')$ is the latent heat of condensation of water vapour at T', and ϵ is the ratio of the densities of water vapour and dry air at the same temperature and pressure.

Awbery and Griffiths (1932) measured the dry- and wet-bulb temperatures of homogeneous air samples with mercury-in-glass thermometers aspirated at 3 m sec^{-1} and determined the vapour pressure independently from the dew point or by an absorption method. From these observations, which were made with values of T' between 20°c and 70°c, Whipple found a mean value of $A=6{\cdot}6\times10^{-4}$, with individual values ranging from 2 to 9×10^{-4} but showing no systematic variation with temperature. In the same temperature range, A calculated from eqn (1 *a*) varies from 6·38 to $4{\cdot}79\times10^{-4}$. On this evidence it seemed possible to neglect the term $e_s(T')/p$, which is principally responsible for the temperature dependence of A.

Müller-Cosna and Maier-Leibnitz (1951) have conducted experiments with a fine-wire thermocouple psychrometer producing air of known humidity by passage over acid of known concentration and temperature. At 200°c they found A to be $6{\cdot}2\times10^{-4}$. On theoretical grounds they derived the same value assuming that the gradients of temperature and humidity were constant across the boundary layer and using Polhausen's value of 1/3 for the ratio of boundary layer thicknesses for momentum and heat. This leads to an equation of the form

$$e_s(T')-e=\left(\frac{K}{D}\right)^{2/3}\left(\frac{c_p}{L(T')\epsilon}\right)p(T-T') \qquad \ldots\ldots(2)$$

where K and D are the coefficients of diffusion for heat and water vapour in air. The value of K/D is discussed later.

Wylie (1949) has suggested that, in the absence of radiative effects, the psychrometer constant should depend simply on the ratio of the heat and water vapour transfer coefficients of the wet bulb. Adopting values of these coefficients found by McAdams (1933) and Powell (1940), Wylie gives

$$Ap=\frac{0{\cdot}27+0{\cdot}567(Vd)^{0{\cdot}56}}{(Vd)^{0{\cdot}60}} \qquad \ldots\ldots(3)$$

where V (cm sec^{-1}) is the velocity of the air stream normal to a wire of diameter d (cm).

For $Vd=10$, 100, and 300 $cm^2\,sec^{-1}$, A assumes values of 7·7, 6·4, and $6{\cdot}1\times10^{-4}$ ($p=760$ mm), in apparent agreement with the fact that wet-bulb depressions increase to a maximum with increasing aspiration. It will be shown, however, that this variation can be ascribed entirely to a radiation effect and is therefore not a fundamental property of the wet bulb as (3) suggests. A more serious objection to (3) is that for constant aspiration A increases—and hence the depression decreases—when d is decreased. In practice the depression of a wet bulb increases to a maximum as the dimensions are decreased. A more rigorous application of transfer principles along lines suggested by Jacob (1949) has been found to give an equation in which the 'constant' shows a much weaker dependence on the Reynolds number of flow.

§ 3. A New Derivation of the Psychrometer Equation

Heat transfer by forced convection in a gas is specified by the Nusselt number Nu which, by dimensional analysis, can be expressed as a function of the Reynolds and Prandtl numbers of the flow, i.e.

$$\mathrm{Nu}=\frac{hd}{K\rho c_p}=\phi\left(\frac{Vd}{\nu},\frac{\nu}{K}\right) \qquad \ldots\ldots(4)$$

where d is a characteristic length, ν the dynamic viscosity of air, ρ the air density, h the heat transfer coefficient and ϕ is a function which must be determined empirically.

The diffusion of small quantities of vapour in air under the action of a concentration field can be similarly represented by a mass transfer coefficient

$$N_M = \phi\left(\frac{Vd}{\nu}, \frac{\nu}{D}\right) \qquad \ldots\ldots(5)$$

by appeal to the principle of similarity of heat and vapour transfer.

The observations of a number of workers for long heated cylinders at right angles to the air stream have been summarized by Jacob (1949) and can be described by the equation

$$\mathrm{Nu} = P\left(\frac{Vd}{\nu}\cdot\frac{\nu}{K}\right)^n = Q\left(\frac{Vd}{\nu}\right)^n \qquad \ldots\ldots(6)$$

where the values of the numerical factors Q and n vary somewhat for different workers but in all cases show a weak dependence on Reynolds number R. The following values are due to Hilpert (1933):

R	1–4	4–40	40–4000
Q	0·891	0·821	0·615
n	0·33	0·39	0·47

When heat and mass transfer occur together we have from (4), (5) and (6)

$$N_M = P\left(\frac{Vd}{\nu}\cdot\frac{\nu}{D}\right)^n \qquad \ldots\ldots(7)$$

i.e.

$$N_M = \mathrm{Nu}\left(\frac{K}{D}\right)^n.$$

The simultaneous use of (4) and (5) implies that the transfers of heat and of vapour occur in non-interacting fields, a condition satisfied by the evaporation of water from a wet-bulb surface. This assumption resembles the 'two-stream' hypothesis of the classical treatment. In the first place, density and temperature differences are small and separation of the air and water vapour by thermal diffusion is therefore negligible. Secondly, since the saturation water-vapour content of air at normal temperatures is of the order of 1%, the surface gradient of vapour does not significantly affect the thermal properties of the air and hence the heat transfer process. This corresponds to the classical assumption that the heat capacity of the vapour can be neglected compared with that of the air.

In the absence of radiative and conductive sources, the heat flux normal to a thermocouple wire of diameter d can be written

$$H = h(T - T') = \mathrm{Nu}\frac{K\rho c_p}{d}(T - T') \qquad \ldots\ldots(8)$$

where T' is now the *observed* wet-bulb temperature.

The water vapour flux is

$$M = N_M \frac{\rho D}{d}\{x_s(T') - x\} \qquad \ldots\ldots(9)$$

where x is the humidity mixing ratio (gm/gm).

In the equilibrium state when T' is constant

$$H = L(T')M. \qquad \ldots\ldots(10)$$

Then combining (8), (9) and (10), and assuming as in the classical derivation that $x_s(T')\simeq\epsilon e_s(T')/p$,

$$e_s(T')-e=A'p(T-T') \qquad \ldots\ldots(11)$$

where

$$A'=\left(\frac{K}{D}\right)^{1-n}\frac{c_p}{L(T')\epsilon}. \qquad \ldots\ldots(11\,a)$$

Equations (1) and (11) differ only by the factor $(K/D)^{1-n}$, which cannot be accurately computed. Montgomery (1947), from independent values of the coefficients, gave $K/D=0{\cdot}85$. A considerable amount of experimental evidence supports a higher value, and Powell (1940) has found $K/D=0{\cdot}90$. Combining this with Hilpert's values of n and with $c_p/L\epsilon=6{\cdot}6\times10^{-4}$ we obtain the following values for $A'\times10^4$ for thermocouple elements of different diameters at various rates of aspiration:

V (cm sec^{-1})	10	50	100	300
d (cm)				
0·01	6·15	6·15	6·19	6·19
0·1	6·19	6·19	6·24	6·24
0·5	6·19	6·24	6·24	6·24

These values are close to the experimental figure of 6·2 found by Müller-Cosna and Maier-Leibnitz.

The additional factor $(K/D)^{1-n}$ arises because the behaviour of the boundary layer of the wet bulb, which is completely ignored in the classical derivation, is introduced through the function ϕ. Since $K<D$ the effect of the boundary layer is to give a slightly greater depression under given conditions than that predicted by (1). The depression decreases slightly with increasing Reynolds number, but in practice such an effect would probably be masked by the opposed and much larger radiation effect discussed in the next section.

The above theory holds only for forced convection when natural convection effects are negligible.

§ 4. Inherent Radiation

In the derivation of (1) and (11) it was assumed that the air flow past the bulb provided the only source of heat. If, however, the surroundings of the wet bulb are at the free-air temperature, the effect of heat gained by radiation may be significant, particularly when the aspiration is slight. Since this effect occurs in all normal psychrometer systems it will be termed the 'inherent radiation' effect.

Following Wylie we may write the flux R of radiant heat normal to the bulb as $h_R(T-T^*)$ where the effective coefficient of radiative heat transfer is $h_R=4\sigma T^{*3}$, T^* is the observed wet-bulb temperature in °K, ρ is Stefan's constant, and $T-T^*\ll T$. The total transfer of sensible heat can therefore be written

$$H+R=(h+h_R)(T-T^*)$$

whence

$$e_s(T^*)-e=A'p\left(1+\frac{h_R}{h}\right)(T-T^*). \qquad \ldots\ldots(12)$$

It is convenient to express the effect in terms of the ratio a of the observed depression to the depression calculated from (11). Since $T' \simeq T^*$ we have

$$e_s(T^*) \simeq e_s(T') + \left(\frac{\partial e}{\partial T}\right)_{T^*} (T^* - T'). \qquad \ldots\ldots(13)$$

From (11), (12) and (13)

$$a = \frac{T - T^*}{T - T'} = \left[1 + \frac{r}{1+r}\frac{h_R}{h}\right]^{-1} \qquad \ldots\ldots(14)$$

where

$$r = \frac{A'p}{(\partial e/\partial T)_{T^*}}. \qquad \ldots\ldots(14a)$$

Since h_R is generally much smaller than h, we may write

$$a \simeq 1 - \frac{r}{1+r}\frac{h_R}{h}. \qquad \ldots\ldots(14b)$$

For a 1 cm diameter bulb, a calculated from (14) and (8) is plotted in figure 1 with an experimental curve given by Wylie. Wylie chose T' arbitrarily to make

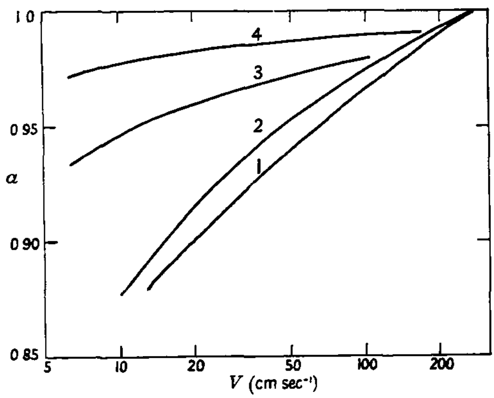

Figure 1. Variation of a with aspiration rate V. 1, $d=1$ cm : from Wylie's experimental curve, plotted as a/a (300); 2, $d=1$ cm : from eqn (14), plotted as a/a (300); 3, $d=0{\cdot}122$ cm : 18 s w.g.; 4, $d=0$ 032 cm : 30 s.w g.

$a=1$ when $V=300$ cm sec^{-1}, and if the theoretical values are similarly adjusted agreement is close. The inherent radiation errors of 18 and 30 s.w.g. thermocouple wires are also plotted and show that a approaches unity only slowly as the aspiration rate is increased.

Powell (1936) found a linear relation between a and $\sqrt{d}$ for fine-wire thermocouple, in 'still' air. It was admitted that the psychrometers were mounted in an open-ended wind tunnel in a large room, circumstances not incompatible with an air velocity of several centimetres per second.

From (6), (8) and (14b) we have

$$\log(1-a) = (1-n)\log d - n\log V + \log\left\{\frac{r}{1+r}\frac{h_R \nu^n}{QK\rho c_p}\right\}.$$

Powell's linear relation with $n=0{\cdot}5$ was obtained by drawing a straight line through five of the six observed points. If the same observations are plotted logarithmically (figure 2), and all are given equal weight, the regression line is

$\log(1-a)=0{\cdot}62 \log d-0{\cdot}46$. This implies that $n=0{\cdot}38$, which compares favourably with Hilpert's value of 0·33 for low Reynolds numbers. Furthermore, this implies that the mean velocity in Powell's tunnel was 5 cm sec^{-1}—a reasonable value consistent with the assumption that (14*b*) is applicable to these observations.

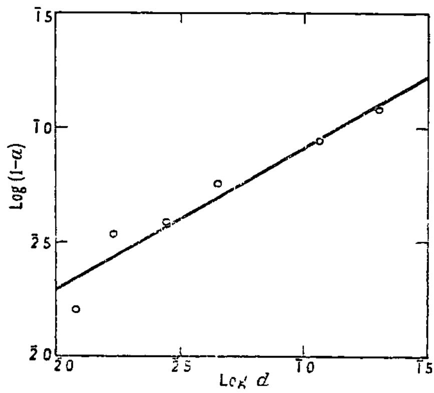

Figure 2. Variation of $1-a$ with d (*after* Powell).
Regression line : $\log(1-a)=0{\cdot}62 \log d-0{\cdot}46$.

§ 5. Conduction and Extraneous Radiation

The temperature of a thermocouple wet bulb will be greater than that predicted by (12) if the junction receives heat by conduction along the wires or if a radiative source exists other than that of the surroundings at air temperature. These effects have been discussed in general terms by Robitzsch (1932) and with special reference to thermocouples by Kettenacker (1932) who derived an expression for a as a function of the properties of the wire and of the air stream. No account was taken, however, of the properties of the wet wick surrounding the wire—a procedure which cannot be justified *a priori*.

The system discussed here consists of a copper–constantan thermocouple wound with a water-saturated cotton thread and stretched at right angles to the air stream between supports supposed held at air temperature. At 18°c the conductivities of copper and constantan are 0·92 and 0·054 cal cm^{-3} sec^{-1} deg^{-1} respectively, and it is therefore assumed that the heat conducted by the constantan portion of the couple can be neglected if the two portions are of roughly equal length. The wick conductivity is assumed to be 0·0014, the value for water, since the conductivity of dry cotton is very much less. Since, in turn, the conductivity of the wick is much less than that of copper, the radial temperature gradient in the wire can be regarded as negligible compared with that of the wick.

The following additional symbols are required: y = distance along copper wire from support, l = length of wire from support to junction, t = thickness of wick, T_w, T_c = temperatures of wick surface and wire respectively along any radius, k', k'' = thermal conductivities of water and copper, S = gain of radiant heat excluding 'inherent' radiation (cal cm^{-1} sec^{-1}).

If the heat conducted to the wick surface from the wire is written

$$C=\frac{k'(T_c-T_w)}{a \ln(1+t/d)}$$

the heat balance at the surface can be represented by

$$H+R+C+S=L(T_w)M. \qquad \ldots\ldots(15)$$

It is convenient to absorb the inherent radiation in the psychrometer constant by writing $A_R=A'(1+h_R/h)$. Then from (8), (12), etc. and (15)

$$e_s(T_w)-e=A_R p(T-T_w)+\frac{A'p}{h}(C+S). \qquad \ldots\ldots(16)$$

Employing again a modified form of (11) and (13),

$$\left\{A_R p+\left(\frac{\partial e}{\partial T}\right)_{T_w}\right\}(T_w-T')=\frac{A'p}{h}(C+S). \qquad \ldots\ldots(17)$$

Writing now

$$\mu=\frac{C+S}{T_w-T'}=h\left(1+\frac{1}{r(T_w)}\right)+h_R \qquad \ldots\ldots(18a)$$

and

$$\psi=\frac{C}{T_c-T_w}=\frac{k'}{d\ln(1+t/d)} \qquad \ldots\ldots(18b)$$

eqn (17) can be written

$$T_w=\frac{\mu T'+\psi T_c+S}{\mu+\psi}. \qquad \ldots\ldots(19)$$

The equation of thermal equilibrium for a cylindrical element of wire of length δy can be obtained by equating the axial flow of heat to the radial flow at the surface:

$$-k''\pi\frac{d^2}{4}\frac{d^2T_c}{dy^2}\delta y=-\pi dC\delta y. \qquad \ldots\ldots(20)$$

Solving for d^2T_c/dy^2 and substituting for T_w from (19) we find

$$\frac{d^2T_c}{dy^2}=\frac{4}{k''d}\frac{\mu\psi}{\mu+\psi}(T_c-T'-S/\mu). \qquad \ldots\ldots(21)$$

If the slight temperature dependence of μ is neglected, the general solution is

$$T_c=c_1\exp\left\{-\left(\frac{4}{k''d}\frac{\mu\psi}{\mu+\psi}\right)^{1/2}y\right\}+c_2\exp\left\{\left(\frac{4}{k''d}\frac{\mu\psi}{\mu+\psi}\right)^{1/2}y\right\}+T'+\frac{S}{\mu}. \quad \ldots(22)$$

If the air temperature T is constant or varies only slowly with time it may be assumed that $T_c=T$ at $y=0$, the first boundary condition. The second condition generally adopted in problems of this kind is $c_2=0$. Hence

$$T_c=\left\{(T-T')-\frac{S}{\mu}\right\}\exp\left\{-\left(\frac{4}{k''d}\frac{\mu\psi}{\mu+\psi}\right)^{1/2}y\right\}+T'+\frac{S}{\mu}. \qquad \ldots\ldots(22a)$$

When $y=l$, T_c, the effective temperature of the junction may be written T^*. Then by arrangement of terms

$$a=\frac{T-T^*}{T-T'}=\left\{1-\exp\left[-\left(\frac{4}{k''d}\frac{\mu\psi}{\mu+\psi}\right)^{1/2}l\right]\right\}\left\{1-\frac{S}{(T-T')(\mu+\psi)}\right\}. \quad \ldots(23)$$

From (18 a) and (18 b) we see that μ is related to the heat exchange between the wire and the air stream, i.e. to the aspiration, while ψ is related to the conduction of heat through the wick. In the case $\mu\gg\psi$ (and $S=0$) we see from (19) that $T_w=T'$, i.e. the wick surface attains the 'true' wet-bulb temperature, and from (22 a) that

$$T^*-T'=(T-T')\exp\left\{-\left(\frac{4\psi}{k''d}\right)^{1/2}l\right\}.$$

The effective wet-bulb temperature is independent of the aspiration rate but may be less than T' since the insulation of the wick may maintain a temperature difference between its surface and the thermojunction beneath it.

In the case $\mu \ll \psi(S=0)$, (19) shows that $T_w < T'$, due to the conduction of heat from the wire to the evaporating surface.

It is obviously important to determine the relative magnitudes of practical values of μ and ψ. The parameter ψ depends only on t and d: values are given in table 1.

Table 1. Values of $\psi = k'/d \ln(1+t/d)$

d (cm)	0 122	0·032	0·008
s.w g.	18	30	44
$t/d=1$ 0	0 017	0 063	0·25
$t/d=0$ 1	0·12	0·46	1·8
$t/d=0{\cdot}01$	1 2	4 4	17

From (18 a) it can be shown that μ is only weakly dependent on wick thickness when this is a small fraction of the wire diameter. (Powell (1936) has demonstrated experimentally that a is only slightly dependent on t in this case.) Values of μ for various V and d have therefore been computed using an arbitrary value of $2t/d = 0{\cdot}1$ (table 2). Since μ involves also the temperature dependent ratio r, this has been chosen arbitrarily as $\frac{1}{2}$ corresponding to $T^* = 18°$C.

Table 2. Values of $\mu = h\{(1+1/r(T_w))\} + h_R$

d (s.w.g)	18	30	44
$V=$ 1 cm sec^{-1}	0·0012	0·0027	0 0072
$V=$ 10 cm sec^{-1}	0·0025	0 0056	0 015
$V=$ 100 cm sec^{-1}	0·0066	0 015	0 033
$V=$1000 cm sec^{-1}	0·019	0 039	0 085

In almost all circumstances, therefore, $\mu \ll \psi$ and (23) can be written

$$a \simeq 1 - \exp\left\{-\left(\frac{4\mu}{k''d}\right)^{1/2} l\right\}. \qquad \ldots\ldots (23\,a)$$

In the next section it will be shown that for accurate work it is desirable that a should be of the order of 0·99. The aspiration rate required to give this value has been calculated as a function of l and d from (23 a) and is shown in figure 3. When the wire diameter is fixed by considerations of strength and rigidity, etc., the conduction error can be reduced to zero by ensuring that the depression in a given air stream is independent both of the aspiration rate *and* of the wick length (see Pasquill 1949).

When conduction effects are negligible compared with those of radiation $T^* = T' + S/\mu$ from (22 a). In the normal case the wet and dry bulbs are affected by the same extraneous radiation but the effect on the depression depends on the different emissivities of the two bulbs. Since appropriate values of these are difficult to determine, an expression for the combined radiation error, though readily derived, is of little practical value.

§ 6. The Error of Humidity Determinations

It is important to relate psychrometer errors expressed in terms of the fractional error a to the corresponding error in a vapour pressure determination.

Considering first the case in which the error is due to spurious heat sources, the calculated vapour pressure will have an error $\Delta e\ (a)$ where

$$e_s(T^*) - (e + \Delta e(a)) = Ap(T - T^*).$$

If the 'true' wet-bulb temperature is defined by (1), then using (13)

$$\Delta e(a) = (1-a)(T-T')\left\{Ap + \left(\frac{\partial e}{\partial T}\right)_{T^*}\right\}. \qquad \ldots\ldots(24)$$

With $a = 0{\cdot}99$, $T = 20°\text{c}$ and a relative humidity of 60%, $\Delta e(a) = 0{\cdot}08$ mm, i.e. about 0·8% of e. If a drops to 0·90, the error rises to 8%. It is clear that in normal conditions of temperature and humidity (and still more at higher temperatures) a should be of the order of 0·99.

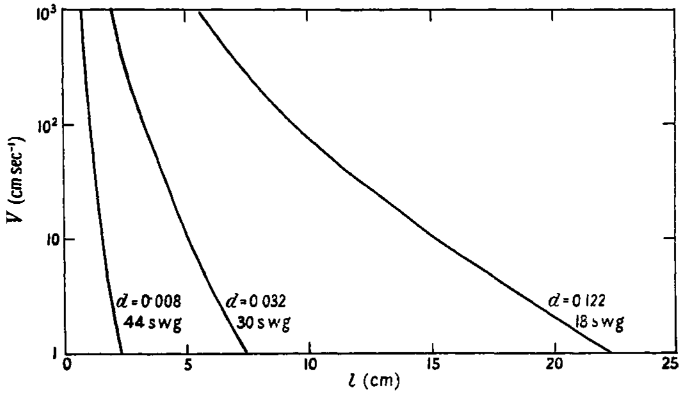

Figure 3. Aspiration rate required to give $a = 0\ 99$ for wires of different diameter and length.

When the error introduced by a is small, it may be of the same order of magnitude as that introduced by an inappropriate value of the psychrometer constant. If the constant be written $A \pm \Delta A$, then the combined error may be written

$$\Delta e(a, A) = \Delta e(a) \mp \Delta A p(T - T') \qquad \ldots\ldots(24\,a)$$

if second order terms are ignored. In the above conditions an error in A of only 0·3% is equivalent to $a = 0{\cdot}99$.

The error in a determination of A when the vapour pressure is measured independently can now be found by putting $\Delta e(a, A) = 0$ and combining (24) and (24 a) to give

$$\frac{\Delta A}{A} = (1-a)\left\{1 + \left(\frac{\partial e_s}{\partial T}\right)_{T^*} \Big/ Ap\right\}.$$

In the special case when A is calculated from the classical equation ignoring inherent radiation, $\Delta A/A = h_R/h$. For a bulb of 0·5 cm diameter (e.g. mercury-in-glass thermometer) aspirated at 3 m sec^{-1} in the above conditions, a from (14 b) is roughly 0·98 and A is over-estimated by 6%. The accurate determination of the psychrometer constant therefore demands that the wet bulb should be as small as is practical if the aspiration is to be kept within reasonable limits. The fine-wire thermocouple is obviously well suited to such work and indeed to all accurate psychrometry.

Acknowledgments

The author is grateful to Mr. B. J. Mason for his encouragement and advice throughout the work. He would also like to thank the Department of Scientific and Industrial Research for a maintenance allowance.

References

Awbery, J. H., and Griffiths, E., 1932, *Proc. Phys. Soc.*, **44,** 132.
Hilpert, R., 1933, *Forsch. Geb. Ingen.*, **4,** 215.
Jacob, M., 1949, *Heat Transfer* (London : Chapman and Hall).
Kettenacker, L., 1932, *Z. InstrumKde*, **52,** 319.
McAdams, W. H., 1933, *Heat Transmission* (New York : McGraw–Hill).
Montgomery, R. B., 1947, *J. Met.*, **4,** 193.
Muller-Cosna, C., and Maier-Leibnitz, H., 1951, *Z. angew. Phys.*, **3,** 343.
Pasquill, F., 1949, *Quart. J. R. Met. Soc.*, **75,** 239.
Powell, R. W., 1936, *Proc. Phys. Soc.*, **48,** 406 ; 1940, *Trans. Instn Chem. Engrs.*, **18,** 36.
Robitzsch, M., 1932, *Z, InstrumKde*, **51,** 80.
Whipple, F. J. W., 1933, *Proc. Phys. Soc.*, **45,** 307.
Wylie, R. G., 1949, *Psychrometry* (Sydney : Commonwealth Scientific and Industrial Research Organisation, National Standards Laboratory).